

Tick Size Wars

Tom Grimstvedt Meling and Bernt Arne Ødegaard*

November 2016

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Keywords: Equity Trading; Limit Order Markets; Tick Sizes; High Frequency Trading

JEL Codes: G10; G20

*Meling is at the University of Bergen. Tom.Meling@econ.uib.no. Ødegaard is at the University of Stavanger. bernt.a.odegaard@uis.no. This paper has benefited from discussions with Terrence Hendershott, Christine Parlour and Tamás László Bátyi.

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Introduction

The tick size, the minimum price increment in the limit order book, is arguably the most controversial market design feature in the current equity market policy debate. Following nearly two decades of regulatory pressure to reduce tick sizes in the United States, there is now a wide-spread concern that the current penny tick size in the United States in fact is too small and is hurting the quality of trading. The main argument is that small tick sizes reduces the profitability of financial intermediation to the extent that the intermediaries withdraw from trading — thus, harming overall stock liquidity. Concerns that small tick sizes deter liquidity provision have prompted U.S. regulators to initiate a comprehensive pilot program which will experimentally increase the tick size for selected small-capitalization stocks.¹

Moreover, there is a growing recognition among policy makers and practitioners alike that tick sizes not only affect within-market trading dynamics, but that they also can affect between-market dynamics. For example, some forms of U.S. equity trading, such as midpoint trading in over-the-counter markets, are exempt from the market-wide penny tick size and can therefore offer trading at tick sizes below one cent. Both regulators and the traditional stock exchanges, such as the NYSE and Nasdaq, have expressed concerns that such “subpenny trading” siphons trading volume away from the main markets and onto dark and largely unregulated trading platforms (e.g. Hatheway, Kwan, and Zheng (2014)).

Recent theoretical work in the academic literature also suggests that between-market differences in tick sizes can shift market shares from large-tick markets to small-tick markets. For example, Buti et al. (2015) predict that when a large-tick market faces competition from a small-tick market, some traders with access to both markets will route their orders to the small-tick market. The mechanism

¹The “Tick size pilot program” was implemented in early October 2016, and is scheduled to last for two years (See *SEC Approves Pilot to Assess Tick Size Impact for Smaller Companies*, SEC News Release, May 6, 2015). The pilot will increase the tick size for three test groups and compare the impact against an unaffected control group, each group comprising approximately 400 securities. Along a similar line, regulators in Europe are considering various options to change tick sizes. The current proposal by European regulators is that tick sizes should be stock-specific, and determined by a function of both the stock price and the stock liquidity.

which generates their theoretical result is that large tick sizes make it more difficult for traders to undercut resting orders in the limit order book to gain execution priority, which induces impatient traders to route their orders to markets where price competition is less constrained by the tick size and undercutting is easier. Consequently, a key prediction of this theoretical framework is that between-market differences in tick sizes have greater consequences for stocks where price competition is constrained than for stocks where price competition is unconstrained by the tick size.

In this paper, we use a unique natural experiment to explore the empirical impact of between-market tick size differences on the dynamics of equity trading. Our empirical setting involves three stock exchanges (Chi-X, Turquoise, and BATS Europe) who sequentially reduced their tick sizes for stocks with an Oslo Stock Exchange (OSE) primary listing. The OSE quickly responded by reducing its own tick sizes, before all markets agreed on a common tick size structure. The unanticipated nature of these tick size changes is conducive to causal interpretation of the impact of tick sizes on equity market dynamics.

We use the events of this “tick size war” to explore three empirical questions. The first question is how between-market tick size differences affect the distribution of market shares. In line with the theoretical predictions of Buti et al. (2015), we find that markets with smaller tick sizes capture market share. For example, following the tick size reduction by Chi-X, the market share of the OSE dropped overnight from 98% to 94% for the stocks where Chi-X competed.

Though we find empirical support for the theoretical prediction that tick sizes affect the distribution of market shares, we find little support for the theorized mechanism through which tick sizes should influence the distribution of trading volume. In particular, we find no relationship between the severity of constraints to price competition and market share loss during the tick size war, as hypothesized by Buti et al. (2015). Instead, we find that the main predictor of market share loss during the tick size war is the extent of high-frequency trading (HFT) in the large-tick market (OSE). Specifically, the impact of between-market differences in tick sizes on the distribution of market shares is greater for stocks with more HFT activity, irrespective of the severity of spread constraints in either market.

To explore the consequence of tick size competition on the quality of trading, we evaluate the same-market and cross-market effects of tick size reductions on liquidity. Our identification approach involves both a difference-in-differences (DiD) design and a regression discontinuity (RD) design. We find that tick size reductions appear to have negative spill-over effects on the liquidity in markets that do not change their tick size (a cross-market effect). In particular, both our empirical designs suggest that stock liquidity at the OSE deteriorated as a consequence of Chi-X reducing its tick sizes for OSE listed stocks. Likewise, we present evidence that order book depth at Chi-X suffered greatly from the OSE retaliatory tick size reduction. In terms of a same-market effect of tick size reductions, we present evidence that order book depth improved at Chi-X following its own tick size reduction. This finding strongly contradicts the existing empirical literature, and illustrates that in a modern equity market with competition between stock exchanges, the conventional wisdom concerning tick size effects may not hold.

Our results connect to several ongoing debates. First, we connect to the recent empirical literature which explores the connection between tick sizes and the distribution of market shares between stock

exchanges (e.g. Bartlett and McCrary (2015), Biais, Bisière, and Spatt (2010), Kwan, Masulis, and McNish (2015)). Consistent with this literature, we find that between-market tick size differences considerably impact the distribution of market shares. Unlike the existing literature, however, our results suggests that high-frequency trading is the main driver of the relationship between tick sizes and the distribution of market shares.

Thus, our results also appear to contradict the recent empirical literature which shows that HFTs prefer to trade in a large-tick size environment. For example, both O’Hara, Saar, and Zho (2015) and Yao and Ye (2015) argue based on supporting empirical evidence that HFTs are more active in liquidity provision and have larger profit margins in a large-tick environment. The mechanism that the authors propose is that the HFT speed advantage becomes more valuable when price competition is constrained by the tick size. Our results, in contrast, suggest that HFT appear to migrate the large-tick market (the OSE) in favor of small-tick competing markets, indicating a polar opposite HFT preference over tick sizes.

Finally, our results can provide guidance to policy makers in the United States and Europe who are currently considering tick size changes as a tool to improve investor welfare (see footnote 1). One implication of our research is that there indeed may be room for efficiency-improving tick size regulation. In particular, our results suggest that individual stock exchanges have incentives to reduce their tick size to capture order flow (which increases their revenues) and, at the same time, that tick size reductions have negative spill-over effects on competing marketplaces. Thus, a conceivable consequence of tick size competition is that the combined liquidity (across all trading venues) available to market participants declines. Policy makers can restrict stock exchanges’ ability to engage in such deleterious tick size competition by enforcing a shared tick size regime across all equity markets competing for the same order flow.

The paper proceeds as follows. Section 1 provides an overview of existing literature; Section 2 provides institutional background on equity trading at the Oslo Stock Exchange; Section 3 describes the data used; Section 4 presents the events of the “tick size war” and an empirical analysis on the distribution of market shares; Section 5 explores the determinants of fragmentation (market share changes); Section 6 investigates how market quality evolves, before Section 7 concludes.

1 Literature

Our research can be placed at the intersection of two literatures. The first is the extensive theoretical and empirical literature on the role of tick sizes in the context of a single limit order market. The second is the (also extensive) literature on competing market places for equity trading. In this section, we provide a brief overview of these literatures, before we summarize the smaller but rapidly growing literature exploring their intersection — namely, tick sizes in the context of competing marketplaces.

1.1 Tick sizes in a single limit order market

In the context of a single limit order book, tick sizes are relevant for the trading behavior of investors because they affect the profitability of different trading strategies. To illustrate this intuition, con-

sider the dynamic model of Foucault (1999). In this model, traders arrive sequentially with private valuations of the equity. They supply liquidity by placing a limit order at the price closest possible to their private valuation. The distance between the limit order price and their private valuation, which is bounded by the tick size, determines the profitability of the trader. Hence, reducing the tick size in the Foucault model would lower expected profits for liquidity suppliers, lower trading costs for liquidity demanders, and reduce the spread between bids and offers. The model also has the implication that depth at the best quotes fall when tick sizes are lowered.

While the Foucault model suggests that trader welfare will increase given a tick size reduction (due to the lowering of liquidity supplier profits), the real-world effects of changes to tick sizes are likely to be more complex. For example, in the Foucault model, trader arrival is exogenous. In practice, however, lowering the profitability of liquidity provision may lead to less overall liquidity provision due to endogenous trader exit. This view was, to some extent, confirmed in early empirical investigations of the US changes in tick size, from eights to sixteens (for surveys of this empirical literature, see Holden, Jacobsen, and Subrahmanyam (2013) and Securities and Exchange Commission (2012)). For example, Goldstein and Kavajecz (2000) argue that, while trading costs for small orders have fallen, trading costs for large institutional orders have increased, perhaps as a result of the withdrawal of liquidity providers from the market.

The recently implemented “Tick Size Pilot Program” in the United States, which focuses only on small and medium sized firms, reflects a suspicion that the “one size fits all” tick size of one cent in the United States may not be optimal for the entire distribution of firms. This argument is consistent with recent theoretical work by Werner, Wen, Rindi, Consonni, and Buti (2015). Their model shows that small tick sizes may be optimal for liquid order books, but that illiquid books may require larger tick sizes. The innovation of their model relative to the earlier literature, (Parlour, 1998; Goettler, Parlour, and Rajan, 2005) is to expand the action set of investors upon arrival in the market, allowing traders to either buy, sell, or not trade. The last option is the innovation in their model. Letting traders choose to withdraw from trading incorporates the notion that lower profitability due to smaller tick sizes may lead financial intermediaries to withdraw from the market. It is this result which leads them to recommend a higher tick size for less liquid stocks.

1.2 Competition between marketplaces

The modern equity trading environment is highly decentralized — investors no longer gather in the same physical locations to negotiate trades. Instead, equity trading is conducted through an intricate web of individual market places, most of which are connected to each other by high-speed communications. The largest of these markets are typically organized as public limit order books. The large markets face competition from smaller markets who continually adapt their market designs, for example by changing the extent of transparency or by reducing the tick size, in order to attract trading volume.

In the early theoretical market microstructure literature, equity market fragmentation was an implausible equilibrium because of the perceived network externalities associated with conducting all trading within a single marketplace. For example, in Pagano (1989) and Chowdhry and Nanda (1991),

markets tend to consolidate in equilibrium because both informed and uninformed traders wish to be part of the largest trading crowd. Informed traders find it easier to hide their trading intentions in a large crowd while uninformed are more likely to trade with other uninformed traders.

Equity markets, however, have fragmented and continue to do so, most likely for a variety of reasons. An argument originally put forward by Harris (1993) is that the new marketplaces enter to cater to the heterogeneous needs of different traders. For example, the extraordinary success of dark and anonymous trading platforms (for example, so-called dark pools) is likely a result of demand from large institutional traders who are concerned with hiding their trading intentions.

Whether a cause or a consequence of equity market fragmentation, high-frequency trading (HFT) has become a central feature in modern markets, since high speed communications and information processing can be viewed as necessary conditions to interact with multiple marketplaces. The key feat of the modern HFT revolution has been to dispose of direct human involvement in equity trading. Instead, sophisticated computer algorithms (albeit programmed by humans) continuously monitor the marketplaces, reacting to new orders and other relevant information, leading to a continuous updating of limit orders in the stock exchange order books. As such, HFT firms can be regarded as a new breed of a financial intermediaries.

Still, there is an ongoing discussion, both in academics and among market practitioners whether HFTs benefit or in fact hurt market quality (Menkveld, 2016). Advocates of HFT point to the overall reduction of equity transaction costs that coincides with the advent of HFT (See e.g. Hendershott, Jones, and Menkveld (2011)). Detractors of HFT do not value the need to trade at millisecond intervals and suspect that the willingness of HFT firms to invest heavily in achieving mere millisecond improvements in speed (Laughlin, Aguirre, and Grundfest, 2014) must mean that they are generating revenues at the expense of other traders (Lewis, 2014).

Whether HFT are benign or not will clearly depend on the strategies they pursue. In his survey of high-frequency trading, Menkveld (2016) groups HFTs into two types: High Frequency Market Makers (HFM) and High Frequency Bandits (HFB). Empirical evidence (Menkveld, 2013; Hagströmer and Nordén, 2013) suggests that a majority of HF traders behave as market makers, with a business model of providing liquidity, compensated by the bid-ask spread. However, the empirical evidence also point to the presence of traders with other strategies (the HF bandits), who for example, use their speed advantage to “snipe” stale quotes before other traders can modify them. Another hypothesized HF strategy involves predicting future order flow, trying to determine the presence of large trades being worked over time, and trading in front of these. Some HFT strategies even resemble illegal price manipulation: for example the “spoofing” strategy involves filling the order book with orders away from the best bid and/or ask in order to manipulate other traders’ order placement strategy.

From the point of view of our research, HFTs enter as a potential catalyst for market quality changes because changes to stock exchange market design (such as tick sizes) may impact HFT strategies. Two empirical studies provide evidence on the strategies pursued by HFTs in marketplaces that are similar to the markets that we study. Menkveld (2013) documents the presence of a high frequency market maker in the trading of Dutch shares at Chi-X, which is one of the marketplaces we consider in our study. Most likely, the market maker documented in Menkveld (2013) also covers

Norwegian shares traded at Chi-X. A possible effect of the change in tick sizes at the Chi-X exchange may be to alter the economics of HF market making at Chi-X (and the OSE). In another empirical study, Hagströmer and Nordén (2013) documents the presence of both HF market makers and HF bandits in their study of stocks with a main listing at the Stockholm stock exchange. The Stockholm exchange is closely related to the OSE in terms of market design and competitive setting, and we can therefore expect that issues related to HFT activity are similar between the two exchanges.

1.3 Tick sizes and competition between marketplaces

There is a growing recognition in the academic literature that tick sizes, much like other market design features, can be used as a competitive weapon for stock exchanges. Much of the existing empirical and theoretical literature is based on the institutional setting in the United States. Under Reg NMS, tick sizes in the US are regulated to be one cent. In principle, it is illegal for stock exchanges to allow trade at tick sizes below one cent. Some forms of trading, however, are exempt from the one-cent rule. For example, midpoint trading in over-the-counter markets, where traders agree to a price equal to the average of the current best bid and ask, may occur at tick sizes below one cent.

Both the SEC and the traditional stock exchanges, such as NYSE and Nasdaq, have expressed concerns that such “subpenny trading” creates opportunities for competing trading venues to, at the cost of a trivial price improvement, “jump the queue” at the limit order books constrained by penny tick sizes (See e.g. Hatheway et al. (2014)). This situation is analyzed theoretically (and empirically) by Buti et al. (2015). In their model, a Public Limit Order book (PLB) faces competition from a “Sub Penny Venue” (SPV). Their model shows that a major determinant of whether traders choose to “queue jump” to the sub-penny trading venue is the degree to which price improvement in the main market is possible. If price competition in the main market is constrained — the spread between bids and asks equals the minimum tick size — traders will have incentives to migrate to the sub-penny trading venue.

Recent empirical literature studies the intersection between equity order flow fragmentation and the cross-market tick size differences. For example, the degree to which US fragmentation is driven by tick size is investigated in Biais et al. (2010), O’Hara et al. (2015), and Bartlett and McCrary (2015). A related empirical literature explores the Canadian introduction of a rule mandating a minimum price improvement when dark venues compete against limit order books: Camerton-Forde, Malinova, and Park (2015) and Foley and Putniņš (2016).

1.4 Empirically testable predictions

Our research considers competing public limit order books that engage in competitive tick size reductions to capture trading volume. The tick size reductions that we study are conducive to causal inference, allowing us to explore three open research questions. The first question we explore is whether between-market tick size differences affect the distribution of market shares across stock exchanges. Our empirical setting corresponds well with the theoretical “Sub-Penny” model of Buti et al. (2015). Therefore, we test the prediction by Buti et al. (2015) that stock exchanges with large tick

sizes should lose market shares to stock exchanges with small tick sizes.

Second, we explore the channels through which tick sizes affect order flow fragmentation. We test the prediction by Buti et al. (2015) that traders are more likely to “queue-jump” when tick sizes constrain the bid-ask spread in the main market. In addition to this theory-driven empirical test, we also explore an alternative driver of fragmentation, namely high frequency trading. This is primarily motivated by the documented presence of different types of HFT at Chi-X, which we expect to also affect trading at the OSE.

