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Do volatility extensions improve the quality of closing call auctions?

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Abstract

To improve the efficiency of the closing price, many equity exchanges apply volatility extensions to their closing call auctions (CCAs). If an imminent auction execution implies a large price change, the order submission period is extended to let traders reconsider their orders. This paper uses the introduction of closing auction volatility extensions at NASDAQ Nordic to provide the first analysis of the effects of such mechanisms. We find that the volatility extensions reduce transitory volatility and deter price manipulation at the close. Consistent with increased trust in the mechanism, the CCA attracts higher volumes after the change.

KEYWORDS
auction safeguard, batch auction, market integrity, price manipulation

JEL CLASSIFICATION
G14, G15, G18

1 | INTRODUCTION

The last price of the day is increasingly important in financial markets. Because it is used for index calculations, derivatives settlement, and portfolio performance evaluation, the closing price has implications beyond the security traded. The widespread use of the closing price makes the market close an increasingly popular trading opportunity, as managers of passive index-tracking products (e.g., exchange-traded funds) want to minimize tracking errors, and holders and issuers of derivatives seek to hedge their bets. Bogousslavsky and Muravyev (2020) show that these flows can lead to large imbalances at the close. Furthermore, the role as benchmark makes the closing price a target for manipulation (Hillion & Suominen, 2004; Madhavan & Panchapagesan, 2000). As envisioned by Economides and Schwartz (1995), most exchanges now rely on a closing call auction (CCA) to determine an efficient closing price. The aim of this paper is to analyze the effects of CCA volatility extensions, a feature that protects the auction mechanism from large and potentially inefficient price changes.

The volatility extension is built to mitigate transitory volatility in the call auction price. A call auction typically consists of two phases: the order entry phase (also known as the batching period), in which orders are entered but no trading takes place, and the uncross, in which the trade price and volume are determined at the intersection of supply and demand. Under a volatility extension regime, the order entry phase is prolonged if the imminent uncross price violates preset price limits, which are known as volatility bands. Similar to circuit breakers in continuous trading, a volatility extension signals to investors that volatility is unusually high and allows them to reconsider their orders. Although circuit breakers are ubiquitous in equity markets and have been thoroughly analyzed in the literature, this paper is the first to analyze the effects of volatility extensions.

We use a quasi-natural experiment to evaluate the effects of CCA extensions. On December 1, 2014, the NASDAQ Nordic equity market introduced a volatility extension in the CCAs of the Stockholm segment of their market. The Copenhagen and Helsinki segments of NASDAQ Nordic, which operate under market structure conditions almost identical to those of the Stockholm market, were unaffected by the change. They serve as a suitable control group in our analyses.[1]

Our sample consists of relatively small stocks. NASDAQ Nordic is at the time of our sample the eighth largest exchange in Europe, and most of our analysis is done on its mid-cap and small-cap segments. As thinly traded stocks are more susceptible to both fundamental volatility and closing price manipulation (Aggarwal & Wu, 2006; Comerton-Forde & Putniņš, 2014), this is exactly the type of securities in which CCA extensions are potentially most useful.

In addition to the important role of closing prices discussed above, our study is motivated by current developments in the European Union and in the United States. In the European Union, since 2018, all regulated exchanges are required to apply volatility curbs in continuous trading as well as in call auctions.[2] In the United States, the efficiency of CCA prices are questioned by recent studies by Bogousslavsky and Muravyev (2020) and Hu and Murphy (2020). The importance of the CCA price efficiency is leveraged by the increasing trading interest at the close. CCA volumes in US markets climbed from about 3% of the average daily volume in 2011 to 8% in 2019, whereas in the European Union it reached 25%, up from 15% in 2016.[3]

We find that the volatility extension improves the closing price efficiency in small-cap and mid-cap stocks. The incidence of extraordinary closing price volatility (as defined by NASDAQ Nordic) is reduced, and the closing price transitory volatility falls significantly, relative to the control group. For large-cap stocks, we find that the closing mechanism functions well both with and without the volatility extension. Accordingly, we focus our analysis on small- and mid-cap stocks.

A potential reason for the drop in transitory volatility at the close is that the volatility extension deters manipulative behavior. To mislead other auction participants, manipulators often either submit or cancel large orders during the last few seconds of the auction. We develop two proxies of such strategies and find statistically significant reductions in both. Though we acknowledge that manipulative strategies are inherently difficult to capture, we view these results as evidence of improved integrity.

[1] According to personal communications with NASDAQ Nordic, the exclusion of Copenhagen and Helsinki from the CCA volatility extension mechanism was due to agreements with local stakeholders and is unrelated to the market quality variables of interest in this paper.

[2] Specifically, Article 48, §5, of the second Markets in Financial Instruments Directive (MiFID II), effective since January 3, reads: "Member States shall require a regulated market to be able to temporarily halt or constrain trading if there is a significant price movement in a financial instrument on that market or a related market" (https://www.esma.europa.eu/databases-library/interactive-single-rulebook/clone-mifid-ii/article-48). The MiFID II guidelines on circuit breakers and trading halts further specify that trading halts include "mechanisms that extend the period of scheduled or unscheduled call auctions" (https://www.esma.europa.eu/sites/default/files/library/esma70-872942901-63_mifid_ii_guidelines_on_trading_halts.pdf).

[3] See TABB Forum, April 9, 2019, After Hours: The Rise in Europe's Closing Auctions. https://research.tabbgroup.com/report/v17-021-after-hours-rise-europes-closing-auctions

Finally, we document that the volatility extension triggers investors to redistribute their trading from the continuous trading session to the CCA. Furthermore, a greater portion of the auction trading volume is due to orders submitted at the beginning of the batching period, and the auction indicative price is less volatile and is established earlier in the batching period. Our interpretation of these patterns is that investor confidence in the CCA mechanism is boosted by the volatility extension, potentially due to a reduction of manipulative strategies.