The third research question we pose is how cross-market differences in tick sizes affect both same-market and cross-market market quality. Our empirical methodology allows us to explore how tick size reductions affect the trading in the tick size-cutting market but also in markets that do not change their tick size. As these between-market dynamics are highly complex, there are few theoretical predictions that can guide us. Therefore, our empirical study on the same-market and cross-market market quality effects is exploratory in nature.

2 Institutional Background

In this section, we describe the competitive situation of European stock exchanges before we provide institutional details on the trading of Norwegian equities — both at the Oslo Stock Exchange and at competing market places.

2.1 Competition for European order flow

National stock exchanges — traditionally situated in a country’s capital — long functioned as the monopoly market places for trading in domestic stocks. Competition for European equity order flow is a recent phenomenon, mainly caused by the 2007 introduction of the MiFID regulation.² Today, European equity trading volume is scattered across numerous market places, which compete vigorously to attract order flow.

Three types of trading venue have emerged to compete for order flow since the introduction of MiFID — Regulated Markets (RMs), Multilateral Trading Facilities (MTFs), and Systematic Internalisers (SIs). RMs, which are the ‘traditional’ stock exchanges, and MTFs, share similar features. For example, both RMs and MTFs can decide on the type of orders allowed on their order books, the structure of member fees (e.g. fixed, variable, maker-taker), and to some extent the transparency of the trading process. Moreover, both RMs and MTFs are allowed to organize primary listings. In practice, however, MTFs do not offer primary listing services, and can be viewed as the European equivalent of ECNs in the United States. Distinct from both RMs and MTFs, SIs are investment firms that systematically match client orders internally or against their own accounts.

²MiFID changed the European equity trading industry in three significant ways. First, by abolishing the “concentration rule” — which forced any regulated trade to be executed on the primary market — the new legislation unleashed competition for order flow between trading venues. Second, MiFID introduced a regulatory framework for the internalization of trading volume. Third, MiFID extended post-trade transparency requirements to over-the-counter transactions in regulated stocks and allowed trade reporting activity to be decentralized.

2.2 The Oslo Stock Exchange

The Oslo Stock Exchange is a medium-sized stock exchange by European standards, currently ranking among the 30 largest (by market capitalization) equity markets in the world. At the end of 2010, the combined market capitalization of the OSE was about 1.8 trillion NOK, spread out over 239 companies. Over the last decade, the OSE has collaborated and shared trading technology with other European stock exchanges. In 2002, the OSE introduced the SAXESS trading platform in cooperation with NASDAQ OMX. In 2009, the OSE partnered with the London Stock Exchange Group (LSEG) and implemented their TradElect trading platform in April 2010. The OSE now employs the Millennium trading system — the same trading system used by, for example, the London Stock Exchange and Borsa Italiana. The collaboration with other exchanges has implied the use of common technology and, to some extent, common market models. Nevertheless, the OSE has remained relatively free to implement individual trading rules and compose an individual market model.

The OSE operates a fully computerized limit order book, and has done so since January 1999. The order book allows conventional limit orders, market orders, iceberg orders and various other common order types. As is normal in electronic order-driven markets, order placements follow price-time priority — orders are first sorted by their price and then, in case of equality, by the time of their arrival.³ The trading day at the OSE consists of three sessions: an opening call period, a continuous trading period, and a closing call period. Call auctions may be initiated during continuous trading if triggered by price monitoring or to restart trading after a trading halt.

The distribution of firm size and trading volume at the OSE is heavily skewed. The OSE is dominated by a few very large companies, of which the largest, Statoil, an oil company, in 2009 accounted for about 25% of OSE market capitalization. Two other companies, Telenor (telecommunications) and Den Norske Bank (integrated financial) each accounted for about 10% of OSE market capitalization. The large firms at the OSE also dominate the trading interest (trading volume) at the exchange. Most of the trading volume at the OSE is in these largest stocks and other members of the OBX index. The OBX index, which is the basis for options trading at the OSE, contains at any point of time the 25 most liquid stocks at the OSE.⁴

2.3 OSE competitors: Chi-X, Turquoise and BATS

Three multilateral trading facilities (MTFs) — Chi-X, Turquoise and BATS Europe — feature prominently in our study due to their proclivity to adapt their market designs to capture market shares. Established in 2007 by a consortium of investment banks, Chi-X was the first MTF launched in Europe. Both BATS Europe and Turquoise were established in 2008 — BATS by BATS Global Markets, a U.S. exchange operator, and Turquoise by a consortium of investment banks. In December, 2009, the London Stock Exchange Group acquired a 60% stake in the Turquoise platform. In late 2011,

³More recently, and after the sample period we study, the OSE has adopted a price-visibility-time priority scheme, where, for price equality, displayed orders are given preference over hidden orders. Moreover, traders have the option to preferentially trade with themselves before trading with other traders. Such orders will execute according to price-counterparty-visibility-time.

⁴The composition of the OBX index is revised twice a year, in June and December, primarily based on total stock trading volume at the OSE over the previous six months. For more details on the OBX, see Meling (2016).

BATS Europe acquired Chi-X.

Like the OSE, these MTFs operate fully computerized matching engines where anonymous orders are matched continuously, following price-time priority. Unlike the OSE, the MTFs aggressively employ maker-taker fees to incentivize liquidity supply. For example, at Chi-X, liquidity demander (takers) pay a transaction fee of 0.3 basis points while liquidity suppliers (makers) earn a rebate of 0.2 basis points.

These competing stock exchanges offer trading in some, but not all, of the 200–300 stocks listed at the OSE. The MTFs initially offered trading in only the largest and most liquid stocks at the OSE, before gradually expanding their selection. For example, Chi-X initially offered trading in only the five largest stocks at the OSE. By 2015, Chi-X offers trading in more than 50 OSE products. Similarly, Turquoise initially opened trading in 28 OSE stocks but has since greatly expanded its selection to by 2015 include more than 150 OSE products.

Some stylized facts, based on publicly available data from Fidessa, a data vendor, may assist comprehension of the extent of the recent order flow competition. At the time of writing, in 2016, more than twenty RMs, MTFs, SIs, or unregulated over-the-counter trading venues offer trading in the most liquid stocks at the Oslo Stock Exchange. OSE retains the largest market share, followed by BATS over-the-counter (OTC), BATS CXE (formerly known as Chi-X), Turquoise, and BATS BXE (formerly known as BATS Europe). The OSE market share of overall trading (including OTC) in its most liquid stocks has declined from 100% in 2007 to close to 40% in 2016.

3 Data

We first present our data sources and define our main outcome variables, before providing some descriptive statistics of the trading activity at the Oslo Stock Exchange, Chi-X, Turquoise, and BATS.

3.1 Data Sources

We use several datasets in our empirical analysis. First, we use proprietary order-level data obtained from the “market surveillance” group at the OSE. This dataset contains information on all orders submitted to the exchange, whether the order is executed or not. Orders are flagged indicating whether they are executed (a trade), canceled, or modified. The fact that we see the individual orders, not just the trades, allows us to calculate measures such as the “order-to-trade” ratio (equivalently, the “quote-to-trade” ratio), the number of messages into the order book per executed order.

Second, to analyze trading in OSE listed stocks on alternative trading venues, we use the ThomsonReuters Tick History Database. This dataset contains trade-and-quote data for OSE listed stocks across all European equity market places. For lit market places (markets with displayed order books) the dataset provides information on the ten best levels of the bid and ask side of the limit order book. The ThomsonReuters data also includes some information on over-the-counter trading of OSE shares through inclusion of trades reported by Markit BOAT (a MiFID-compliant trade reporting facility).

We supplement these datasets with information on end-of-day prices, OBX index constituency, and tick size levels, obtained from the Oslo Stock Exchange Information Service (OBI).

3.2 Sample restrictions

In our empirical analysis, we focus exclusively on stocks with a primary listing on the Oslo Stock Exchange (OSE) for which we have detailed data on the trading process. We confine the sample period to the calendar year 2009 which encompasses all the relevant tick size changes. Moreover, we restrict attention to the trading that occurs on the OSE, Chi-X, Turquoise, and BATS Europe order books as these were the four exchanges involved in the “tick size war.”

We only consider stocks in the large-cap index at the OSE, the OBX index. Only OBX index stocks were affected by the July 6, 2009 tick size reduction by the OSE. Moreover, while Chi-X, Turquoise, and BATS offered trading in several stocks at the OSE, most of their trading activity was focused on OBX index stocks. Therefore, our sample comprises the 26 individual stocks in the OBX index.⁵

3.3 Variable definitions

In our empirical analysis, we explore the impact of the tick size war of 2009 on a number of common measures of stock market quality. To measure the transaction cost dimension of stock liquidity we use three spread measures of liquidity. First, the *relative spread* is defined as the difference between the current best bid and ask divided by the quote midpoint. We update the relative spread whenever the limit order book is updated, and calculate the average of these estimates throughout the trading day.

Second, the *effective spread* captures the cost of demanding liquidity. We define the effective proportional half-spread for trade j in stock i as $q_{ji}(p_{ji} - m_{ji})/m_{ji}$, where q_{ji} is an indicator variable that equals +1 for buyer-initiated trades and -1 for seller-initiated trades; p_{ji} is the trade price; and m_{ji} is the quote midpoint prevailing at the time of the trade. To determine whether an order is buyer or seller initiated, we compare the transaction price to the previous quote midpoint — if the price is above (below) the midpoint we classify it as a buy (sell). We compute average effective spreads across all transactions during the trading day.

Third, the *realized spreads* measure the gross revenue to liquidity suppliers after accounting for adverse price movements following a trade. The 5-minute realized spread for transaction j in stock i is given by $q_{ji}(p_{ji} - m_{i,j+5\min})/m_{ji}$, where $m_{i,j+5\min}$ is the quote midpoint 5 minutes after the j 'th trade. q_{ji} and p_{ji} are defined as before. Similar to the effective spread, we calculate the daily average of realized spreads for all trades during the day.

We estimate the *depth* of the limit order book by calculating the sum of pending trading interest at the best bid and ask prices. Our measure of order book depth is updated whenever the limit order book is updated, and averaged across all order book states throughout the trading day. To proxy for the noise in the price process, we estimate *realized volatility* as the second (uncentered) sample moment of the within-day 10 minute returns

We proxy for order flow fragmentation by the dispersion of trading volume across trading venues. In particular, we define our measure of order flow fragmentation for each stock i on date t as the

⁵One stock (RCL) moves into the OBX index and another (AKER) moves out of the OBX index during the sample period (the relevant OBX revision date is June 19, 2009). We do not remove these stocks from the sample.

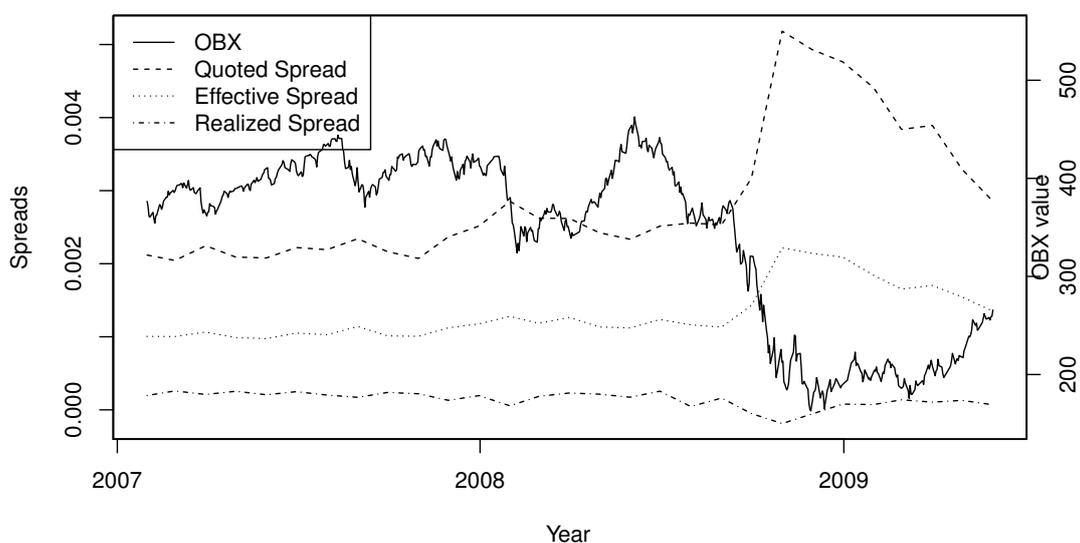
number of shares traded on venue v relative to the total trading volume across the OSE, CHI, TQ, and BATS. This measure can be interpreted as the daily market share of venue v in stock i .

3.4 Evolution of stock liquidity at the OSE (2007–2009)

To place the tick size war of 2009 into context, in Figure 1, we plot time-series of stock liquidity and stock prices for OBX index stocks at the Oslo Stock Exchange in the period 2007 to May, 2009. The figure shows that stock liquidity worsened significantly as stock prices declined during the financial crisis in the Autumn of 2008. During the first few months of 2009, however, both stock prices and stock liquidity at the OSE were gradually improving. This is particularly evident for average quoted spreads, which declined from 0.5% at the height of the financial crisis to about 0.25% in May, 2009 — almost the same level as before the crisis.

The sample period we consider surrounding the tick size war — the calendar year 2009 — is thus at the tail-end of the financial crisis in 2008. This means that our data sample is drawn from a period when stock liquidity was improving for reasons probably unrelated to the tick size war of 2009. In later sections, when we estimate the impact of the tick size war on stock liquidity, we explicitly address these potentially confounding trends with rigorous empirical specifications.

Figure 1 Evolution of stock prices and liquidity, 2007-2009:05



The figure presents the daily price level of the OBX index (right axis) and monthly averages of three spread measures of stock liquidity (left axis). The spread measures of liquidity are quoted (relative) spreads, effective spreads, and realized spreads. Spread measures of liquidity are first computed on the stock-day level, based on all the quotes and trades on the exchange any given day, before they are averaged across all stocks in the OBX index on a monthly basis.

Table 1 Descriptive statistics, January–May 2009

| | mean | std | min | median | max | <i>n</i> |
|----------------------------|--------|--------|--------|--------|---------|----------|
| Oslo Stock Exchange | | | | | | |
| Relative spread (%) | 0.404 | 0.212 | 0.089 | 0.341 | 1.668 | 2626 |
| Effective spread (%) | 0.132 | 0.065 | 0.036 | 0.116 | 0.573 | 2626 |
| Realized spread (%) | 0.025 | 0.061 | -0.596 | 0.021 | 0.762 | 2626 |
| Depth (thousand NOK) | 733 | 835 | 72 | 442 | 16758 | 2626 |
| Realized Volatility (%) | 0.970 | 1.790 | 0.179 | 0.677 | 46.864 | 2626 |
| Volume (thousands NOK) | 193023 | 322364 | 3000 | 71233 | 3942873 | 2626 |
| Chi-X | | | | | | |
| Relative spread (%) | 2.366 | 1.705 | 0.159 | 1.809 | 8.589 | 2368 |
| Effective spread (%) | 0.556 | 0.437 | 0.059 | 0.414 | 3.248 | 1863 |
| Realized spread (%) | 0.174 | 0.513 | -4.160 | 0.077 | 5.404 | 1859 |
| Depth (thousand NOK) | 187 | 106 | 12 | 174 | 981 | 2388 |
| Realized Volatility (%) | 0.558 | 0.269 | 0.047 | 0.515 | 5.603 | 1693 |
| Volume (thousands NOK) | 2364 | 4594 | 0 | 782 | 66823 | 2507 |
| BATS | | | | | | |
| Relative spread (%) | 0.696 | 0.752 | 0.099 | 0.529 | 9.856 | 1429 |
| Effective spread (%) | 0.294 | 0.281 | 0.042 | 0.219 | 4.209 | 654 |
| Realized spread (%) | 0.106 | 0.676 | -7.046 | 0.113 | 4.043 | 653 |
| Depth (thousand NOK) | 78 | 45 | 16 | 74 | 993 | 1674 |
| Realized Volatility (%) | 0.500 | 0.305 | 0.045 | 0.434 | 3.033 | 415 |
| Volume (thousands NOK) | 212 | 363 | 1 | 93 | 5777 | 1581 |
| TRQ | | | | | | |
| Relative spread (%) | 0.536 | 0.723 | 0.118 | 0.360 | 7.798 | 656 |
| Effective spread (%) | 0.233 | 0.265 | 0.047 | 0.172 | 3.155 | 608 |
| Realized spread (%) | 0.105 | 0.311 | -1.751 | 0.073 | 2.251 | 611 |
| Depth (thousand NOK) | 136 | 71 | 3 | 124 | 801 | 750 |
| Realized Volatility (%) | 0.522 | 0.258 | 0.086 | 0.472 | 2.390 | 611 |
| Volume (thousands NOK) | 1618 | 2519 | 1 | 843 | 37203 | 889 |
| Market Shares | | | | | | |
| OSE | 99.0 | 1.5 | 77.4 | 99.6 | 100.0 | 3747 |
| Chi-X | 1.3 | 1.5 | 0.0 | 0.8 | 22.6 | 2321 |
| BATS | 0.2 | 0.3 | 0.0 | 0.1 | 2.8 | 1613 |
| TRQ | 0.4 | 0.6 | 0.0 | 0.3 | 11.0 | 908 |

The table summarizes stock trading characteristics separately for trading at the Oslo Stock Exchange, Chi-X, BATS, and Turquoise. The sample period is January–May, 2009 (time period before the tick size war). Market quality measures: *Quoted (relative) spread*: The difference between the best bid and best ask in the order book, divided by price. Averaged across all order books during a trading day. *Effective spread*: Difference between trade price and a pre-trade benchmark, relative to trade price. *Realized spread*: Difference between trade price and a post-trade benchmark, relative to trade price. *Depth*: The total (NOK) amount outstanding at the best bid and ask. *Volume*: The total amount (in NOK) traded. *Realized volatility*: The (uncentered) standard deviation over ten minute interval returns. *Market shares*: The proportion of share trading volume on a given trading venue relative to the total share trading volume across the OSE, Chi-X, BATS, and Turquoise. At the OSE, the sample comprises all OBX index stocks.