Our study contributes to several strands of the literature. Several empirical studies document how CCAs can help to improve the efficiency of the closing price (Schwartz, 2001) and overcome order imbalances and information asymmetries at the end of the trading day (Aitken et al., 2005; Barclay et al., 2008; Economides, & Schwartz, 1995; Kandel et al., 2012; Madhavan, 1992; Pagano & Schwartz, 2003). We contribute by analyzing how volatility extensions influence the CCA quality. We also introduce new measures of batching period market quality and highlight the role of call auction market integrity.

We also contribute to the emerging literature on call auction design. Economides and Schwartz (1995) note that auction design is important to improve the efficiency of closing prices, and empirical studies by McCormick (2001), Comerton-Forde and Rydge (2006), Kandel et al. (2012), and Lin et al. (2019) follow in this vein. Dyhrberg et al. (2019) analyze the effects that the CCA and its design have on market liquidity and efficiency in 43 exchanges worldwide. They consider volatility curbs, but they do not distinguish volatility extensions from other approaches to curb closing price volatility (e.g., price collars and manual interventions; see Section 2). Our study is also more granular than theirs in that we analyze the order entry phase activity, which helps us to understand the economic channels of the effects observed.

Finally, our study relates to the literature on volatility curbs and extends it to the auction setting. Previous studies in this field focus on price limits and circuit breakers in continuous trading (for literature reviews, see Kim & Yang, 2004 and Harris, 1998). We contribute to the literature by analyzing whether volatility extensions increase market integrity and investors' trust in the auction mechanism.

2 | CALL AUCTION VOLATILITY CURBS AROUND THE WORLD

Table 1 presents an overview of call auction volatility curbs implemented at major equity exchanges around the world as of December 2019.

There are two types of volatility curbs: the volatility extension[4] and the price collar. Similar to the volatility extension, the price collar applies preset volatility bands. However, if the equilibrium price falls outside the price limits, the auction trade is not delayed but executed at the price limit. Although the volatility extension is the most common volatility curb at EU exchanges and the subject of our empirical investigation, the price collar is common in the US equity markets.

The length of the auction extensions varies from 1 min (at the Oslo Børs) to 10 min (at the Toronto Stock Exchange), and the number of extensions can be either one (most common) or two (the London Stock Exchange and the Tel Aviv Stock Exchange).

In the US equity markets, the NYSE, NYSE Arca, and NASDAQ all operate price collars for the opening call auction as well as for the reopening auction following trading halts. NYSE Arca applies price collars for the closing auction too, whereas NASDAQ uses a volatility extension. At the NYSE, under unusual market conditions, the designated market maker may arbitrarily delay the auction execution. For the reopening of markets following trading halts, which by definition occur at times of high volatility, the US exchanges harmonized their procedures in 2017. In accordance with

[4] Although call auction volatility extensions are used at exchanges around the world, there is no consensus on the terminology. For example, NASDAQ Nordic and NASDAQ Baltic calls them *auction safeguards* (https://bit.ly/2JKWc6B), the London Stock Exchange names them *price monitoring extensions* (https://www.lseg.com/documents/guide-new-trading-system-doc) and in the United States, NASDAQ uses the term *auction time extensions* (http://www.nasdaqtrader.com/content/NewsAlerts/2017/LULD_12_Sheet.pdf).

TABLE 1 Call auction volatility curbs around the world

Exchange	Type of volatility curb	Call auction session
Europe		
Borsa Istanbul	(None)	
Euronext (Lisbon, Amsterdam, Brussels, Paris, London)	Price collar	Open, close
London Stock Exchange	Vol. extension (twice, 5 min)[a]	Open, intraday, close
NASDAQ Baltics	Vol. extension (once, 3 min)	Open, close
NASDAQ Copenhagen and Helsinki	Vol. extension (once, 3 min)	Open
NASDAQ Stockholm and Iceland	Vol. extension (once, 3 min)	Open, reopen, close
Oslo Børs	Vol. extension (once, 1 min)	Open, reopen, close
Spanish Stock Exchange	Vol. extension (once, 2 min)	Open, close
SIX Swiss Exchange	(None)	–
Xetra	Vol. extension (once, flexible dur.)	Open, close
Italian Bourse	Vol. extension (once, 2 min)[b]	Open, close
Americas		
NASDAQ	Price collar	Open, reopen
	Vol. extension (1-min increments)[c]	Close
NYSE	Price collar	Open, reopen
	Vol. extension[d]	Open, reopen, close
NYSE Arca	Price collar	Open, reopen, close
Toronto Stock Exchange	Vol. extension (once, 10 min)	Close
B3—Brazil Stock Exchange	Vol. extension (once, up to 5 min)	Close
Asia		
Hong Kong Stock Exchange	Price collar	Open, reopen, close
Moscow Exchange	Vol. extension (once, 3 min)	Close
Tel Aviv Stock Exchange	Vol. extension (twice, 3–4 min)[e]	Open, close
Africa		
Johannesburg Stock Exchange	Vol. extension (once, 5 min)	Open, intraday, close

[a]If the hypothetical execution price after the first auction extension still lies outside the predefined price bands, a second extension is triggered.
[b]For the opening auction, if the hypothetical execution price after the first extension still lies outside the predefined price bands, a second extension is triggered.
[c]There is no limit on the number of extensions. The closing auction is extended successively if, after each 1-min extension, there is a market order imbalance or if the indicative price moves by more than 5% or USD 0.50 (whichever is greater) in the last 15 s of the batching period.
[d]There are no preset rules on the range of deviation or the length of the auction extension. The extension is triggered at the discretion of the designated market maker under unusual market conditions and when order imbalances could cause large price dislocations.
[e]If the hypothetical execution price after the first auction extension still lies outside the predefined price bands, a second extension is triggered.
The table presents information about call auction volatility curbs around the world as of December 2019. The authors are thankful to Sean Foley for providing information on the closing mechanisms and call auction designs of numerous exchanges around the world.

the exchanges' joint filing with the US Securities and Exchange Commission (2016), the reopening auctions should be extended if the auction equilibrium price violates preset volatility bands or if there is a market order imbalance. The auction should then be extended by 5-min increments with gradually increasing volatility bands until the uncross can take place.[5]

3 THEORETICAL PREDICTIONS

To our knowledge, there is no theoretical work on volatility curbs specific to the call auction setting. Hence, we use the literature on circuit breakers as our starting point for formulating hypotheses on the effects of CCA extensions.