3.5 Descriptive statistics: Comparing OSE and the MTFs

Table 1 summarizes our main outcome variables for the period January–May 2009 (the period before the tick size war) separately for the OSE, Chi-X, BATS, and Turquoise. The four stock exchanges in our sample differ notably in terms of estimated market quality. Transaction costs are smallest at the OSE with an average effective spread of 0.13%, followed by Turquoise with an average effective spread of 0.23%. The most expensive trading venue is Chi-X, with an average effective spread of 0.56%. Similarly, for our other two measures of transaction costs, relative and realized spreads, transaction costs are considerably smaller at the OSE than at the competing stock exchanges.

This comparison of transaction costs across exchanges may, however, be misleading. For example, as indicated by the number of observations, Chi-X is active in more stocks than the other alternative markets, BATS and Turquoise. That BATS and Turquoise appear to have smaller transaction costs than Chi-X may be because their trading activity is limited to only the most liquid stocks. Another reason to caution against a direct comparison of transaction costs is that our spread measures of liquidity do not account for the maker-taker fees applied at the MTFs. As such, we are comparing the gross transaction costs between venues, which may differ substantially from the net transaction costs, depending on the aggressiveness on the trading strategy.

The OSE order books are by far the deepest. The average order book depth at the OSE is 733 thousand NOK. While this average to some degree is inflated by the depth in Statoil (The median OSE depth is 442 thousand), all the other exchanges (Chi-X, BATS, and Turquoise) have depths below 200 thousand. The OSE is also (by far) the most actively traded venue. Consequently, the OSE holds a commanding market position for trading in stocks with an OSE primary listing. The average market share of OSE in the period January–May 2009 is 99%. The Chi-X market share is 1.3% in the shares they trade in while BATS and Turquoise hold a market share of less than half a percent.

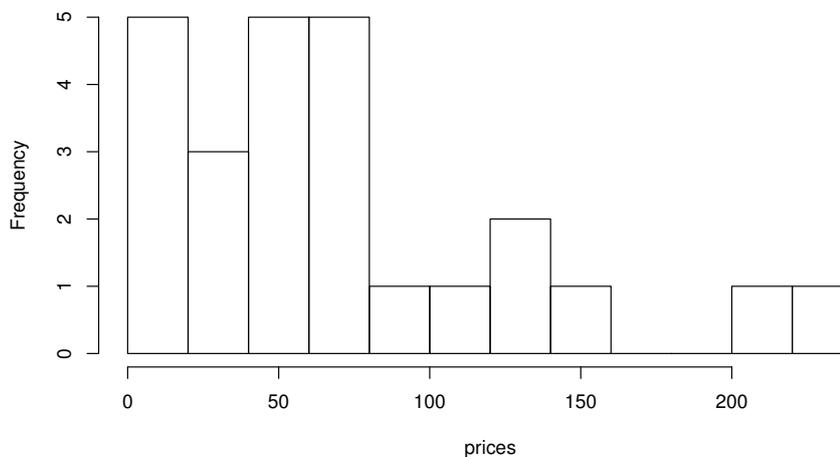
3.6 Distribution of stock prices at the OSE

Central to our later empirical analyses will be the distribution of stock prices at the Oslo Stock Exchange. Tick sizes for OSE listed stocks are determined by a step-function of prices — higher priced stocks have larger tick sizes (the tick size schedules are discussed in Section 4). To inform about the distribution of stock prices at the OSE, and thus, the range of possible tick sizes, in Figure 2 we plot the distribution of (end-of-day) stock prices for our sample of stocks on the last trading day of May, 2009. The figure shows that most of our sampled stocks are priced below 150 NOK. The lowest stock price in our sample is 3.68 NOK while the highest stock price is 226.25 NOK.

4 Tick size war for OSE listed stocks

The purpose of this paper is to explore the empirical impact of a series of tick size reductions for OSE listed stocks during the Summer of 2009, which we collectively refer to as the “tick size war.” In this section, we first summarize the sequence of events during the “tick size war” of 2009 before we explore changes to market shares surrounding the events.

Figure 2 Distribution of stock prices at the OSE (May, 2009)



The histogram presents the distribution of stock prices at the Oslo Stock Exchange on the last trading day of May, 2009. The sample comprises all OBX index stocks. Stock prices are denominated in Norwegian Krone (NOK).

4.1 The events of the tick size war

It is convenient to divide the tick size war into three distinct phases. In the first phase, which we call the *break-out phase*, three MTFs – Chi-X, Turquoise and BATS – challenged the market positions of the Scandinavian primary markets (Oslo, Stockholm, and Copenhagen) by successively reducing the tick size for their selection of Danish, Norwegian, and Swedish stocks. The tick size war commenced on June 1, 2009, when Chi-X reduced its tick sizes. Turquoise followed on June 8, reducing its tick sizes for Scandinavian stocks as well as for five London listed stocks. Finally, BATS Europe reduced its tick sizes for Scandinavian stocks, ten London stocks, and five Milan stocks on June 15.⁶

The tick size reductions by Chi-X, Turquoise, and BATS during the *break-out phase* were substantial. In Table 2, we summarize the tick size schedules used by all four stock exchanges throughout the calendar year 2009. At the time of the Chi-X tick size reduction, on June 1, 2009, the OSE operated with three tick size schedules: a flat tick size of NOK 0.01 for Statoil (the most liquid stock at the OSE); a general tick size schedule for all OBX shares, with tick sizes varying between 0.01 and 0.25; and a separate tick size schedule for all illiquid (non-OBX) shares. The new Chi-X tick size schedule, in contrast, introduced a NOK 0.001 tick size for all OSE stocks traded at Chi-X with prices below NOK 10 and a NOK 0.005 tick size for stocks priced above NOK 10. The tick size schedules introduced by Turquoise and BATS were less aggressive, but they still offered substantially smaller tick sizes than the OSE.

We can point out that before the tick size war, tick sizes for stocks listed at the OSE were large compared to the current penny tick size in the United States. For example, converted at the 2009 exchange rate of 6.3 NOK per USD, the pre-tick-size-war tick size of NOK 0.01 for Statoil translates

⁶These dates have been collected from a BATS Europe study of pan-European tick size changes (BATS, 2009).

Table 2 Tick size schedules at the OSE, Chi-X, BATS, and TQ.**Panel A: The Oslo Stock Exchange**

| - July 2009 | | | July 2009 | | | Fall 2009 - | | |
|-------------------------------------|---------------|--------------|----------------------|---------------|--------------|----------------------|------------------|--------------|
| | Price band | Tick Size | | Price band | Tick Size | | Price band | Tick Size |
| Most Liquid stocks (Statoil) | - | 0.01 | All OBX Stocks | - | 0.01 | All OBX stocks | - 0.4999 | 0.0001 |
| | | | | | | | 0.5 - 0.9995 | 0.0005 |
| | | | | | | | 1 - 4.9990 | 0.001 |
| | | | | | | | 5 - 9.995 | 0.005 |
| | | | | | | | 10 - 49.990 | 0.01 |
| Other OBX stocks | - 14.99 | 0.01 | | | | | 50 - 99.95 | 0.05 |
| | 15 - 49.95 | 0.05 | | | | | 100 - 499.90 | 0.1 |
| | 50 - 99.90 | 0.10 | | | | | 500 - 999.50 | 0.5 |
| | 100 - 249.75 | 0.25 | | | | | 1,000 - 4,999.00 | 1 |
| | 250 - 499.50 | 0.50 | | | | | 5,000 - 9,995.00 | 5 |
| | 500 - | 1.00 | | | | | 10,000 - | 10 |
| | | | | | | | | |
| Non- OBX stocks (illiquid) | - 9.99 | 0.01 | | | | | | |
| | 10 - 14.95 | 0.05 | | | | | | |
| | 15 - 49.90 | 0.10 | | | | | | |
| | 50 - 99.75 | 0.25 | | | | | | |
| | 100 - 249.50 | 0.50 | | | | | | |
| | 250 - | 1.00 | | | | | | |

Panel B: Chi-X and Turquoise/BATS

| Chi-X - June 2009 | | | Turquoise/BATS - June 2009 | | |
|-----------------------------|---------------|--------------|-----------------------------------|---------------|--------------|
| | Price band | Tick Size | | Price band | Tick Size |
| OBX Shares (selected) | 0 - 9.99 | 0.001 | OBX shares (selected) | - | 0.0001 |
| | 10 - | 0.005 | | 1 - | 4.9995 |
| | | | | 5 - | 9.999 |
| | | | | 10 - | 49.995 |
| | | | | 50 - | 99.99 |
| | | | | 100 - | 499.95 |
| | | | | 500 - | 999.90 |
| | | | | 1,000 - | 4,999.50 |
| | | | | 5,000 - | 9,999 |
| | | | | 10,000 - | 99,995 |
| | | | | 100,000 - | 10 |

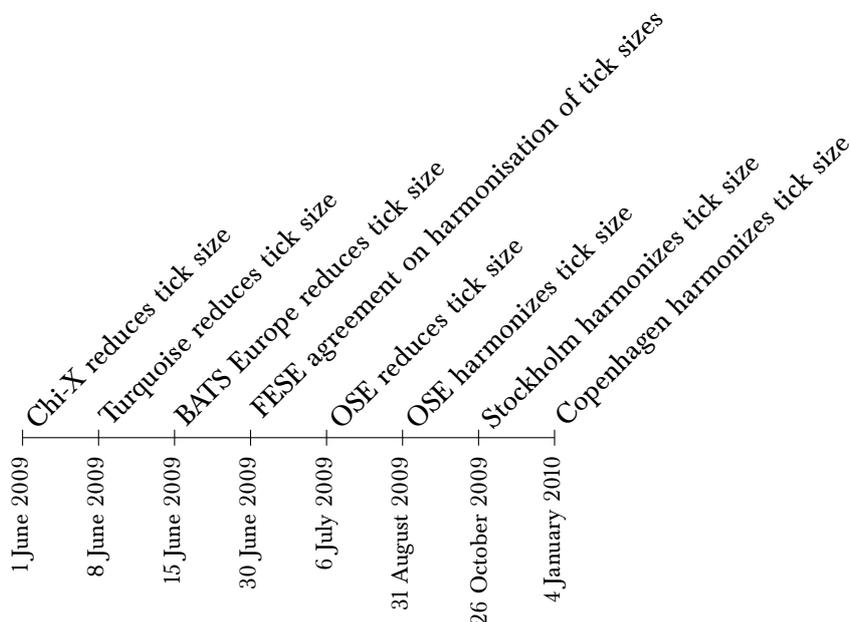
The table presents the tick size schedules used by the Oslo Stock Exchange (OSE), Chi-X, Turquoise, and BATS Europe during the tick size war of June, 2009. Chi-X implemented its tick size schedule on June 1, 2009, Turquoise on June 8, 2009, and finally BATS Europe on June 15, 2009. The tick size schedules for BATS Europe and Turquoise have been collected from BATS (2009). The tick size schedule for Chi-X has been collected from BATS-CHIX (2012) (the 'eurozone' tick size schedule).

into 0.15 cents. However, the post-war Chi-X tick size of 0.005 translates to only 0.08 cents. Thus, the tick size war pushed tick sizes for OSE listed stocks below the current US tick size regime.

In the second phase of the tick size war – the *retaliation phase* – the OSE responded in kind to its tick size cutting competitors. On July 6, 2009, the OSE reduced its tick size uniformly to 0.01 for the 25 stocks in the OBX index. In a press release, the OSE declared that other trading venues “offer trading with tick sizes that are significantly lower than Oslo Børs offers. Oslo Børs has therefore found it necessary to respond to these changes.” Doing so, the OSE largely nullified the between-market tick size differences that arose during the *break-out phase*.

The final stage of the tick size war is the *harmonization phase*. On June 30, 2009, the Federation of European Securities Exchanges (FESE) brokered a harmonization of tick sizes between the stock exchanges and the MTFs. FESE argued that the recent lowering of tick sizes was not in the interest of end investors and that too granular prices could have detrimental effects on stock market depth. The FESE agreement facilitated a pan-European harmonization of tick size schedules for the most actively traded stocks, which significantly simplified and reduced the number of different tick size schedules used by the exchanges. The far-right panel of Panel A in Table 2 displays the tick size schedule chosen by the OSE. These changes were to be implemented within two weeks and six months depending on the needs of the exchange. The Scandinavian markets responded in steps. OSE harmonized tick sizes August 31, 2009. The other markets followed later, Stockholm on October 26 and Copenhagen on January 4, 2010. In figure 3 we illustrate the timeline of events.

Figure 3 Time-line of the events of the tick size war



4.2 Market shares during the tick size war

We begin our empirical analysis by exploring the evolution of stock exchange market shares during the tick size war. To quantify the changes in market shares, we define three time periods. We define a *pre-war* period from May 1 to May 31, a *break-out* period from June 1 to July 5, and a *retaliation* period from July 6 to August 31. Within each of these time periods, we compute market shares for each stock i on date t for trading venue v .

In Table 3, we present the average market share for each trading venue in each of the three time periods, as well as the change in market share between a given time period and the pre-war period. The change in market share with corresponding statistical inference is obtained by separately comparing daily observations of market shares in one period (the break-out period or the retaliation period) to daily observations of market shares in the pre-war period in a regression framework, with standard errors clustered at the stock-level.

Table 3 Distribution of market shares during tick size war

| | Pre-war May 1 - May 31 | Break-out June 1 - July 5 | Retaliation July 6 - August 31 |
|----------------------------|---------------------------|------------------------------|-----------------------------------|
| <i>Oslo Stock Exchange</i> | | | |
| Market share | 97.60 | 94.74 | 94.95 |
| Diff. | | -2.86*** | -2.65*** |
| <i>Chi-X</i> | | | |
| Market share | 2.19 | 4.87 | 4.67 |
| Diff. | | 2.67*** | 2.48*** |
| <i>Turquoise</i> | | | |
| Market share | 0.34 | 0.45 | 0.44 |
| Diff. | | 0.11** | 0.10** |
| <i>BATS</i> | | | |
| Market share | 0.16 | 0.17 | 0.11 |
| Diff. | | 0.01 | -0.04** |

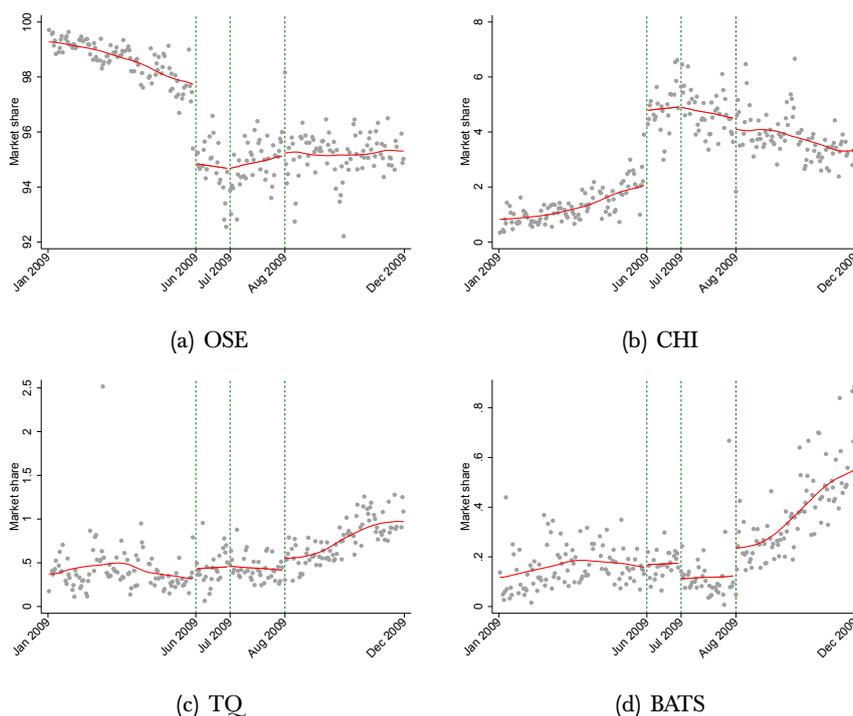
The table presents average market shares for trading in stocks with an Oslo Stock Exchange primary listing, separately for the Oslo Stock Exchange, Chi-X, Turquoise, and BATS Europe. Market share in stock i on date t for venue v , is given by the share trading volume on venue v relative to the share trading volume across OSE, Chi-X, Turquoise, and BATS. Average market shares are computed for three time periods: the pre-war period (May 1 to May 31); the break-out period (June 1 to July 5); and the retaliation period (July 6 to August 31). The table also presents the change in market share between a given period (the break-out period or the retaliation period) and the pre-war period. The between-period changes in market share are obtained by separately comparing daily observations of market shares in either the break-out period or the retaliation period to daily observations of market shares in the pre-war period in a regression framework. Standard errors are clustered at the stock level.

Table 3 shows an exodus of trading volume from the OSE to Chi-X. Before the tick size war, OSE market shares averaged 97.6% while Chi-X, the biggest competitor, operated with an average market share of 2.19%. During the break-out period, OSE market shares declined by a highly statistically significant 2.86 percentage points. These market shares were captured almost exclusively by Chi-X, which saw its market share more than double in the same period. Turquoise market shares for OSE listed stocks increased slightly, while we find no impact on the market shares of BATS. Most of the order flow fragmentation occurs during the break-out period in June, while market shares remain

relatively stable following the OSE tick size period (the retaliation period).

To assess whether it is plausible that the market share changes in Table 3 are causally linked to tick size reductions, in Figure 4, we provide evidence on the timing of the market share changes. The figure shows an immediate and sizeable transfer of market shares from the OSE to Chi-X on the day of the Chi-X tick size reduction. Market shares for Turquoise and BATS show no such patterns. Following the OSE decision to reduce tick sizes in July, the Oslo Exchange reclaims some of its lost market shares from Chi-X. Overall, Figure 4 provides appealing evidence that the market share changes during the Summer of 2009 are causally related to the tick size reductions during the tick size war.

Figure 4 Time-series: Market shares



The figure presents daily cross-sectional averages of market shares for trading in stocks with an Oslo primary listing, separately for the Oslo Stock Exchange (OSE), Chi-X (CHI), Turquoise (TQ), and BATS Europe (BS). Market share in stock i on date t for venue v , is given by the share trading volume on venue v relative to the share trading volume across OSE, Chi-X, Turquoise, and BATS. The left vertical break indicates June 1, 2009, the date when Chi-X reduced tick sizes for OSE listed stocks. The right vertical break indicates July 6, 2009, the date when OSE reduced tick sizes for OSE listed stocks. Red lines are local polynomial smoothing regressions with a bandwidth of 20 trading days are fit separately for the January-May, June-July, and July-December periods.

Hence, our empirical analysis provides support for the theoretical prediction by Buti et al. (2015) that exchanges with small tick sizes should capture market shares from exchanges with large tick sizes. Indeed, it is clear from both Table 3 and Figure 4 that the OSE loses market shares to Chi-X, and that the likely cause of this market share transfer is a between-market difference in tick sizes. What is not immediately clear, however, is why Chi-X, and not the other tick size-reducing exchanges, is able to capture trading volume from the OSE. We believe that the answer to this question is a combination of three factors. First, Chi-X may have benefited from a “first-mover” advantage. Traders may have been

settled and content with trading on the Chi-X platform when Turquoise and BATS decided to reduce tick sizes. Second, out of the four stock exchanges, Chi-X operated with the smallest tick sizes during the *break-out* phase. Third, trading at Chi-X was already established and well-functioning before the tick size war; its market share, trading volume, and order book depth was reasonably high compared to Turquoise and BATS, which may explain why traders migrated to Chi-X and not the other MTFs.

Though our findings in Table 3 mostly pass the bar of statistical significance, it is not clear how we should assess the economic significance of the tick size reductions during the tick size war. On the one hand, a market share transfer of approximately 3% only amounts to a 50 million USD loss in trading volume, given a total trading volume of 10.22 billion NOK at the OSE on May 29, 2009. On the other hand, the 3% market share change was sufficient to prompt the OSE to make considerable changes to its market structure. It may be the case that the OSE judged the 3% market share change as economically sufficient by itself to respond to the Chi-X tick size reduction. More realistically, however, the OSE responded because the Chi-X tick size reduction also had impact on the overall quality of trading at the OSE. In Section 6, we explore the market quality dimension of the tick size war.

5 Why do some stocks fragment more than others?

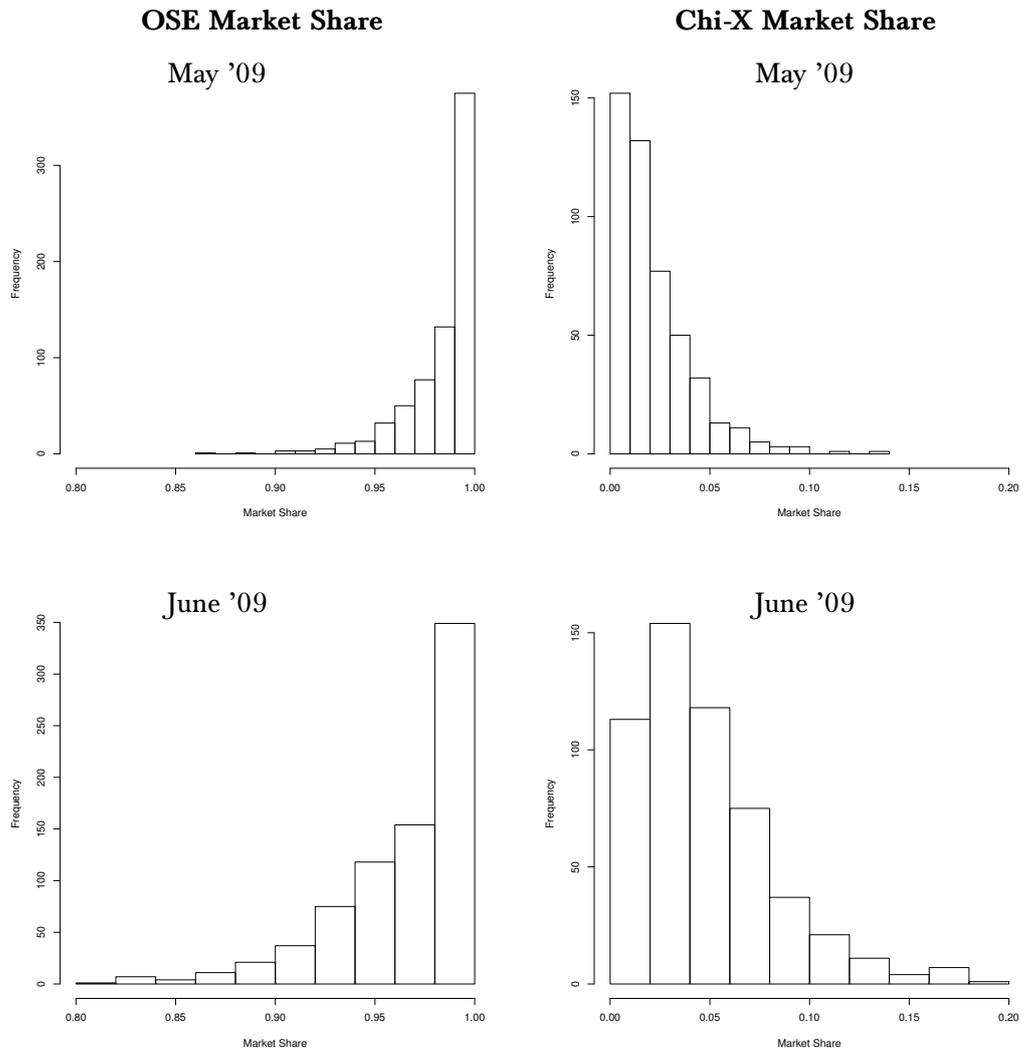
As we discussed in our survey of the existing literature (Section 1), we aim to distinguish between two competing mechanisms for how cross-market differences in tick sizes affect the distribution of market shares. The first mechanism we consider is whether tick sizes affect market share changes by constraining the bid-ask spread in the main market — thus, leading traders to “queue-jump” by sending orders to the satellite market (Buti et al., 2015). The second mechanism we consider is whether tick sizes affect the distribution of market shares through its impact on the trading behavior of high-frequency traders (HFT).

To distinguish between our candidate mechanisms, we estimate cross-sectional regressions where the change in market share between May and June 2009 is the dependent variable and proxies for tick size constraints and HFT at the OSE are separate explanatory variables. The cross-sectional variation in market share changes that we aim to explain is illustrated in Figure 5. Since trading at BATS and Turquoise appears to be largely unaffected by the tick size war, judging by their lack of market share capture, we focus our current analysis on the trading that occurs at the OSE and Chi-X. Consequently, our measure of market share is now computed as the distribution of share trading volume between the OSE and Chi-X. Figure 5 clearly illustrates the movement of market share from the OSE to Chi-X through the space of one month.

5.1 Proxies for tick size constraints and HFT

Before we perform our cross-sectional regressions, we generate empirical proxies for the extent of tick size constraints and high-frequency trading. Our primary tool to explore whether tick size constraints affect market share changes is a commonly used proxy for how severely tick sizes constrain price competition (see e.g. O’Hara et al. (2015)). For each stock-day in the pre-tick-size-war period (May

Figure 5 The changing distribution of market share, May-June 2009



The figure presents the distribution of daily market shares at the Oslo Stock Exchange (left) and Chi-X (right). The top panel presents the distribution of market shares during May, 2009. The bottom panel presents the distribution of market shares during June, 2009.

2009), we infer whether the daily average quoted bid-ask spread equals a single tick or multiple ticks. In a multiple-tick trading environment, traders can gain execution priority by undercutting existing bids in the book. In contrast, in a one-tick trading environment, such price competition is fully constrained by the tick size. To construct a binary measure of whether a stock is “tick-constrained”, we compute the average number of “ticks-per-spread” (the quoted spread divided by the tick size) during the pre-war period. If this number is less than two, we say that the stock is tick constrained.⁷ In the sample, the average ticks-per-spread has a minimum of 1.272 and a median of 1.886.

To proxy for the extent of high-frequency trading, we exploit that HFTs tend to insert, modify, and cancel orders more often than non-HFTs. Therefore, the common proxy for the extent of HFT activity is to count the number of orders in the limit order book and compare it to the number of executed trades (the order-to-trade-ratio, OTR). The OTR is assumed to be increasing in the amount of algorithmic trading.⁸ In May 2009 (the pre-war period), the OTR for our sample of OBX shares varied between 3.8 and 16, with a median of 7.

In addition to our proxies for tick size constraints and HFT activity, we allow for alternative drivers of market share changes. Specifically, in our cross-sectional regressions, we include as regressors measures of trading costs (quoted or effective spreads) as well as measures of trading volume (NOK volume or order book depth).

5.2 Cross-sectional regression results

Table 4 presents estimates from cross-sectional regressions where the change in OSE market share between the pre-war period and the break-out period is the dependent variable. Beginning with our proxy for tick size constraints, the table shows a negative regression coefficient, which indicates that tick size constrained shares fragment more as a result of the Chi-X tick size reduction in June 2009 (lower OSE market share). This positive relationship between tick size constraints and order flow fragmentation is in line theoretical predictions (Buti et al. (2015)). However, the relationship is not statistically significant in any of the regression specifications in Table 4.

In contrast, we find a strong and statistically significant relationship between our measure of HFT in the pre-war period and subsequent order flow fragmentation. Specifically, stocks that tend to have more HFT activity at the OSE fragment more following the Chi-X tick size reduction. This result remains statistically significant across various regression specification. As a consequence, our results more strongly favor that between-market tick size differences affect the distribution of market shares through its impact on HFT activity. This result contrasts with the existing empirical evidence from U.S. markets, which suggests that between-market tick size differences affect market shares because of queue-jumping driven by differences in the severity of spread constraints (e.g. Buti et al. (2015)).

One explanation for why we find no relationship between our binary measure of tick size constraints and market share changes during the tick size war could be that our proxy does not capture the relevant aspect of tick size constraints. In particular, what matters to traders is not necessarily

⁷We have also used the actual number of “ticks per spread” as an explanatory variable. The conclusions with this specification are similar.

⁸The OTR is also commonly termed the “quote-to-trade” or the “message-to-trade” ratio. See Jørgensen, Skjeltorp, and Ødegaard (2016) for a study of order to trade ratios at the OSE.

Table 4 Explaining market share changes with OSE characteristics

| | <i>Dependent variable:</i> | | | | | | | |
|-------------------------|----------------------------|----------------------|-------------------|-------------------|----------------------|--------------------|---------------------|----------------------|
| | Change in OSE Market Share | | | | | | | |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| Quoted (rel) spread | 2.756 (2.625) | | | | | | 6.004 (4.073) | |
| Effective spread | | 13.538* (6.456) | | | | | | 18.728** (7.161) |
| Depth | | | -0.001 (0.005) | | | | | 0.001 (0.006) |
| Volume | | | | 0.001 (0.003) | | | -0.00000 (0.005) | |
| Tick Constrained | | | | | -0.007 (0.006) | | -0.005 (0.005) | -0.005 (0.005) |
| Order to Trade | | | | | | -0.002* (0.001) | -0.003** (0.001) | -0.002*** (0.001) |
| Constant | -0.034*** (0.008) | -0.045*** (0.009) | -0.010 (0.066) | -0.046 (0.053) | -0.022*** (0.004) | -0.013 (0.007) | -0.019 (0.116) | -0.045 (0.090) |
| Observations | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 |
| Adjusted R ² | 0.004 | 0.120 | -0.039 | -0.035 | 0.031 | 0.144 | 0.316 | 0.416 |

Note:

*p<0.05; **p<0.025; ***p<0.01

The table presents cross-sectional regressions explaining changes in OSE market share between the pre-war period (May '09) and the break-out period (June-July 5). Each column is a separate regression. Explanatory variables: *Quoted (relative)spread*: The difference between best bid and best ask in the order book, divided by price. Averaged across all order books during a trading day. *Effective spread*: Difference between trade price and a pre-trade benchmark, relative to trade price. *Depth*: The natural log of the total (NOK) amount outstanding at the best bid and ask. *Volume*: The natural log of the total amount (in NOK) traded. *Tick Constrained*: Dummy variable equal to one if "Spreads per tick" (Quoted spread divided by tick size) is less than two. *Order to Trade Ratio*: The number of orders (messages) in the trading system per trade. All the explanatory variables are measured as averages over daily observations at the OSE during May, 2009 (the pre-war period).

whether the bid-ask spread at the OSE is constrained by the tick size or not, but whether the spread at the OSE is more or less constrained than at Chi-X. To address this possibility, we construct an alternative proxy for spread constraints which measures the difference in spread constraints between the OSE and Chi-X. We calculate the “Relative Tick” as the average of daily difference between the “Spreads per tick” measured at the OSE and Chi-X during the tick size war. The greater “Relative Tick”, the greater the incentive to “queue-jump” to the alternative market.

Moreover, to address the possibility that cross-market differences in tick size constraints are correlated with cross-market differences in stock liquidity, we generate a set of *relative liquidity* measures. Specifically, we compute the average of daily differences between trading characteristics (e.g. effective spreads and order book depth) at the OSE and Chi-X during the pre-war period, and evaluate these variables both in separate regressions and in multivariate regressions together with “Relative Tick.”