To assess the merit of volatility curbs, it is important to distinguish between fundamental and transitory volatility (Fama, 1989; Greenwald & Stein, 1991; Harris, 1998). Fundamental volatility contributes to price discovery, whereas transitory volatility may be due to the order imbalances of uninformed traders, transaction costs, or price manipulation. Just like a circuit breaker in continuous trading, an auction extension can mitigate transitory volatility in the call auction by offering a period of relief during which traders can reconsider their orders.

Volatility curbs are aimed to mitigate transitory volatility, but they may also delay price discovery (see Kim & Yang, 2004). This reasoning carries over to the call auction setting although the delay is limited to the length of the volatility extension.[6]

Based on this discussion, we formulate our first hypothesis.

H1: *The introduction of a CCA volatility extension improves the efficiency of the closing price by reducing the transitory volatility.*

To understand the channels of an improvement in closing price efficiency, we now consider how a CCA volatility extension can influence the incentives of market participants and formulate hypotheses related to market integrity and auction attractiveness.

Market integrity is a key priority in the design of the closing price mechanism. Hillion and Suominen (2004) point out that, if appropriate safeguards are not in place, the closing price may be subject to manipulative strategies. Though the use of a call auction generally diminishes the scope for price manipulation, Madhavan and Panchapagesan (2000) show that prices may still be distorted if the auction order flow is thin and the order imbalance is high. Comerton-Forde and Rydge (2006) present empirical evidence showing that the call auction design (degree of transparency and matching algorithm design) can improve the efficiency of the closing price.

A trigger of the CCA extension signals to market participants that there is an extraordinary amount of volatility in the auction. We predict that (the threat of) such an alarm bell deters manipulative strategies and thus improves market integrity.

H2: *The introduction of a volatility extension improves the integrity of the CCA mechanism.*

Economides and Schwartz (1995) argue that call auctions are good for market efficiency because they consolidate the order flow in time and space. Accordingly, policy makers should design call auctions to incentivize traders to

[5] For examples of the new rules for reopening call auctions, see https://www.nyse.com/network/article/nyse-increases-resiliancy-during-extreme-volatility and http://www.nasdaqtrader.com/content/NewsAlerts/2017/LULD_12_Sheet.pdf

[6] Two aspects of circuit breakers that do not apply to auction extensions are volatility spillovers (see Lehmann, 1989) and the magnet effect (Subrahmanyam, 1994). Volatility spillovers can happen when price limits are narrowly set. In the call auction setting, this can apply for price collars. For volatility extensions, in contrast, the auction uncross price is delayed but not constrained. The magnet effect of circuit breakers can emerge when the traded price is close to the volatility bands. Traders who fear that trading will be ceased may amplify volatility by trading more aggressively. In a call auction setting with a volatility extension, aggressive orders do not lead to earlier execution.

participate. As manipulation discourages investor participation (Comerton-Forde & Putniņš, 2014), alleviating such strategies can improve auction attractiveness.

Domowitz and Madhavan (2001) argue that call auction participants value the possibility of cancelling and modifying orders during the batching period. The CCA volatility extension allows them to reconsider their orders at times of turbulence. We expect this signal to reduce the auction monitoring costs, making the mechanism more attractive to market participants.

H3: *The introduction of a volatility extension improves the attractiveness of the CCA mechanism.*

4 | EMPIRICAL SETTING AND PRELIMINARY ANALYSIS

4.1 | CCA volatility extensions at NASDAQ Nordic

NASDAQ Nordic is the eighth largest stock exchange in Europe (based on turnover statistics for November 2014; see the Federation of European Securities Exchanges, 2014) and the primary venue for most Danish, Finnish, Icelandic, and Swedish equities. The trading system INET is also used for NASDAQ in the United States.

The NASDAQ Nordic continuous limit order book market is open on weekdays from 9:00 a.m. to 5:25 p.m., except for Copenhagen listings, which close at 4:55 p.m.[7] On trading days before public holidays, the closing time is 12:55 p.m.[8]

4.1.1 | CCAs at NASDAQ Nordic

The CCA order entry phase starts and runs for 5 min immediately after the continuous trading ends. Standard orders resting in the continuous limit order book are then transferred to the auction order book. During the batching period, limit and market orders can be entered, modified, and cancelled at any time.

At the uncross, which is at 5:30 p.m. for the Stockholm and Helsinki segments and at 5:00 p.m. for the Copenhagen segment, trading takes place if there are orders to buy and sell at crossed or equal prices. The closing price is set at the level that maximizes the auction trading volume. Auction orders are executed in accordance to price-internal-visibility-time priority.[9]

During the CCA, the trading system disseminates, in real time, the prices and depth at the best bid and ask levels, indicative closing information, and imbalance information. Indicative closing information refers to the closing price and volume that would result if the current limit order book status were to prevail at the time of the uncross. Imbalance information is the volume and direction of orders that would not be executed if the current status were to prevail at the uncross.

[7] Stockholm and Copenhagen follow Central European time (UTC + 1) and Helsinki follows Eastern European time (UTC + 2). The Helsinki segment opening hours overlap perfectly with those of the Stockholm segment. However, stated in local time, the Helsinki segment is open between 10:00 a.m. and 6:25 p.m. In all subsequent references to time, we use UTC + 1.