Table 5 presents estimates from our cross-sectional regressions using differences in trading characteristics between the OSE and Chi-X as explanatory variables. The table confirms our previous findings that the extent of tick size constraints is a poor explanatory variable for the extent of market share changes during the tick size war. The only statistically significant explanatory variable we find is trading volume — shares that tend to be heavily traded at the OSE compared to Chi-X fragment less despite cross-market differences in the tick size.

Table 5 Explaining fragmentation with difference main market (OSE) and aggressor (Chi-X)

| <i>Dependent variable:</i> | | | | | | | |
|----------------------------|----------------------|----------------------|----------------------|----------------------|--------------------|-------------------|----------------------|
| Change in OSE Market Share | | | | | | | |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| Quoted (rel) spread | -0.156 (0.274) | | | | | -0.273 (0.313) | |
| Effective spread | | -0.587 (1.172) | | | | | 0.793 (1.073) |
| Depth | | | 0.002 (0.007) | | | 0.003 (0.008) | |
| Volume | | | | 0.009*** (0.003) | | | 0.011*** (0.003) |
| Relative Tick | | | | | -5.861 (6.370) | -5.512 (6.670) | -5.698 (5.078) |
| Constant | -0.029*** (0.004) | -0.029*** (0.004) | -0.030*** (0.011) | -0.068*** (0.011) | -0.019* (0.008) | -0.028 (0.017) | -0.064*** (0.013) |
| Observations | 25 | 25 | 25 | 25 | 26 | 25 | 25 |
| Adjusted R ² | -0.029 | -0.032 | -0.039 | 0.341 | -0.006 | -0.074 | 0.354 |

Note:

*p<0.05; **p<0.025; ***p<0.01

The table presents cross-sectional regressions explaining changes in OSE market share between the pre-war period period (May, 2009) and the break-out period (June-July 5). Each column is a separate regression. Explanatory variables: *Quoted (relative) spread*: The difference between best bid and best ask in the order book, divided by price. Averaged across all order books during a trading day. *Effective spread*: Difference between trade price and a pre-trade benchmark, relative to trade price. *Depth*: The natural log of the total (NOK) amount outstanding at the best bid and ask. *Volume*: The natural log of the total amount (in NOK) traded. *Tick Constrained*: "Spreads per tick" - Quoted spread (average through trading day) divided by tick size. All explanatory variables are first computed on a daily basis as $X_{OSE} - X_{CHI}$ on a daily basis, and then averaged within the pre-war period May, 2009 (Quoted (relative) spread, Effective spread, Depth, Volume) or the break-out period June 1 to July 6 (Relative tick).

6 What happens to market quality?

In this section, we explore the consequences of the tick size war on the quality of trading at both the OSE and Chi-X. While there are strong theoretical predictions on how tick size reductions affect market quality in a single-market setting — for example, Foucault (1999) predicts tighter bid-ask spreads and reduced order book depth — there is little theoretical guidance on the impact of tick size reductions in our multi-market setting. For this reason, our empirical analysis on the effect of the tick size war on market quality will be exploratory in nature, rather than a test of theoretical predictions.

6.1 The causal identification problem

In order to inform about the empirical impact of tick size reductions in a multi-market setting, we seek to provide causal estimates of the same-market and cross-market market quality impacts of the tick size war between the OSE and Chi-X. Causal estimates can only be obtained by comparing the evolution of outcomes to a valid counterfactual — that is, the evolution of the same outcome in the absence of some 'treatment.' In our setting, we are interested in how measures of market quality would evolve during June and July 2009 in the counterfactual scenario of no tick size war.

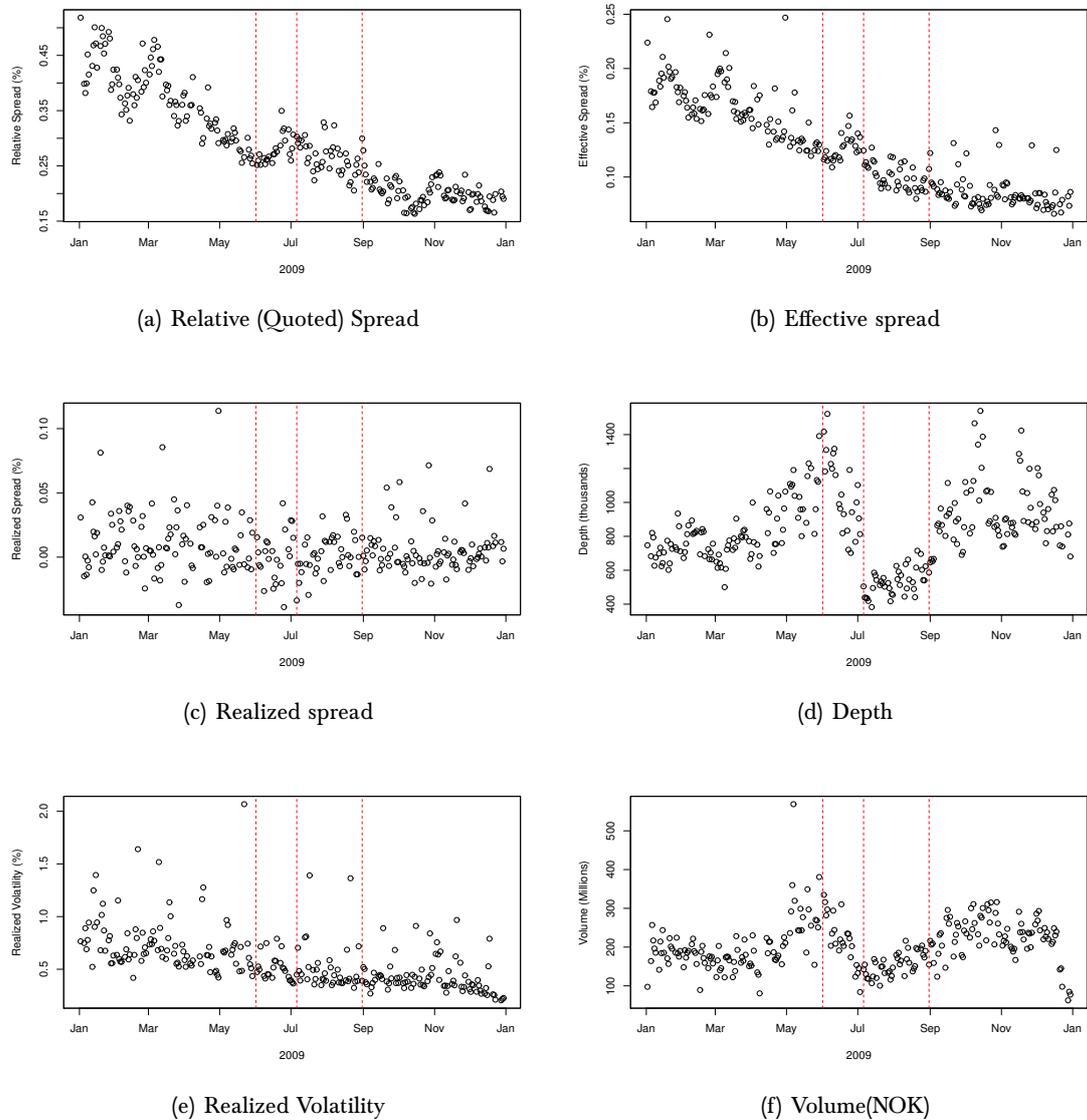
A much-used empirical strategy in the market microstructure literature is to compare outcomes after an event to the same outcome before the event — thus, treating the pre-event period as the counterfactual scenario. In Table 6, we perform such a before-and-after analysis, and present averages of various market quality measures for four different time periods: the pre-war period (May, 2009); the break-out period (June 1 to July 5); the retaliation period (July 6 to August 31); and the post-war period (September). The before-and-after exercise indicates that spread measures of stock liquidity improve at both the OSE and Chi-X during the tick size war, while order book depths remain largely unchanged throughout June before plummeting in July.

There are (at least) two reasons why, in our case, before-and-after estimates are unlikely to inform us about the causal impact of the events of the tick size war on market quality. First, beginning in early 2009, measures of stock liquidity at the OSE were steadily improving for reasons unrelated to the tick size war (see Figure 6). Going further back in time, as we show in Figure 1 in Section 3.4, we find that the persistent trends to stock liquidity in 2009 reflect a recovery from a period of low liquidity during the financial crisis in the Autumn of 2008. If unaccounted for, the before-and-after estimators assign such pre-existing trends to the impact of the tick size war.

The second reason why comparing market quality during June and July to market quality in May is unlikely to identify the causal impact of the tick size war, is that trading behavior tends to be different during the Summer months (June and July) on account of public holidays. To provide some perspective on this potentially confounding factor, in Table 7, we present market quality statistics from the same subperiods as in Table 6 but, instead, one year before (2008) and one year after (2010) the tick size war. Most notable is the tendency of trading volume to be considerably lower during the Summer months compared to both May and September.

Thus, in order to identify the causal impact of the tick size war on market quality, we must specify an empirical identification strategy that circumvents the issues of pre-existing trends and different

Figure 6 Time-series: Market quality OSE 2009



The figure presents time-series of market quality measures at the Oslo Stock Exchange, in the period January 1, 2009, to December 31, 2009. All observations are daily cross-sectional averages, computed across all OBX listed stocks. Panel (a) shows the effective spread, expressed in basis points. Panel (b) shows the realized spread, expressed in basis points. Panel (c) shows order book depth, expressed in thousands. Panel (d) shows volatility. Panel (e) shows currency volume, expressed in millions. Panel (f) shows share volume, expressed in thousands. In all plots, the left vertical break indicates June 1, 2009, the start of the 'tick size war'. The middle vertical break indicates July 6, 2009, the date of OSEs tick size reduction. The right vertical break indicates August 31, 2009, when tick sizes were harmonized across all exchanges.

Table 6 Before-and-after estimates

| Liq.measure | Market | Pre May | Breakout 1jun-5jul | Retaliation 6jul-3laug | Post Sep |
|------------------------------|--------|------------|-----------------------|---------------------------|-------------|
| Quoted (relative) Spread (%) | OSE | 0.308 | 0.302 | 0.292 | 0.239 |
| | Chi-X | 1.542 | 0.988 | 0.681 | 0.501 |
| Effective Spread (%) | OSE | 0.106 | 0.101 | 0.083 | 0.073 |
| | Chi-X | 0.388 | 0.320 | 0.229 | 0.157 |
| Realized Spread (%) | OSE | 0.018 | 0.017 | 0.015 | 0.017 |
| | Chi-X | 0.051 | 0.038 | 0.043 | 0.029 |
| Realized Volatility (%) | OSE | 0.909 | 0.779 | 0.591 | 0.553 |
| | Chi-X | 0.553 | 0.515 | 0.400 | 0.401 |
| Depth (Thousand NOK) | OSE | 983 | 951 | 564 | 734 |
| | Chi-X | 217 | 248 | 183 | 185 |
| Volume (Million NOK) | OSE | 280 | 212 | 149 | 208 |
| | Chi-X | 5 | 8 | 6 | 7 |
| Turnover (%) | OSE | 1.44 | 1.04 | 0.67 | 0.87 |
| | Chi-X | 0.02 | 0.04 | 0.03 | 0.03 |

The table reports subperiod averages of a number of market quality measures at the OSE and Chi-X. Market quality measures: *Quoted (relative) spread*: The difference between best bid and best ask in the order book, divided by price. Averaged across all order books during a trading day. *Effective spread*: Difference between trade price and a pre-trade benchmark, relative to trade price. *Depth*: The total (NOK) amount outstanding at the best bid and ask. *Volume*: The total amount (in NOK) traded. All the variables are measured as averages (panel A) over daily observations in the given time interval. The numbers are averages over stock-level averages.

trading behavior during the Summer months. In the following sections, we propose two candidate empirical strategies — a regression discontinuity design and a difference-in-differences design. In the regression discontinuity design, we isolate immediate changes to market quality following a tick size change, which we argue are unlikely to be correlated with confounding factors. In the difference-in-differences specification, we use a control group of non-fragmented OSE stocks to control for common confounding factors, such as less active trading during the Summer months.

6.2 Regression discontinuity estimates

Our first attempt to produce causal estimates of the impact of the tick size war on market quality involves adopting a rigorous empirical methodology inspired by the so-called regression discontinuity design literature. The regression discontinuity design focuses on changes in market quality that occur immediately after the tick size event in question (either the Chi-X June 1 tick size reduction or the OSE July 6 tick size reduction). We conjecture that such local variation is unlikely to be correlated with other determinants of our outcomes, which gives the potential for causal identification.

To describe our empirical approach, let y_{it} be the outcome of interest (for example, effective spreads) and t^* be the exact implementation date of a given tick size event.⁹ We estimate the following regression model:

$$y_{it} = \alpha + \beta^{Pre-trend}(t - t^*) + \beta^{Gradual}(t - t^*) \times Event_t + \beta^{Jump}Event_t + \varepsilon_{it}, \quad (1)$$

⁹Our current description of the regression discontinuity design is highly condensed. In Appendix A, we provide a more elaborate discussion of the design and its methodological assumptions.

Table 7 Liquidity measures, comparable subperiods, 2008 and 2010

Panel A: 2008

| Liq.measure | Market | May | 1jun-5jul | 6jul-31aug | Sep |
|------------------------------|--------|-------|-----------|------------|-------|
| Quoted (relative) Spread (%) | OSE | 0.242 | 0.274 | 0.299 | 0.446 |
| | Chi-X | | 0.415 | 0.629 | 0.666 |
| Effective Spread (%) | OSE | 0.087 | 0.097 | 0.102 | 0.145 |
| | Chi-X | | 0.133 | 0.190 | 0.233 |
| Realized Spread (%) | OSE | 0.029 | 0.028 | 0.028 | 0.037 |
| | Chi-X | | 0.025 | 0.033 | 0.053 |
| Realized Volatility (%) | OSE | 0.694 | 0.703 | 0.795 | 1.346 |
| | Chi-X | | 0.361 | 0.415 | 0.661 |
| Depth (Thousand NOK) | OSE | 2625 | 2212 | 2477 | 1295 |
| | Chi-X | | 341 | 303 | 246 |
| Volume (Million NOK) | OSE | 480 | 363 | 291 | 380 |
| | Chi-X | | 1 | 4 | 6 |
| Turnover (%) | OSE | 1.23 | 0.89 | 0.84 | 1.33 |
| | Chi-X | | 0.00 | 0.01 | 0.01 |

Panel B: 2010

| Liq.measure | Market | May | 1jun-5jul | 6jul-31aug | Sep |
|------------------------------|--------|-------|-----------|------------|-------|
| Quoted (relative) Spread (%) | OSE | 0.277 | 0.281 | 0.270 | 0.221 |
| | Chi-X | 0.499 | 0.487 | 0.438 | 0.352 |
| Effective Spread (%) | OSE | 0.085 | 0.084 | 0.084 | 0.078 |
| | Chi-X | 0.160 | 0.140 | 0.137 | 0.119 |
| Realized Spread (%) | OSE | 0.013 | 0.016 | 0.018 | 0.024 |
| | Chi-X | 0.035 | 0.037 | 0.043 | 0.036 |
| Realized Volatility (%) | OSE | 0.721 | 0.581 | 0.499 | 0.429 |
| | Chi-X | 0.502 | 0.448 | 0.390 | 0.313 |
| Depth (Thousand NOK) | OSE | 535 | 497 | 544 | 788 |
| | Chi-X | 238 | 202 | 166 | 182 |
| Volume (Million NOK) | OSE | 305 | 198 | 176 | 196 |
| | Chi-X | 14 | 12 | 12 | 9 |
| Turnover (%) | OSE | 1.07 | 0.83 | 0.60 | 0.64 |
| | Chi-X | 0.05 | 0.05 | 0.04 | 0.03 |

The table reports subperiod averages of a number of market quality measures at the OSE and Chi-X. Market quality measures: *Quoted (relative) spread*: The difference between best bid and best ask in the order book, divided by price. Averaged across all order books during a trading day. *Effective spread*: Difference between trade price and a pre-trade benchmark, relative to trade price. *Depth*: The total (NOK) amount outstanding at the best bid and ask. *Volume*: The total amount (in NOK) traded. All the variables are measured as averages over daily observations in the given time interval.

where

$$Event_t = \begin{cases} 1, & \text{if } t \geq t^* \\ 0, & \text{otherwise} \end{cases}$$

and $(t - t^*)$ is an event-time counting variable centered on the event date t^* . This variable is decreasingly negative for all dates leading up to t^* , and increasingly positive for all dates after t^* . Since event-time is centered on t^* , the coefficient β^{Jump} identifies a discrete change in y_{it} occurring exactly on the day of the event. Under the identifying assumption that there are no simultaneous shocks to y_{it} at t^* , the coefficient β^{Jump} can be interpreted as the immediate effect of an event implemented on date t^* . Similarly, $\beta^{Gradual}$ can be interpreted as the *per-day* impact of the event, identified by a change in the linear trend $(t - t^*)$ exactly on the day of the event.¹⁰

We estimate model (1) separately for stocks traded at the OSE and Chi-X, and for a variety of liquidity measures (outcomes y_{it}). Since the model formulation only allows us to center event-time around one event date t^* at a time, we estimate equation (1) separately for our two events of interest — the Chi-X June 1 tick size reduction and the OSE July 6 tick size reduction. We label these events t_1^* and t_2^* , respectively.

Consistent estimation of β^{Jump} and $\beta^{Gradual}$ requires a strong assumption about the functional form of the relationship between $(t - t^*)$ and y_{it} . We follow the standard approach in the regression discontinuity literature and estimate local linear regressions within small estimation ranges close to the event date $t = t^*$ (Hahn, Todd, and van der Klaauw (2001); Lee and Lemieux (2010)). In particular, surrounding the June 1 event, we restrict the sample period to April 1 to July 5, and surrounding the July 6 event, we use a sample period from June 1 to August 31.

Table 8 shows results of this regression discontinuity analysis, allowing us to estimate the impact of the events of the tick size war. In Panel A of the figure we document an unambiguously negative impact of the Chi-X tick size reduction on OSE market quality. For example, offering comparatively large tick sizes causes a *daily* exodus of OSE trading volume and order book depth by 6% and 2.7%, respectively, and, presumably as a consequence, a daily increase in effective spreads by 0.1 basis points — strongly suggesting a less liquid market.

In contrast, the impact of the Chi-X tick size reduction on Chi-X market quality is ambiguous. First, the coefficient estimates imply immediate improvements in Chi-X order book depth and trading volume, by respectively 14.5 and 72 per cent. These effects, however, appears to dissipate over time. Our estimates of $\beta^{Gradual}$ imply that out of the initial 14.5% (72%) improvement in depth (trading volume), 1.4 (5.9) percentage points dissipates per day. Moreover, there is evidence that spread measures of liquidity at Chi-X worsened during the tick size war.

Panel B of Table 8 assesses the impact of the OSE tick size reduction on OSE market quality. Consistent with a voluminous empirical literature, we find a simultaneous and immediate decrease

¹⁰While the coefficient β^{Jump} is likely to represent the causal immediate impact of the events of the tick size war on stock outcomes, $\beta^{Gradual}$ is unlikely to represent the causal gradual impact of the events — which makes it difficult to interpret the overall event effect in the regression discontinuity design. The reason for this is that, unlike β^{Jump} , the regression coefficient $\beta^{Gradual}$ is estimated based on changes in y_{it} that occur far from the event dates t^* of interest, leaving the estimation of $\beta^{Gradual}$ vulnerable to bias from the pre-existing trends and seasonal effects that we discussed in Section 3.4. To provide an estimate of the overall event effect which takes into account both pre-existing trends and seasonal effects, in Section 6.3, we estimate a difference-in-differences design.

Table 8 Market quality regressionsPanel A: Chi-X tick size reduction ($t^* = \text{June 1, 2009}$)

| | <i>Espread</i> | <i>Rspread</i> | <i>Depth</i> | <i>Volatility</i> | <i>Volume</i> |
|---------------------|-------------------|------------------|-------------------|-------------------|--------------------|
| OSE | | | | | |
| $\beta^{Pre-trend}$ | -0.001*** (-4.29) | 0.000 (0.07) | 0.012*** (8.08) | 0.000 (1.38) | 0.017*** (5.51) |
| $\beta^{Gradual}$ | 0.001*** (3.50) | -0.000 (-1.13) | -0.027*** (-7.78) | -0.000* (-2.01) | -0.060*** (-12.95) |
| β^{Jump} | -0.003 (-1.16) | 0.000 (0.01) | 0.051 (1.24) | -0.001 (-0.47) | 0.087 (1.42) |
| <i>N</i> | 1612 | 1612 | 1612 | 1612 | 1612 |
| Adj. R^2 | 0.04 | -0.00 | 0.03 | -0.00 | 0.04 |
| CHI-X | | | | | |
| $\beta^{Pre-trend}$ | -0.006*** (-5.10) | -0.004** (-2.60) | 0.006*** (4.31) | -0.000 (-0.58) | 0.033*** (9.29) |
| $\beta^{Gradual}$ | 0.006*** (3.26) | 0.004** (2.75) | -0.014*** (-4.18) | -0.000 (-0.79) | -0.059*** (-7.52) |
| β^{Jump} | -0.006 (-0.20) | 0.024 (0.50) | 0.145*** (2.92) | 0.000 (0.33) | 0.723*** (6.98) |
| <i>N</i> | 1412 | 1409 | 1550 | 1318 | 1497 |
| Adj. R^2 | 0.06 | 0.02 | 0.06 | -0.00 | 0.15 |

Panel B: OSE tick size reduction ($t^* = \text{July 6, 2009}$)

| | <i>Espread</i> | <i>Rspread</i> | <i>Depth</i> | <i>Volatility</i> | <i>Volume</i> |
|---------------------|-------------------|----------------|-------------------|-------------------|--------------------|
| OSE | | | | | |
| $\beta^{Pre-trend}$ | 0.001* (1.81) | -0.000 (-1.42) | -0.015*** (-4.94) | -0.000* (-1.90) | -0.043*** (-12.58) |
| $\beta^{Gradual}$ | -0.001*** (-2.85) | 0.000* (1.72) | 0.015*** (4.19) | 0.000* (1.78) | 0.056*** (12.53) |
| β^{Jump} | -0.017*** (-4.89) | -0.000 (-0.05) | -0.318*** (-6.20) | -0.001 (-0.75) | 0.009 (0.13) |
| <i>N</i> | 1690 | 1690 | 1690 | 1689 | 1690 |
| Adj. R^2 | 0.05 | 0.00 | 0.11 | 0.00 | 0.05 |
| CHI-X | | | | | |
| $\beta^{Pre-trend}$ | 0.000 (0.02) | -0.000 (-0.43) | -0.009*** (-2.96) | -0.000 (-1.40) | -0.033*** (-3.50) |
| $\beta^{Gradual}$ | -0.003 (-1.47) | 0.000 (0.31) | 0.004 (0.94) | 0.000 (0.13) | 0.038*** (3.26) |
| β^{Jump} | -0.037 (-1.70) | 0.014 (0.68) | -0.070 (-1.29) | -0.001*** (-3.27) | 0.025 (0.22) |
| <i>N</i> | 1647 | 1647 | 1677 | 1590 | 1664 |
| Adj. R^2 | 0.04 | -0.00 | 0.10 | 0.08 | 0.02 |

The table presents regression discontinuity estimates of the impact of the tick size war (top panel), and OSEs tick size reduction (bottom panel), on market quality outcomes. *Espread* is the effective spread, in percentage points. *Rspread* is the realized spread, percentage points. *Depth* is the order book depth, log-transformed. *Volatility* is the realized volatility. *Volume* is the NOK trading volume, log-transformed. The regression specification is $y_{it} = \alpha + \beta^{Pre-trend}(t - t^*) + \beta^{Gradual}(t - t^*) \times Event_t + \beta^{Jump}Event_t + \varepsilon_{it}$, where $(t - t^*)$ is an event-time counting variable centered on the event date t^* (June 1, 2009 for top panel, July 6, 2009 for bottom panel). $Event_t$ is a dummy variable equal to 1 for all observations $t \geq t^*$. Surrounding the June 1 event, we restrict the sample period to April 1 to July 5. Surrounding the July 6 event, we restrict the sample period to June 1 to August 31. Standard errors are clustered at the stock-level. t-statistics in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

in both effective spreads and order book depth (-31.8%) following the OSE tick size reduction. At the same time, by reducing its tick sizes in line with its competitors, the OSE is able to abate the exodus of trading volume and order book depth spurred by the tick size war. This is indicated by highly significant and positive coefficient estimates of $\beta^{Gradual}$. In fact, the existing negative trend in OSE trading volume is fully reversed and becomes positive ($\beta^{Gradual} + \beta^{PreTrend} > 0$). Similarly, the existing negative trend in order book depth is nullified ($\beta^{Gradual} + \beta^{PreTrend} \approx 0$).

Trading at Chi-X appears to stabilize following the OSE retaliatory tick size reduction. For example, the volatility of prices at Chi-X declines significantly following OSEs tick size reduction. Moreover, the erratic trading volume at Chi-X appears to normalize — after a gradual decline in trading volume throughout the break-out phase, the trend tapers following OSEs tick size reduction (captured by $\beta^{Gradual}$).

6.3 Difference-in-differences estimates

As an alternative way to identify the effect of the tick size war on market quality outcomes, we use a difference-in-differences specification.¹¹ In the difference-in-differences specification, we use a control group of stocks that are not directly affected by the tick size war to control for the influence of common pre-existing trends on our estimates of the effect of the tick size war. Specifically, the difference-in-differences event effect is measured as the change in outcomes for a “treated” group of stocks before and after an event relative to the corresponding change in outcomes for a control group of stocks unaffected by the event. In contrast to the regression discontinuity design used in Section 6.2, which disentangles the immediate and gradual event effects, the DiD design produces a single and easily interpretable measure of the overall event effect.

We define two treatment groups which we evaluate in the difference-in-differences specification. The first treatment group is OBX index stocks traded on the OSE. The second treatment group is OBX index stocks traded on Chi-X. Both groups were directly affected by the Chi-X tick size reduction for OSE listed stocks on June 1, 2009 and the OSE tick size reduction for OBX index stocks on July 6, 2009. These treatment samples are identical to the OSE and Chi-X samples analyzed in previous sections.

We compare separately the evolution of stock trading in our two treatment samples to a single control sample. Our initial control sample consists of a sample of non-OBX index OSE stocks. These stocks, which trade at higher tick sizes at the OSE (see Table 2), were not traded on the multilateral trading facilities (MTFs) Chi-X, Turquoise, or BATS throughout the calendar year 2009. Since these stocks were not traded on the three MTFs, they were not directly affected by the MTF tick size reductions during June 2009. Moreover, since these stocks did not belong to the OBX index, they were not directly affected by the OSE tick size reduction on July 6. In order to maximize the comparability between our highly liquid OBX index treatment group stocks and our control group stocks, we use as control sample the 25 most-traded non-OBX stocks, where we use overall trading volume during May 2009 to rank the stocks outside the OBX index.

¹¹Appendix B provides further details on our difference-in-difference specification. For example, the appendix provides summary statistics from our control group sample as well as several robustness tests.

The difference-in-differences design is implemented with the following regression model:

$$y_{it} = \alpha_i + \alpha_t + \tau Treatment_{it} + \omega_{it}, \quad (2)$$

where $Treatment_{it} = 1$ for stock i that belongs to the treatment group on date $t \geq t^*$ and zero otherwise; α_i are stock-level fixed effects; and α_t are date-level fixed effects. The inclusion of stock and date fixed effects in equation (2) controls for constant differences in y_{it} between treatment and control sample stocks and ensures that the effect of $Treatment_{it}$ on y_{it} is measured net of the time trend in the control sample. Under the identifying assumption that treatment and control stocks follow the same trend in y_{it} in the absence of treatment, the coefficient τ in equation (2) can be interpreted as the causal impact of the tick size war on stock market quality.

Equation (2) is estimated separately for the two events of interest — the Chi-X tick size reduction on June 1, 2009 and the OSE tick size reduction on July 6, 2009. As in the regression discontinuity design, we restrict the sample period surrounding the June 1 event to April 1 to July 5. Surrounding the July 6 event, we use a sample period from June 1 to August 31.

In the top panel of Table 9, we use the difference-in-differences specification to assess the impact of the Chi-X tick size reduction ($t_1^* = \text{June 1, 2009}$) on the quality of trading at the OSE and Chi-X. The table shows that stock liquidity at the OSE deteriorates as a result of the Chi-X tick size reduction. For example, effective (realized) spreads increase by 9.9 (6.5) basis points for OSE listed stocks directly affected by the tick size reduction relative to a control group of OSE listed stocks not affected by the tick size reduction. Moreover, trading volume at the OSE declines by 12.5%, although this effect is statistically insignificant.¹² For trading at Chi-X, we find that the Chi-X tick size reduction caused an increase in trading volume by more than 300% (log coefficients transformed by $e^\tau - 1$) — which corresponds to the increased Chi-X market share documented in Section 4. Still, we find only weak evidence that Chi-X market quality increased. In particular, effective and realized spreads decrease but the effects are statistically insignificant. Order book depth at Chi-X improves by almost 15%, but the coefficient is only statistically significant at the 10% level.

In the bottom panel of Table 9, we evaluate the impact of the OSE tick size reduction ($t_2^* = \text{July 6, 2009}$) on stock market quality. The OSE tick size reduction causes a considerable reduction in order book depth at both the OSE (−42.5%) and Chi-X (−20%) — both effects measured relative to OSE listed stocks with no tick size change. We find no impact of the OSE tick size reduction on spread measures of liquidity at the OSE. In contrast, effective spreads at Chi-X appear to decline following the OSE tick size reduction, though this effect is not robust to alternative specifications of the difference-in-differences design (see Appendix B).

¹²Why, given the considerable reduction in OSE market shares documented in Section 4, does OSE trading volume not decline more following the Chi-X tick size reduction? One explanation is that when traders reduce their trading activity in OBX listed stocks due to the tick size war they also halt trading in other OSE stocks. In the difference-in-differences specification, such a spillover effect between treatment and control stocks would result in a zero estimated treatment effect. Another explanation is that the market shares gained by Chi-X from the OSE during the tick size war does not come at the expense of lower OSE trading volume. Instead, the market share gained by Chi-X may be a result of investors increasing their overall trading activity at Chi-X without reducing trading activity at the OSE. Unfortunately, we cannot distinguish between these explanations in the current regression specification.

Table 9 Difference-in-differencesPanel A: Chi-X tick size reduction ($t^* = \text{June 1, 2009}$)

| | <i>Espread</i> | | <i>Rspread</i> | | <i>Depth</i> | | <i>Volatility</i> | | <i>Volume</i> | |
|------------|----------------|---------|----------------|---------|--------------|--------|-------------------|---------|---------------|---------|
| OSE | | | | | | | | | | |
| τ | 0.099*** | (2.70) | 0.065** | (2.56) | 0.101 | (1.23) | -0.001 | (-0.68) | -0.125 | (-0.84) |
| N | 3018 | | 3021 | | 3157 | | 2921 | | 3126 | |
| Adj. R^2 | 0.66 | | 0.29 | | 0.85 | | 0.05 | | 0.88 | |
| CHI | | | | | | | | | | |
| τ | -0.052 | (-1.09) | -0.008 | (-0.18) | 0.148* | (1.76) | -0.000 | (-0.51) | 1.147*** | (6.67) |
| N | 2825 | | 2825 | | 3106 | | 2629 | | 3022 | |
| Adj. R^2 | 0.52 | | 0.19 | | 0.63 | | 0.10 | | 0.64 | |

Panel B: OSE tick size reduction ($t^* = \text{July 6, 2009}$)

| | <i>Espread</i> | | <i>Rspread</i> | | <i>Depth</i> | | <i>Volatility</i> | | <i>Volume</i> | |
|------------|----------------|---------|----------------|---------|--------------|---------|-------------------|---------|---------------|--------|
| OSE | | | | | | | | | | |
| τ | -0.002 | (-0.09) | -0.035 | (-1.66) | -0.425*** | (-5.23) | -0.000 | (-0.16) | 0.147 | (1.18) |
| N | 3121 | | 3120 | | 3271 | | 3022 | | 3226 | |
| Adj. R^2 | 0.72 | | 0.38 | | 0.82 | | 0.05 | | 0.89 | |
| CHI | | | | | | | | | | |
| τ | -0.077** | (-2.21) | -0.023 | (-0.92) | -0.201** | (-2.44) | 0.001 | (1.11) | 0.171 | (1.31) |
| N | 3078 | | 3077 | | 3258 | | 2923 | | 3200 | |
| Adj. R^2 | 0.63 | | 0.30 | | 0.58 | | 0.12 | | 0.68 | |

The table presents estimates of τ from the difference-in-differences specification applied separately to the Chi-X tick size reduction ($t^* = \text{June 1, 2009}$) and the OSE tick size reduction ($t^* = \text{July 6, 2009}$). Surrounding the June 1, 2009, event, we restrict the sample period to April 1, 2009, to July 5, 2009. Surrounding the July 6, 2009 event, we restrict the sample period to June 1, 2009, to August 31, 2009. The regression specification is $y_{it} = \alpha_i + \alpha_t + \tau \text{Treatment}_{it} + \omega_{it}$. Treatment_t is a dummy variable equal to 1 for all treatment group observations on dates $t \geq t^*$. The difference-in-differences specification is estimated separately for two treatment groups. The first treatment group is OBX index stocks traded on the OSE. The second treatment group is OBX index stocks traded on Chi-X. Our control sample of stocks consists of the 25 most-traded (based on total trading volume) non-OBX index OSE stocks that were not traded on the multilateral trading facilities (MTFs) Chi-X, Turquoise, or BATS throughout the calendar year 2009. *Espread* is the effective spreads, in percentage points. *Rspread* is the realized spreads, in percentage points. *Depth* is order book depth, transformed with the natural logarithm. *Volatility* is measured in percentage points. *Volume* is trading volume in NOK, transformed with the natural logarithm. Standard errors are clustered at the stock-level.