[8] For the technical details presented here, see the INET market model, which holds complete information about the market structure of NASDAQ Nordic. The document is available at: http://www.nasdaqomx.com/digitalAssets/90/90375_nasdaq-omx-nordic-market-model-2.23.pdf

[9] Internal priority means that orders with price priority that are posted by the same exchange member on different sides of the trade (e.g., on behalf of different clients) are executed against each other, regardless of their visibility and time priority. The same priority rules apply for continuous trading.

4.1.2 | The volatility extension

NASDAQ Nordic introduced volatility extensions on December 1, 2014. In addition to the CCA of the Stockholm segment, the volatility extension was introduced in the opening call auctions of the Stockholm, Copenhagen, and Helsinki listings.[10]

The volatility extension is triggered if the uncross price deviation from the reference price, defined as the price of the last trade in the continuous trading session, exceeds the volatility bands. The volatility extension prolongs the batching period by 3 min. At the end of the extension, the uncross takes place regardless of what the equilibrium price is.

The volatility bands are typically set at ±5% of the reference price. The volatility bands are tighter for stocks that are part of the large-cap indexes (OMXS30 for Stockholm, OMXH25 for Helsinki, and OMXC20 for Copenhagen) and wider for penny shares and certain illiquid stocks.[11]

4.2 | Data and sample

We access tick-by-tick data on trades, quotes, and auction uncross information from the Tick History database, maintained by Refinitiv. The data are time-stamped to the microsecond. The trade data include prices, volumes, and qualifiers indicating whether a trade is executed in the auction or in the continuous limit order book. The quote data include order book information such as the aggregate order volumes available at each price level. Specific to the auction mechanism, Tick History reports the indicative uncross information and the imbalance information during the batching period as well as uncross information at the end of the auction. The prices and volumes disseminated in the indicative uncross information are denoted *Indicative Price* and *Indicative Volume*, respectively. The corresponding variables for the actual auction uncross are denoted *Closing Price* and *Closing Volume*. *Order Imbalance* stands for the imbalance information (defined as above).

Our sample includes large-, mid-, and small-cap stocks listed at NASDAQ Nordic.[12] We retain stocks that remain in the same size segment throughout the entire sample period and that have trading activity for all the months of the sample. In total, 546 of 586 stocks are included in the sample (285 listed in Stockholm, 125 in Helsinki, and 136 in Copenhagen). We include data from 6 months before to 6 months after the event, implying a pre-event period from June 1, 2014 to November 30, 2014, and a post-event period from December 1, 2014 to May 31, 2015.

4.3 | Market characteristics

Table 2 reports the characteristics of the markets that we study based on 6 months preceding the introduction of the extensions. As expected, the trading volume of stocks at NASDAQ Nordic increases with market capitalization. Large-caps also have a higher proportion of their volume in the CCA (≃15% for the treatment group and 12% for the control

[10] NASDAQ Nordic refers to the extensions as *auction safeguards*. The technical details and scope regarding the introduction of CCA extensions are based on official NASDAQ documents available at https://bit.ly/2WUSri2 and http://www.nasdaqomx.com/digitalAssets/95/95742_q-a-auction-safeguards-and-extension-nov-2014.pdf. NASDAQ Nordic also includes the Reykjavik listings, where both the opening and closing auctions are subject to extensions. We exclude the Reykjavik segment because the volatility bands are determined differently from the other segments. Outside NASDAQ Nordic, the volatility extensions were introduced at the same time as for NASDAQ Baltic (including the Riga, Tallinn, and Vilnius listings) and First North (a NASDAQ-operated venue for growth companies in Europe) for both the opening and closing auctions.

[11] Exchanges often maintain some degree of discretion over when an extension should be applied. We validate the official parameters by evaluating actual volatility extensions in our data set and find that they are almost perfectly consistent with the published thresholds. Details and examples on how the volatility bands are applied and how we identify them in the data are given in Section A of the Appendix in the Supporting Information.

[12] The capitalization categories are defined by the exchange and do not map directly to other definitions. For example, virtually all mid-caps in our sample are valued at less than USD 2 billion, which would make them small-caps according to US terminology. Our large-cap category is, according to US standards, a mix of mid-caps and large-caps.

TABLE 2 Market characteristics

	Treatment group			Control group					
	NASDAQ Stockholm			NASDAQ Helsinki			NASDAQ Copenhagen		
	Large	Mid	Small	Large	Mid	Small	Large	Mid	Small
Trading Currency	SEK	SEK	SEK	EUR	EUR	EUR	DKK	DKK	DKK
Number of Stocks	87	91	107	32	37	56	27	25	84
Market Capitalization (million EUR)									
Average	5923.8	440.9	61.4	8680.9	622.7	48.9	4318.0	449.6	47.1
Min	47.7	16.7	0.8	250.2	55.9	0.4	103.2	63.5	0.4
Max	50,349.5	1671.1	315.7	77,479.7	1536.3	310.6	25,054.3	1536.7	171.1
Total	515,371.6	43,213.0	6879.8	243,065.1	16,814.1	4841.7	151,128.4	17,535.2	2875.7
Daily Average Trading Volume (million EUR)	1209.03	73.91	10.33	405.75	23.82	1.95	481.51	28.91	3.51
Opening call auction (%)	1.51	2.33	4.48	1.92	3.05	6.22	1.57	2.34	4.72
Continuous trading (%)	83.61	92.15	93.10	86.54	88.37	90.17	86.77	90.78	92.43
Intraday call auction (%)	–	–	0.60	–	0.97	0.76	–	0.86	0.70
Closing call auction (%)	14.89	5.51	1.82	11.54	7.60	2.85	11.66	6.02	2.15
Daily Average Turnover	0.23	0.17	0.15	0.17	0.14	0.04	0.32	0.16	0.12
Relative Quoted Spread	25.38	79.77	171.02	25.27	78.76	201.54	22.14	71.26	228.05
Volatility	0.02	0.03	0.03	0.02	0.02	0.03	0.02	0.02	0.03