6.4 Discussion

Section 4 showed that Chi-X, by reducing its tick size for stocks listed at the Oslo Stock Exchange (OSE), was able to capture market shares from the OSE. The analysis also showed that the OSE was able to limit the exodus of order flow by reducing its own tick sizes. In this section, we use a regression discontinuity (RD) and difference-in-differences (DID) design to estimate the impact of the Chi-X tick size reduction and the OSE tick size reduction on the quality of trading at both Chi-X and the OSE.

Our findings suggest that tick size reductions affect the quality of trading in tick-size-reducing marketplaces (a same-market effect). However, our results deviate (in some instances) considerably from the existing empirical literature. For example, we find that order book depth at Chi-X improved after its June 1, 2009 tick size reduction, which is the opposite of the standard result in the literature. The most likely explanation for our conflicting result is that, in a multi-market setting such as ours, tick sizes are used competitively by stock exchanges to capture order flow from competing marketplaces. This means that even though traders may be deterred from supplying liquidity when tick sizes are small, which deteriorates order book depth, the net effect of reducing the tick size on order book depth may be positive if small tick sizes also imply an inflow of trading interest captured from competing marketplaces.

We also find that tick size reductions in one marketplace have spill-over effects to marketplaces that do not change their tick size (a cross-market effect). For example, both our RD and DID designs suggest that stock liquidity at the OSE deteriorated as a consequence of Chi-X reducing its tick sizes for OSE listed stocks. Likewise, evidence from our DiD specification suggests that order book depth at Chi-X suffered greatly from the July 6, 2009, OSE tick size reduction. Consequently, our research provides evidence that tick size reductions can impose negative externalities on the liquidity in competing marketplaces.

There are two main implications of our findings. The first implication is that, in judging the merit of market structure innovations in modern equity trading, it is insufficient to assess the impact on individual stock exchanges in isolation. For example, by exploring the June 1, 2009, Chi-X tick size reduction using data from Chi-X alone would yield the conclusion that smaller tick sizes unambiguously improve the quality of trading. Such a conclusion would be valid for investors who only trade at Chi-X. However, the conclusion that smaller tick sizes improve the quality of trading would be misleading or even incorrect for traders that can choose between trading at Chi-X (where liquidity improved) and the OSE (where liquidity deteriorated).

The second implication of our research is that there may be room for efficiency-improving tick size regulation in modern equity trading. In particular, our results suggest that individual stock exchanges have incentives to reduce their tick size to capture order flow (which increases their revenues) and, at the same time, that tick size reductions have negative spill-over effects on competing marketplaces. Thus, a conceivable consequence of tick size competition is that the combined liquidity (across all trading venues) available to market participants diminishes. Policy makers can limit stock exchanges' ability to engage in such deleterious tick size competition by strictly enforcing a shared tick size regime across all equity markets competing for the same order flow.

7 Conclusion

We explore an event where three stock exchanges (Chi-X, Turquoise, BATS Europe) in 2009 reduced their tick sizes (the minimum price increment in the limit order book) for stocks with a primary listing at the Oslo Stock Exchange (OSE). The main market, the OSE, quickly responded by reducing its own tick sizes, before all markets agreed on a common tick size structure. We use the events of this tick size war to test empirical hypotheses for how tick sizes affect the distribution of market shares and the quality of trading.

Consistent with recent theoretical work by Buti et al. (2015), we find that markets with comparatively small tick sizes are able to capture market shares. However, we find little empirical support for the theorized mechanism through which tick sizes should influence the distribution of market shares. In particular, we find no relationship between the severity of constraints to price competition and market share loss during the tick size war, as hypothesized by Buti et al. (2015). Instead, we find that the main predictor of market share loss during the tick size war is the extent of high-frequency trading (HFT) in the large-tick market (OSE). Specifically, the impact of between-market tick size differences on the distribution of market shares is greater for stocks with more HFT activity, irrespective of the severity of spread constraints in either market.

We use both a regression discontinuity (RD) design and a difference-in-differences (DiD) design to assess the consequence of the tick size war on the quality of trading in both the main market (OSE) and its main competitor (Chi-X). We find that tick size reductions have negative spill-over effects on the liquidity in markets that do not change their tick size (a cross-market effect). For example, both our empirical designs suggest that stock liquidity at the OSE declined following the Chi-X tick size reduction of OSE listed stocks. Similarly, we find that order book depth at Chi-X suffered greatly from the OSE retaliatory tick size reduction. In terms of a same-market effect of tick size reductions, we present intriguing evidence that order book depth improved at Chi-X following its own tick size reduction, which strongly contradicts the existing empirical literature. This finding serves to illustrate that in modern equity markets with competition between stock exchanges, the conventional wisdom concerning the impact of tick sizes on stock liquidity may not hold.

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Appendix

A Elaboration: Regression discontinuity design

In Section 6, we use a regression discontinuity design to estimate the impact of the tick size war on market quality at the OSE and Chi-X. In this appendix, we elaborate on the regression discontinuity specification and provide some evidence on the validity of the empirical design applied to our setting.

A.1 Methodology

We propose a regression discontinuity methodology to identify the causal impact of the ‘tick size war’ for Nordic stocks on stock outcomes (e.g. trading quality, liquidity). While the ‘tick size war’ actually comprises two distinct events — the Chi-X tick size reduction for OSE listed stocks on June 1, 2009 and the OSE tick size reduction for OBX index stocks on July 6, 2009 — consider for now the evaluation of some arbitrary event implemented on date t^* , on the outcomes y_{it} for stock i on date t . In our descriptive analyses (Section 6.1), we used a before-and-after estimator to assess the effect of this event on stock outcomes:

$$y_{it} = \alpha + \gamma Event_t + \omega_{it}, \quad (3)$$

where

$$Event_t = \begin{cases} 1, & \text{if } t \geq t^* \\ 0, & \text{otherwise} \end{cases}$$

The before-and-after effect of interest is captured by the coefficient γ , while the error term ω_{it} represents all other determinants of the outcome. The coefficient γ is derived by computing the mean of y_{it} over *all* periods $t < t^*$, and subtracting it from the mean of y_{it} computed over *all* periods $t \geq t^*$. In Section 6.1, our estimates of γ suggested that the events of the tick size war generally improved spread measures of liquidity at both the OSE and Chi-X but reduced order book depth.

The coefficient γ , however, is unlikely to represent the causal impact of the events of the tick size war on outcomes y_{it} . The reason for this is that most of our outcome variables, such as stock liquidity and order book depth, are influenced by persistent trends that pre-date the tick size war (see the discussion in Section 3.4). Absent an adjustment for such pre-existing trends, equation 3 will erroneously attribute the trends to the impact γ of the tick size war.

In Section 6, we approach the issue of pre-existing trends by focusing only on the variation in outcomes that occurs *exactly* on the date t^* of the event, in a regression discontinuity design. We conjecture that such local variation is unlikely to be correlated with other determinants of y_{it} , which may facilitate causal inference. We implement the regression discontinuity design with the following regression model:

$$y_{it} = \alpha + \underbrace{\beta^{Pre-trend}(t - t^*) + \beta^{Gradual}(t - t^*) \times Event_t}_{Added\ terms} + \beta^{Jump}Event_t + \varepsilon_{it} \quad (4)$$

where $(t - t^*)$ is an event-time counting variable, centered on the event date t^* . This variable is decreasingly negative for all dates leading up to t^* , and increasingly positive for all dates after t^* . Since event-time is centered on t^* , the coefficient β^{Jump} identifies a discrete change in y_{it} occurring exactly on the day of the event.¹³ Similarly, $\beta^{Gradual}$ can be interpreted as the *per-day* impact of the event, identified by a change in the linear trend $(t - t^*)$ exactly on the day of the event. We estimate model (4) separately for the two markets, and for a variety of outcomes y_{it} .

Our design shares both the strengths and the weaknesses of the regression discontinuity design. First, by focusing only on variation in outcomes close to $t = t^*$, the RD design gives the potential for causal inference, since such local variation is unlikely to be correlated with other determinants of y_{it} . Indeed, as long as there are no simultaneous shocks to y_{it} at t^* , the coefficients β^{Jump} and $\beta^{Phasein}$ capture the immediate and gradual causal effects of an event implemented at date t^* .

Consistent estimation of the coefficients β^{Jump} and $\beta^{Phasein}$, however, requires a strong assumption about the functional form of the relationship between $(t - t^*)$ and y_{it} . This assumption is needed because in order to estimate the effects that occur close to $t = t^*$, it is necessary to use data away from this point as well (Lee and Lemieux, 2010). Two main approaches are taken in the RD literature to estimate equation (4) when the functional form of $(t - t^*)$ is unknown. The first approach, which is widely preferred, is to restrict the sample size on either side of t^* , and estimate equation (4) with local linear regressions. If there is a concern that the regression function is not linear over the entire range of $(t - t^*)$, restricting the estimation range to values closer to the event date $t = t^*$ is likely to reduce biases in the RD estimates (Hahn et al., 2001; Lee and Lemieux, 2010). The second approach, in contrast, uses all the available data and allows for a flexible relationship between y_{it} and $(t - t^*)$, by expanding equation (4) with polynomials in $(t - t^*)$.

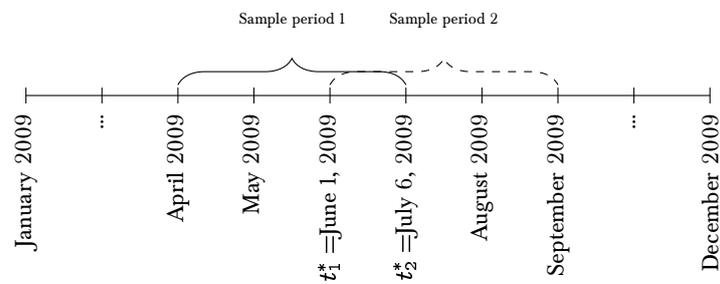
We estimate equation (4) with local linear regressions, and restrict the amount of data we use before and after an event t^* . In order to do so, we make two definitions. First, we define the event dates t^* of interest. We wish to estimate the impact of the onset of the 'tick size war', on June 1, 2009, as well as OSEs tick size reduction on July 6, 2009. We label these events t_1^* and t_2^* , respectively. As equation (4) only allows us to center event-time around one event date at a time, we must estimate equation (4) separately for the events t_1^* and t_2^* .

Second, we define sample periods separately for each of these events. In small event windows surrounding the events t_1^* and t_2^* , a linear approximation of the functional form of $(t - t^*)$ is likely to be appropriate. Figure 7 illustrates how we restrict the sample periods surrounding both t_1^* and t_2^* . First, surrounding the June 1, 2009, event, we restrict the sample period to April 1, 2009, to July 5, 2009. Second, surrounding the July 6, 2009 event, we restrict the sample period to June 1, 2009, to August 31, 2009.¹⁴ Figure 8 provide compelling graphical evidence that within these event windows, a linear functional form of $(t - t^*)$ indeed appears appropriate.

¹³In contrast, in the 'traditional' before-and-after event-study methodology (equation 3), which does not include $(t - t^*)$ as a regressor, the coefficient on $Event_t$ captures the difference in mean outcomes before-and-after, where the means are computed over the entire 'before' and 'after' periods.

¹⁴The cutoff dates used to restrict the samples are far from arbitrary. For example, in restricting the sample period for the July 6, 2009 event, we end the sample on August 31, 2009, as this is the introduction date of FESE harmonized tick size schedules, and effectively the conclusion of the tick size war. Similarly, we begin that sample on June 1, 2009, so as to not sample data before the tick size war began. Doing so, however, means we have overlap between the two sample periods during June 2009. This is inevitable if we wish to estimate the impact of OSE's tick size reduction, on July 6.

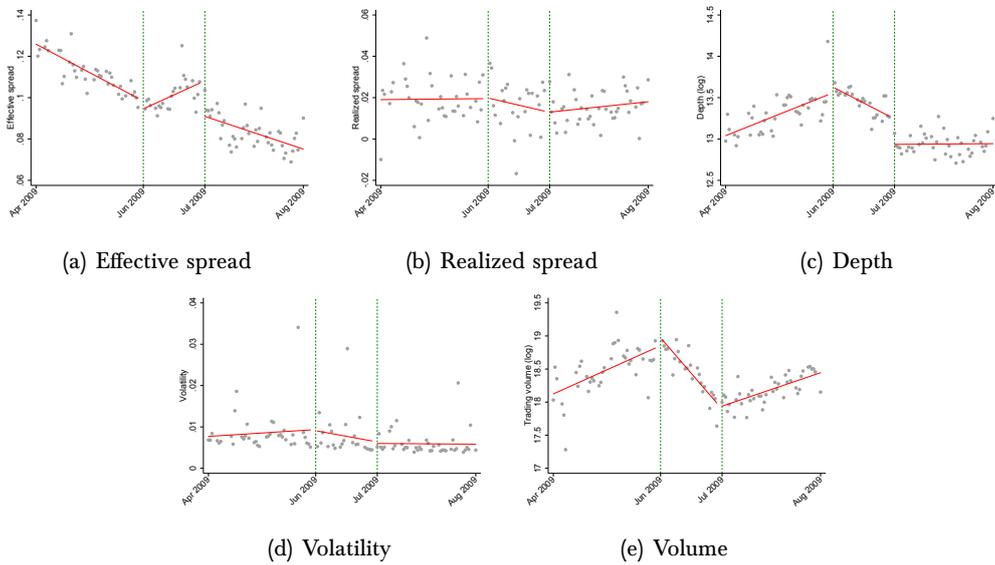
Figure 7 Illustration: Sample restrictions



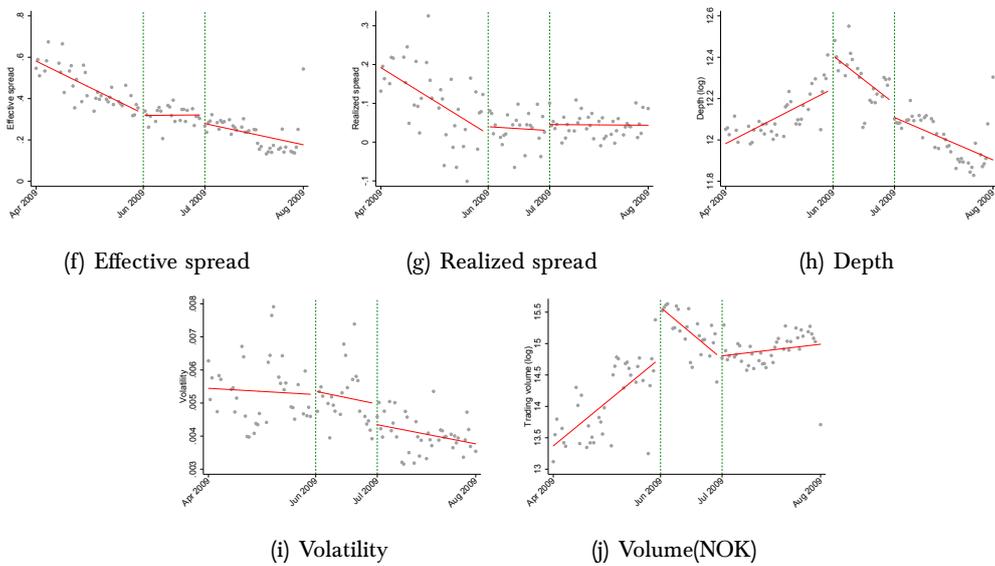
The figure illustrates how we define sample periods surrounding our two event dates. Our first event, t_1^* , is the beginning of the 'tick size war' on June 1, 2009. Our second event, t_2^* , is the Oslo Stock Exchange tick size reduction on July 6, 2009. First, surrounding the June 1, 2009, event, we restrict the sample period to April 1, 2009, to July 5, 2009. Second, surrounding the July 6, 2009 event, we restrict the sample period to June 1, 2009, to August 31, 2009. Solid curly braces span the sample period surrounding June 1, 2009. Dashed curly braces span the sample period surrounding July 6, 2009.