Note: This table reports summary statistics of the sample markets (NASDAQ Stockholm, Helsinki, and Copenhagen) for large, mid, and small caps. The statistics are averaged across trading days from June 1, 2014 to November 30, 2014. Data on *Trading Currency*, *Number of Stocks*, and *Market Capitalization* are obtained as of November 30, 2014 from NASDAQ Nordic (2014). The variable *Daily Average Trading Volume* is calculated for different trading sessions as the sum of intraday trading volumes, measured in EUR. The trading volumes in Swedish kronor (SEK) and Danish kroner (DKK) are converted into EUR using the following exchange rates: SEK/EUR = 9.266 and DKK/EUR = 7.441 (official exchange rates on November 28, 2014, according to the European Central Bank). The variable *Daily Average Turnover* is computed as the ratio between *Daily Average Trading Volume* and the average *Market Capitalization*. The variable Relative Quoted Spread is calculated as the ratio between the closing bid–ask spread and the midpoint. Volatility is computed as the ratio between the highest and lowest trading prices of the day and the average midpoint.

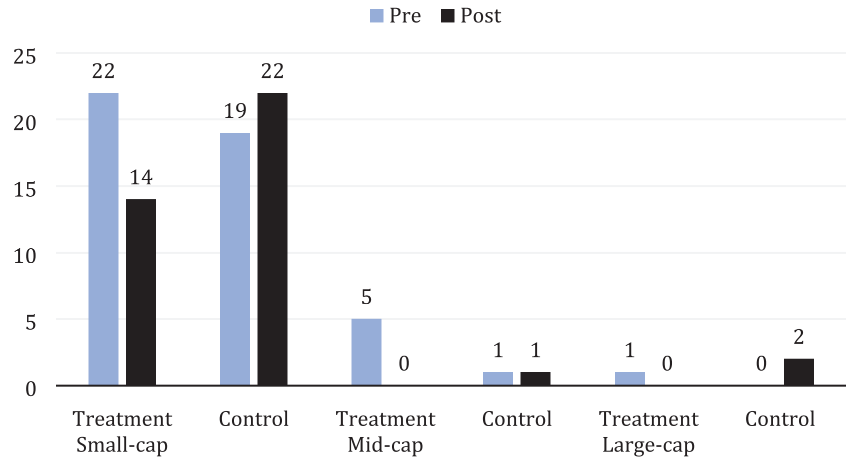

FIGURE 1 Extraordinary closing price volatility. This figure shows the incidence of *Extraordinary Closing Price Volatility* before and after the introduction of CCA extensions. The bar chart reports the number of different stock-days where the price change from the end of the continuous trading session to the end of the CCA is large enough to fulfil the conditions for an auction extension. The results are reported for both the pre- and post-event periods for each market capitalization segment (small-cap, mid-cap, and large-cap) and for the treatment group (NASDAQ Stockholm) as well as the control group (NASDAQ Copenhagen and Helsinki). The pre-event period (*Pre*) contains all trading days from June 1 to November 30, 2014. The post-event period (*Post*) contains all trading days from December 1, 2014 to May 31, 2015

group) than mid-caps (≃6% and 7% for the treatment and control groups, respectively) and small-caps (2% for both the treatment and control groups). The lower CCA volumes for small- and mid-cap stocks suggest that they are likely to be more sensitive to order imbalances, increasing the likelihood of mispricing or manipulation.

An important observation that can be made from Table 2 is that our treatment group (NASDAQ Stockholm) is, in many respects, similar to the control group (NASDAQ Helsinki and NASDAQ Copenhagen). There are 285 stocks in the treatment group compared to 261 in the control group. The average market capitalization is around EUR 1.9 billion in the treatment group and around EUR 1.5 billion in the control group.[13] The average relative quoted spread and volatility is also comparable across the different size segments of the treatment and control groups. Finally, the tendency of a lower CCA volume in smaller stocks is reflected in both groups.

4.4 | Extraordinary closing price volatility

To obtain a preliminary view of the effects of the CCA extension, we calculate the incidence of *Extraordinary Closing Price Volatility*. Specifically, we form a binary variable indicating for each stock-day whether the CCA volatility bands are violated. For the treatment group post-event period, this count equals the incidence of CCA extensions. For other stock-days, we use the volatility bands described in Section A of the Appendix in the Supporting Information to detect hypothetical triggers. We define hypothetical triggers as price changes that would have caused an extension, had the CCA extension been in operation.

Figure 1 shows the number of stock-days featuring *Extraordinary Closing Price Volatility*. The bars are grouped by stock segments as classified by NASDAQ Nordic, treatment and control markets, and the periods before and after the event.

[13] We note that the maximum market capitalization for the small-caps (mid-caps) in each geographic segment exceeds the minimum of the mid-caps (large-caps) in the same segment. These observations are not data errors, but due to the exchange's categorization of stocks being done periodically. That is, the market capitalizations reported in the table are not the same as those used for the categorization.

After the introduction of the CCA volatility extension, *Extraordinary Closing Price Volatility* drops in all size segments for the treatment stocks. Note that this result is not mechanical because we base the volatility measure on the scheduled closing time and not on the actual closing time if there is an extension. We find no corresponding reduction for the control group, signaling that the decline in volatility is due to the introduction of the CCA extension.[14]

It is important to note that *Extraordinary Closing Price Volatility* is rare. Of 137,046 stock-days across stock segments and periods, there are only 87 cases of such closing price movements. This low incidence is consistent with other volatility curbs and reflects the policy makers' intention not to intervene in trading in anything but extreme instances. It is well-known, however, that volatility curbs influence trader behavior also in anticipation of an intervention (see, e.g., Hautsch & Horvath, 2019; Subrahmanyam, 1994).