Figure 8 Market quality OSE

Panel A: OSE



Panel B: Chi-X



The figure presents time-series of market quality measures at the Oslo Stock Exchange (Panel A) and Chi-X (Panel B), in the period April 1, 2009, to August 31, 2009. All observations are daily cross-sectional averages, computed across all OBX listed stocks. Panel (a) shows the effective spread. Panel (b) shows the realized spread. Panel (c) shows order book depth, log-transformed. Panel (d) shows volatility. Panel (e) shows currency volume, log-transformed. In all plots, the left vertical break indicates June 1, 2009, the start of the 'tick size war'. The right vertical break indicates July 6, 2009, the date of OSE's tick size reduction. Linear regression lines (red) are fit separately within each event window. The regression lines correspond exactly with those generated in equation (4).

B Robustness tests: Difference-in-differences

In Section 6.3, we use a difference-in-differences specification to estimate the impact of the events of the tick size war on market quality at the OSE and Chi-X. In the difference-in-differences specification, we use a control group of stocks that are not directly affected by the tick size war to control for the influence of common confounding factors on our estimates of the effect of the tick size war. In this section, we explore the robustness of our benchmark difference-in-differences results to alternative specifications.

B.1 Benchmark difference-in-differences specification

Before describing our robustness tests, we begin by restating the benchmark difference-in-differences specification estimated in Section 6.3. In the benchmark model, we define two separate treatment groups. The first treatment group is OBX index stocks traded on the OSE. The second treatment group is OBX index stocks traded on Chi-X. Both groups were directly affected by the Chi-X tick size reduction for OSE listed stocks on June 1, 2009 and the OSE tick size reduction for OBX index stocks on July 6, 2009.

The control group is constructed in two steps. First, we construct a sample of 173 non-OBX index OSE stocks that were not traded on the multilateral trading facilities (MTFs) Chi-X, Turquoise, or BATS throughout the calendar year 2009. Since these stocks were not traded on the three MTFs, they were not directly affected by the MTF tick size reductions during June 2009. Moreover, since these stocks did not belong to the OBX index, they were not directly affected by the OSE tick size reduction on July 6, 2009. Second, we reduce the initial control sample of 173 stocks to the 25 most-traded stocks based on overall trading volume in the month of May, 2009, in order to provide a more comparable control group to our highly liquid treatment group.

We implement the difference-in-differences design with the following regression model:

$$y_{it} = \alpha_i + \alpha_t + \tau Treatment_{it} + \omega_{it}, \quad (5)$$

where $Treatment_{it} = 1$ for stock i that belongs to the treatment group on date $t \geq t^*$ and zero otherwise; α_i are stock-level fixed effects; and α_t are date-level fixed effects. The inclusion of stock and date fixed effects in equation 5 controls for constant differences in y_{it} between treatment and control sample stocks and ensures that the effect of $Treatment_{it}$ on y_{it} is measured net of the time trend in the control sample.

Equation 5 is estimated separately for the two events of interest — the Chi-X tick size reduction on June 1, 2009 and the OSE tick size reduction on July 6, 2009. As in the main text, surrounding the June 1 event, we restrict the sample period to April 1 to July 5. Surrounding the July 6 event, we use a sample period from June 1 to August 31.

Table 9 in the main text presented estimates from the benchmark difference-in-differences model. The table suggests that both our spread measures of liquidity at the OSE deteriorated as a result of the June 1, 2009, Chi-X tick size reduction while Chi-X depth and trading volume increased. The table also shows that order book depths at both the OSE and Chi-X declined considerably following

the July 6, 2009, OSE tick size reduction.

B.2 Robustness test: Alternative control samples

Our first robustness test is to estimate the benchmark difference-in-differences design using two alternative control group specifications. The first alternative control group, which we label Control group 1, comprises all 173 non-OBX index OSE stocks that were not traded on the multilateral trading facilities (MTFs) Chi-X, Turquoise, or BATS throughout the calendar year 2009. Recall that the benchmark control group comprises the 25 most-traded stocks from Control group 1. The second alternative control group, which we label Control group 2, retains from Control group 1 only stocks with positive trading volume at least 200 out of the 251 trading days during the calendar year 2009. This requirement excludes the least liquid stocks from the control sample and potentially creates a better comparison group for our liquid OBX index treatment group. Control group 2 holds 81 stocks.

To facilitate a comparison between our three control group specifications, in Table 10, we present summary statistics from both the benchmark control group specification, Control group 1, and Control group 2. The table illustrates that stocks in the benchmark control group are the most liquid while stocks in Control group 1 are the least liquid. This is no surprise, as both the benchmark control group and Control group 2 are derived from Control group 1 conditional on a parameter of stock liquidity.

Table 10 Summary statistics control sample

| | μ | σ | Min. | Median | Max. | N |
|--------------------------------|----------|-----------|---------|----------|------------|-------|
| Benchmark control group | | | | | | |
| Effective spread (%) | 0.813 | 0.579 | 0.154 | 0.706 | 7.113 | 2162 |
| Realized spread (%) | 0.440 | 0.655 | -5.128 | 0.310 | 8.333 | 2162 |
| Depth (thousand NOK) | 177.087 | 159.135 | 17.445 | 126.398 | 1677.866 | 2515 |
| Volatility (%) | 1.037 | 0.845 | 0.052 | 0.874 | 15.012 | 1948 |
| Trading volume (thousand NOK) | 4753.817 | 19930.033 | 5.400 | 1349.027 | 650334.994 | 2408 |
| Control group 1 | | | | | | |
| Effective spread (%) | 1.312 | 1.042 | 0.000 | 1.021 | 9.285 | 7652 |
| Realized spread (%) | 0.753 | 1.320 | -17.407 | 0.470 | 16.988 | 7605 |
| Depth (thousand NOK) | 193.372 | 2006.586 | 3.633 | 83.152 | 77185.746 | 14678 |
| Volatility (%) | 1.188 | 1.190 | 0.026 | 0.921 | 36.017 | 5498 |
| Trading volume (thousand NOK) | 1766.009 | 15014.750 | 1.000 | 196.785 | 882447.457 | 11565 |
| Control group 2 | | | | | | |
| Effective spread (%) | 1.151 | 0.825 | 0.000 | 0.947 | 7.637 | 6068 |
| Realized spread (%) | 0.650 | 1.009 | -5.128 | 0.441 | 13.967 | 6036 |
| Depth (thousand NOK) | 120.527 | 119.086 | 6.060 | 84.583 | 1677.866 | 8100 |
| Volatility (%) | 1.112 | 0.995 | 0.052 | 0.896 | 36.017 | 4652 |
| Trading volume (thousand NOK) | 1952.345 | 11910.515 | 1.600 | 327.423 | 650334.994 | 7586 |

The table presents summary statistics from our three difference-in-differences control group specifications. The baseline control group consists of non-OBX index OSE stocks that were not traded on the multilateral trading facilities (MTFs) Chi-X, Turquoise, or BATS throughout the calendar year 2009. In Control group 1, we further restrict the control sample to stocks with more than 200 trading days throughout 2009. In Control group 2, we restrict the sample to the 25 most traded stocks in the baseline control group based on total trading volume during May 2009. Summary statistics are computed using observations from January to May, 2009. The table lists means (μ), standard deviations (σ), minimum (Min.) and maximum values (Max.), medians, and number of observations (N).

Estimates from the difference-in-differences model using Control group 1 are presented in Table

11, labeled as specification 1. In the top panel of Table 11, we assess the impact of the Chi-X tick size reduction ($t_1^* = \text{June 1, 2009}$) on the quality of trading at the OSE and Chi-X. The table shows that stock liquidity at the OSE deteriorates as a result of the Chi-X tick size reduction. For example, effective spreads increase by 0.88 percentage points for OSE listed stocks directly affected by the tick size reduction relative to a control group of OSE listed stocks not affected by the tick size reduction. Moreover, trading volume at the OSE declines by 12.5%, although this effect is statistically insignificant. For trading at Chi-X, we find that the Chi-X tick size reduction caused an increase in trading volume by more than 300% (log coefficients transformed by $e^\tau - 1$) — which corresponds to the increased Chi-X market share documented in Section 4. Still, we find only weak evidence that Chi-X market quality increased. In particular, effective and realized spreads decrease and depth increases but these effects are all statistically insignificant.

In the bottom panel of Table 11, we evaluate the impact of the OSE tick size reduction ($t_2^* = \text{July 6, 2009}$) on stock market quality. The OSE tick size reduction causes a considerable reduction in order book depth at both the OSE (-45%) and Chi-X (-22%) — both effects measured relative to OSE listed stocks with no tick size change. At the same time, the smaller tick sizes appear to increase trading volume at both the OSE and Chi-X, although these effects are measured with much noise. We find no impact of the OSE tick size reduction on spread measures of liquidity or volatility at neither the OSE nor Chi-X.

Estimates from the difference-in-differences model using Control group 2 are presented in Table 11, labeled as specification 2. The results in Table 11 support our previous findings that the Chi-X tick size reduction on June 1, 2009 adversely affected stock liquidity at the OSE, and that the OSE tick size reduction on July 6, 2009 reduced order book depths at both the OSE and Chi-X. In addition, the table provides weakly statistically significant evidence that stock liquidity at Chi-X (measured by effected spreads) improved during the tick size war.

B.3 Robustness test: Shorter sample period

As our final robustness test, we return to the benchmark control group specification but shorten the sample period surrounding our two event dates (June 1, 2009 and July 6, 2009) to reduce the potential for confounding factors influencing our estimates. Specifically, we restrict the sample period to comprise only ten trading days before and after each of the event dates. Estimates from this robustness test are presented in Table 11, labeled as specification 3. Shortening the sample period increases the noise in our estimates but our main empirical conclusions remain the same. In particular, we find that the Chi-X tick size reduction increased effective spreads at the OSE and trading volume at Chi-X, and that the OSE tick size reduction reduced order book depth at the OSE by appreciable amounts.

Table 11 Difference-in-differences robustness testsPanel A: Chi-X tick size reduction ($t^* = \text{June 1, 2009}$)

| | <i>Espread</i> | | | <i>Rspread</i> | | | <i>Depth</i> | | | <i>Volatility</i> | | | <i>Volume</i> | | |
|------------|--------------------|--------------------|------------------|-------------------|-------------------|-----------------|-----------------|-----------------|------------------|-------------------|-------------------|-------------------|--------------------|--------------------|--------------------|
| | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| OSE | | | | | | | | | | | | | | | |
| τ | 0.088*** (3.21) | 0.077*** (2.76) | 0.088* (1.97) | 0.047 (1.35) | 0.051* (1.69) | 0.041 (1.19) | 0.035 (0.66) | 0.027 (0.52) | 0.079 (0.90) | -0.001 (-0.56) | -0.000 (-0.27) | -0.003 (-1.45) | -0.125 (-1.19) | -0.129 (-1.08) | -0.000 (-0.00) |
| N | 6717 | 5729 | 998 | 6698 | 5716 | 999 | 10615 | 6620 | 1019 | 5358 | 4903 | 981 | 8884 | 6425 | 1018 |
| Adj. R^2 | 0.61 | 0.60 | 0.63 | 0.24 | 0.25 | 0.18 | 0.76 | 0.84 | 0.88 | 0.14 | 0.09 | 0.05 | 0.83 | 0.85 | 0.88 |
| CHI | | | | | | | | | | | | | | | |
| τ | -0.064 (-1.61) | -0.075* (-1.86) | 0.013 (0.27) | -0.027 (-0.56) | -0.021 (-0.47) | 0.014 (0.23) | 0.082 (1.47) | 0.074 (1.36) | 0.148* (1.69) | -0.000 (-0.38) | 0.000 (0.38) | -0.001 (-0.75) | 1.143*** (8.53) | 1.141*** (7.81) | 0.820*** (5.15) |
| N | 6524 | 5536 | 955 | 6502 | 5520 | 956 | 10564 | 6569 | 999 | 5066 | 4611 | 915 | 8780 | 6321 | 990 |
| Adj. R^2 | 0.56 | 0.52 | 0.50 | 0.23 | 0.22 | 0.14 | 0.60 | 0.68 | 0.72 | 0.26 | 0.24 | 0.07 | 0.62 | 0.60 | 0.65 |

Panel B: OSE tick size reduction ($t^* = \text{July 6, 2009}$)

| | <i>Espread</i> | | | <i>Rspread</i> | | | <i>Depth</i> | | | <i>Volatility</i> | | | <i>Volume</i> | | |
|------------|--------------------|--------------------|------------------|-------------------|-------------------|-----------------|-----------------|-----------------|------------------|-------------------|-------------------|-------------------|--------------------|--------------------|--------------------|
| | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| OSE | | | | | | | | | | | | | | | |
| τ | 0.088*** (3.21) | 0.077*** (2.76) | 0.088* (1.97) | 0.047 (1.35) | 0.051* (1.69) | 0.041 (1.19) | 0.035 (0.66) | 0.027 (0.52) | 0.079 (0.90) | -0.001 (-0.56) | -0.000 (-0.27) | -0.003 (-1.45) | -0.125 (-1.19) | -0.129 (-1.08) | -0.000 (-0.00) |
| N | 6717 | 5729 | 998 | 6698 | 5716 | 999 | 10615 | 6620 | 1019 | 5358 | 4903 | 981 | 8884 | 6425 | 1018 |
| Adj. R^2 | 0.61 | 0.60 | 0.63 | 0.24 | 0.25 | 0.18 | 0.76 | 0.84 | 0.88 | 0.14 | 0.09 | 0.05 | 0.83 | 0.85 | 0.88 |
| CHI | | | | | | | | | | | | | | | |
| τ | -0.064 (-1.61) | -0.075* (-1.86) | 0.013 (0.27) | -0.027 (-0.56) | -0.021 (-0.47) | 0.014 (0.23) | 0.082 (1.47) | 0.074 (1.36) | 0.148* (1.69) | -0.000 (-0.38) | 0.000 (0.38) | -0.001 (-0.75) | 1.143*** (8.53) | 1.141*** (7.81) | 0.820*** (5.15) |
| N | 6524 | 5536 | 955 | 6502 | 5520 | 956 | 10564 | 6569 | 999 | 5066 | 4611 | 915 | 8780 | 6321 | 990 |
| Adj. R^2 | 0.56 | 0.52 | 0.50 | 0.23 | 0.22 | 0.14 | 0.60 | 0.68 | 0.72 | 0.26 | 0.24 | 0.07 | 0.62 | 0.60 | 0.65 |

The table presents estimates of τ from the difference-in-differences specification applied separately to the Chi-X tick size reduction ($t^* = \text{June 1, 2009}$) and the OSE tick size reduction ($t^* = \text{July 6, 2009}$). Surrounding the June 1, 2009, event, we restrict the sample period to April 1, 2009, to July 5, 2009. Surrounding the July 6, 2009 event, we restrict the sample period to June 1, 2009, to August 31, 2009. The difference-in-differences is estimated for three different robustness specifications, labeled 1, 2 and 3. In specification 1, we further restrict the baseline control sample to only comprise stocks with 200 or more trading days during the calendar year 2009. In specification 2, the control sample comprises the 25 most traded stocks in the baseline control sample, based on total trading volume in May 2009. In specification 3, we restrict the sample period to 10 trading days before and after each of the two events (June 1, 2009 and July 6, 2009) using the same control sample as in specification 2. The difference-in-differences regression specification is $y_{it} = \alpha_i + \alpha_t + \tau \text{Treatment}_{it} + \omega_{it}$. Treatment_t is a dummy variable equal to 1 for all treatment group observations on dates $t \geq t^*$. The difference-in-differences specification is estimated separately for two treatment groups. The first treatment group is OBX index stocks traded on the OSE. The second treatment group is OBX index stocks traded on Chi-X. *Espread* is the effective spreads, in percentage points. *Rspread* is the realized spreads, in percentage points. *Depth* is order book depth, transformed with the natural logarithm. *Volatility* is measured in percentage points. *Volume* is trading volume in NOK, transformed with the natural logarithm. Standard errors are clustered at the stock-level.