Related to this, we note that the decline in *Extraordinary Closing Price Volatility* is concentrated in small- and mid-cap stocks. The incidence almost halves in these segments, from 27 instances before the introduction of the extensions, to 14 afterward. In the large-cap segment, there is only one hypothetical trigger in the period before the introduction and none afterward. We interpret the low incidence of *Extraordinary Closing Price Volatility* in the large-cap segment as that the closing mechanism functions well both before and after the change, which may be due to the high CCA volumes reported for large-caps in Table 2. Given that volatility bands rarely affect the large-cap stocks, we focus our subsequent analysis on the small- and mid-cap stocks.

We emphasize that the evidence presented here is preliminary. The reduction in *Closing Price Extraordinary Volatility* in the treatment group is consistent with H1, but there are too few events to assess statistical significance. Furthermore, the analysis here does not account for marketwide changes in volume and volatility, and it does not separate transitory shocks from fundamental volatility. In the next section, we outline a methodology that addresses all these concerns.

5 | METHODOLOGY

The fact that NASDAQ Nordic introduces a CCA volatility extension in one of its geographical segments while keeping the other segments unaffected provides a quasi-natural experiment setup. Our identification of the effects of the volatility extension on auction quality and attractiveness hinges on observed changes in the treatment group being benchmarked to changes in the control group. The validity of this approach is leveraged by the fact that the treatment and control groups otherwise operate under almost identical market structures and have similar characteristics in terms of market capitalization and trading activity (as discussed in Subsection 4.3).

5.1 | Difference-in-differences analysis

We employ a difference-in-differences regression model to assess the impact of the CCA volatility extension while controlling for factors unrelated to the event. Specifically, to investigate the influence of the event on a variable $Y_{i,t}$ (where i is an index for stocks and t is an index for trading days), we set up the following regression model:

$$Y_{i,t} = \alpha + \beta_1 Post_{i,t} + \beta_2 Treatment_{i,t} + \beta_3 Post_{i,t} Treatment_{i,t} + \gamma \boldsymbol{Controls}_{i,t} + \varepsilon_{i,t}, \quad (1)$$

where $Post_{i,t}$ is a dummy variable that equals 1 for trading days in the post-event period (December 1, 2014 to May 31, 2015) and $Treatment_{i,t}$ is a dummy variable that equals 1 for stocks in the treatment group. The parameter of primary interest is β_3, which captures the effect of the introduction of a CCA extension in the treatment group relative to the

[14] The result could potentially be driven by a large shock that induces high volatility in several stocks at the same time, or by a few stocks that repeatedly trigger the extension. We find no support for such concerns. Instances of *Closing Price Extraordinary Volatility* are not clustered on a specific stock or day, neither on days when derivatives contracts expire, nor at the end of a quarter or year. The instances are dispersed across stocks and time, and thus appear to be idiosyncratic. For further details, see Section B of the Appendix in the Supporting Information.

control group. ***Controls***$_{i,t}$ is a matrix of ***control*** variables, including *Volatility* and *Volume*, with *Volatility* computed as the difference between the highest and lowest daily traded prices, divided by the average midpoint, and *Volume* as the natural logarithm of the daily traded euro (EUR) volume.

5.2 | Measures of closing price efficiency

To evaluate H1, which states that the volatility extension improves closing price efficiency, we analyze changes in transitory volatility at the market close.

In the absence of transitory volatility, the variance of 24-h stock returns should be the same, regardless of the time of day when the stock prices are sampled. This reasoning underlies several studies on the merits of opening and closing price mechanisms, for example, Amihud and Mendelson (1987). To assess changes in closing price transitory volatility due to changes in the closing price mechanism, we consider the variance ratio of closing price returns and morning price returns. A variance ratio greater than unity indicates that the transitory volatility in the closing price returns exceeds that of the morning price returns.

Accordingly, we define the excess transitory volatility (*ETV*) as the difference between the variance ratio and one:

$$ETV_{i,j} = \frac{\mathrm{Var}\left(\ln\left(P_{i,t+1}^{Close}\right) - \ln\left(P_{i,t}^{Close}\right)\right)}{\mathrm{Var}\left(\ln\left(P_{i,t+1}^{Morning}\right) - \ln\left(P_{i,t}^{Morning}\right)\right)} - 1, \tag{2}$$

where $P_{i,t}^{Close}$ denotes the *Closing Price*, and $P_{i,t}^{Morning}$ is the *Morning Price*. We define the latter as either the midprice of the bid–ask spread prevailing at 10:00 a.m., or as the volume-weighted average trade price from 9:30 a.m. to 10:30 a.m. The reason that we use prices from the continuous trading session rather than the opening auction price is to avoid the influence of the introduction of volatility extensions in the opening auctions in both the control and the treatment groups. The two alternative measures of the *Morning Price* address potential concerns that our results are driven by the choice of benchmark price. We calculate the *ETV* for each stock *i* and each period $j = [Pre, \ Post]$, where *Pre* and *Post* refer to the pre-event and post-event periods, respectively. The index *t* refers to trading days in the given period *j*.

To be included in the analysis of transitory volatility, we require a stock to have price observations for both the *Morning Price* and the *Closing Price* in at least two-thirds of all trading days.[15]

5.3 | Proxies of market integrity

Market integrity is an elusive concept that is difficult to quantify. Our strategy to identify changes in market integrity is to analyze changes in trading and order activity that are consistent with manipulative behavior.

How can the closing auction price be manipulated? Comerton-Forde and Putniņš (2011) characterize closing price manipulation in the continuous limit order book as aggressive trading with the purpose of moving the closing price to an artificial level. The manipulative activity is typically concentrated to the last instances before the market close, such that other participants have little time to respond. In the CCA setting, a manipulator has the same incentives to concentrate the activity in the very end of the trading session, but the price distortion may be achieved through aggressive order submissions and cancellations, rather than actual trading.

Our first proxy of manipulative closing auction behavior is designed to capture the following strategy. To achieve an artificially high closing price, for example, a manipulator enters a large sell order in the batching period with the purpose to create an impression of selling pressure. The large sell order may then trigger buy orders from other investors

[15] Missing prices are due, at times, to the low levels of trading activity in illiquid stocks. To obtain the daily returns required to measure *ETV*, we backfill missing prices. Specifically, a missing *Morning Price* is replaced by the previous *Closing Price*. If there is no *Closing Price* available from the auction, the last trade price of the continuous session is used.

who believe they will buy at a good price. Shortly before the auction uncross, the manipulator cancels the large sell order. If the buyers do not follow suit before the uncross, the equilibrium price becomes artificially high. To capture activities consistent with this strategy, we measure the rate of cancellations in the final 10 s of the batching period. If the introduction of CCA extensions undermines this strategy, in line with H2, the late cancellations should decrease. Specifically, we define the *Late Cancellation Rate* as:

$$Late\,Cancellation\,Rate = \frac{Cancellations_{CCA}^{Late}}{Closing\,Volume}, \tag{3}$$

where $Cancellations_{CCA}^{Late}$ is the EUR value of orders that are cancelled during the final 10 s of the batching period. To normalize the measure across stock-days, we divide by *Closing Volume*, defined as the EUR uncross volume. The variables in Equation (3), and all the following variables in this section, are observed on a stock-day frequency. For brevity, the indexes i and t are omitted.

It is important to note that limit order cancellations are typically part of legitimate liquidity-demanding or market-making strategies (e.g., Hasbrouck & Saar, 2009; van Kervel, 2015). But cancellations at the very end of the batching period of a CCA may be associated with closing price manipulation. In particular, if there is a significant treatment group reduction in the *Late Cancellation Rate* following the introduction of CCA extensions, relative to the control group, we view this as evidence of increasing market integrity.

An alternative strategy for manipulating the CCA is to submit a large order at the end of the batching period. If other traders do not have time to respond, it could push the equilibrium price to an artificial level. This strategy differs from the previous one in that it is likely to result in trades for the manipulator, whereas the former strategy does not. A manipulator may be willing to go through with this strategy if the auction price is used for the valuation of a related position, for example an option contract. We approximate the prevalence of such strategies by analyzing the auction order imbalance, defined as the *absolute* volume of orders that would remain unexecuted if the order book is unchanged before the auction uncross.[16] We define *Late Order Imbalance* as:

$$Late\,Order\,Imbalance = \frac{Order\,Imbalance_{CCA}^{Late}}{Order\,Imbalance_{CCA}^{Early}}, \tag{4}$$

where $Order\,Imbalance_{CCA}^{Late}$ is the average *Order Imbalance* of the last 10 s of the order entry phase, and $Order\,Imbalance_{CCA}^{Early}$ is the average *Order Imbalance* of the preceding part of the batching period.

We emphasize that order imbalance variations are typically unproblematic. But shocks in the very end of the batching period, potentially causing changes in the equilibrium price, may be due to price manipulation. We argue that a reduction in *Late Order Imbalance* associated with the introduction of CCA extensions, seen in the treatment group relative to the control group, indicates an increase in market integrity.

5.4 | Proxies of auction attractiveness

The most straightforward way to assess whether the auction becomes more attractive is to investigate whether traders migrate to or from the auction mechanism. We define the *Relative Closing Volume* as:

$$Relative\,Closing\,Volume = \frac{Closing\,Volume}{Total\,Volume}, \tag{5}$$

[16] The exchange disseminates the expected imbalance in real time to market participants during the batching period. The expectation is based on the assumption that there are no more submissions, cancellations, or modifications before the auction uncross.

where *Total Volume* is the total stock-day trading volume, including the call auctions. We expect the *Relative Closing Volume* to be increasing in auction attractiveness.

Another aspect of call auction attractiveness can be seen through the lens of investor activity during the CCA. For example, if investors are not concerned about closing price volatility, they are more likely to submit orders early in the batching period to gain time priority. If investors worry that the closing price is inefficient or that the market lacks integrity, in contrast, they may postpone their orders until the end. This point is akin to viewing limit orders as free options that are offered to all market participants, with the limit price being the strike price (Copeland & Galai, 1983). The value of such options is increasing in expected volatility, which thus deters traders to submit limit orders. Below, we outline four proxies of auction attractiveness based on batching period activity.

The exchange disseminates the first indicative uncross information when there are crossing prices in the call auction limit order book. We denote the time of the first indicative uncross information as $t_{first\ indicative}$, and the scheduled uncross time (in the absence of a volatility extension) as $t_{uncross}$. We then define:

$$\textit{First Indicative Time to Uncross} = t_{uncross} - t_{first\ indicative}, \tag{6}$$

where time is measured in seconds. We argue that a higher value of *First Indicative Time to Uncross* signals higher auction attractiveness, because it demonstrates that investors trust the auction mechanism enough to commit their trading interests early on.

Increasing trust in the auction can also be demonstrated by market participants posting larger orders early in the batching period. To capture this dimension of trust, we let $t_{indicative\ volume}$ denote the first time when the *Indicative Volume* equals or exceeds the subsequent *Closing Volume*. Similar to the previous proxy, we define:

$$\textit{Indicative Volume Time to Uncross} = t_{uncross} - t_{indicative\ volume}, \tag{7}$$

where time is measured in seconds. By the same reasoning as above, we expect the *Indicative Volume Time to Uncross* to be increasing with auction attractiveness.

An alternative way to evaluate trust in the auction mechanism is to measure the proportion of the *Closing Volume* that is generated by orders posted early in the batching period. To this end, we define:

$$\textit{Early Trading Interest} = \frac{\textit{First Indicative Volume}}{\textit{Closing Volume}} \times \frac{\textit{First Indicative Time to Uncross}}{300}, \tag{8}$$

where the first term is the ratio of the *First Indicative Volume* (the *Indicative Volume* posted at $t_{first\ indicative}$) and the *Closing Volume* (both measured in EUR) and the second term is a weighting factor that gives greater weight to orders submitted earlier in the batching period (note that the scheduled batching period duration is 300 s). The variable *Early Trading Interest* is designed to increase with auction attractiveness.

Finally, we argue that higher CCA attractiveness should lead to lower indicative price volatility. Traders who trust the integrity of the market are likely to post their orders earlier in the batching period and to submit larger orders. Such behavior should make the call auction order book more resilient to liquidity shocks. We define *Indicative Price Volatility* as the difference between the highest and lowest indicative prices disseminated during the batching period (denoted *Indicative Price*$_{high}$ and *Indicative Price*$_{low}$, respectively):

$$\textit{Indicative Price Volatility} = \ln\left(\textit{Indicative Price}_{high}\right) - \ln\left(\textit{Indicative Price}_{low}\right). \tag{9}$$

We expect the *Indicative Price Volatility* to be decreasing with auction attractiveness.

6 RESULTS

6.1 Closing price efficiency

We investigate whether the reduction in extraordinary volatility carries over to our measure of *ETV*. According to H1, the introduction of the CCA extension should reduce transitory volatility. Table 3 shows the event study estimates, along with standard errors clustered on stocks to adjust for correlation in the cross-section.

Columns 1 and 2 of Table 3 show the results for the full sample. The primary coefficient of interest is β_3, which corresponds to $Post_{i,j} Treatment_{i,j}$ and captures the effect of the introduction of the volatility extension in the treatment group relative to the control group. Consistent with H1, we obtain negative estimates of β_3 for the transitory volatility, regardless of whether the *Morning Price* is defined as a spread midpoint or as an average trade price. The estimates for the *ETV* based on the midprice version of the *Morning Price* indicate that the ETV before the introduction is 0.086 (0.096 – 0.010 = 0.086) in the treatment group. After the event, the treatment group *ETV* falls to 0.021 (0.086 – 0.028 – 0.037 = 0.021). The fact that the measures are positive indicates that the closing price is subject to ETV relative to the morning price. The reduction in ETV, from 0.086 to 0.021, is significant at the 5% level.

The reduction in *ETV* could potentially be driven by a decrease in overall volatility in the post-event period. We address this concern in Table 4, in which we present the results of a test of difference in means before and after the introduction of the extensions for two alternative volatility measures. The *High–Low Volatility* is the log difference of the highest and lowest transaction price of the day. The *Open-to-Close Volatility* is the absolute log difference between the opening and the closing price. The results show that the post-event period is characterized by higher, rather than lower, levels of volatility for both the treatment and the control groups. Hence, we rule out the explanation that lower levels of overall volatility in the post-event period are behind the change in *ETV* and attribute the improvement to the introduction of the CCA extension.

Another potential concern is that the volatility extension effect could be concentrated to a few stocks where extraordinary volatility is more common. We address this concern by splitting the sample into *Volatile stocks* and *Non-volatile stocks*. The categorization is based on the average volatility of each stock in the pre-event period, using the median volatility as cut-off point. The results of the subsample analysis are presented in columns 3–6. In line with our reasoning above, we find that the decrease in closing price transitory volatility is indeed stronger for *Volatile stocks*, but the reduction remains statistically significant in both subsamples. The ETV is reduced by 45% for *Volatile stocks* and by 17% for *Non-volatile stocks*. We conclude from this exercise that the reduction in transitory volatility is not isolated to the most volatile stocks.

6.2 Market integrity

Figure 2 reports the average evolution of the auction cancellation rate (Panel a) and the auction order imbalances (Panel b) for the small-cap and the mid-cap stocks of our treatment group. The cancellation rate is the EUR value of orders that are cancelled during a given interval of the batching period, divided by the SEK *Closing Volume* on the same stock-day. The order imbalance is defined as the absolute difference between the SEK volumes posted at the best bid and ask prices at the end of a given interval of the batching period. Both variables are measured on a 10-s frequency.

We note a perceptible reduction in both the cancellation rate and the order imbalance toward the end of the auction. This finding supports the hypothesis of improved market integrity. In particular, the sharp increase in order imbalances in the end of the auction, which is mitigated after the event, is consistent with manipulative strategies. We note that there are differences between the pre- and post-period observations earlier in the auction too, but as emphasized above, auction price manipulators have strong incentives to act in the very end of the auction. For this reason, we do not interpret the earlier fluctuations as variation in market integrity.

TABLE 3 Difference-in-differences analysis of closing price efficiency

	All stocks		Volatile stocks		Non-volatile stocks	
	ETV(Midprice)	*ETV(Trade)*	*ETV(Midprice)*	*ETV(Trade)*	*ETV(Midprice)*	*ETV(Trade)*
	(1)	(2)	(3)	(4)	(5)	(6)
Intercept	0.096***	0.082***	−0.037***	−0.023	0.139***	0.121***
	(0.012)	(0.013)	(0.018)	(0.020)	(0.021)	(0.023)
$Treatment_{i,j}$	−0.010	−0.034***	0.126***	0.069***	−0.085***	−0.092***
	(0.015)	(0.017)	(0.022)	(0.023)	(0.019)	(0.021)
$Post_{i,j}$	−0.028***	−0.043***	0.049***	−0.009	−0.065***	−0.055***
	(0.014)	(0.012)	(0.028)	(0.020)	(0.016)	(0.015)
$Treatment_{i,j}\ Post_{i,j}$	−0.037***	−0.038***	−0.089***	−0.052***	−0.034***	−0.049***
	(0.017)	(0.016)	(0.032)	(0.026)	(0.020)	(0.020)
$Volatility_{i,j}$	0.247	0.256	0.293	0.161	2.188	1.568
	(0.210)	(0.169)	(0.178)	(0.129)	(2.143)	(2.176)
$Volume_{i,j}$	−0.0004	0.002***	0.002***	0.004***	−0.001	0.002***
	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)
Number of observations	372	364	186	182	186	182
Number of stocks	186	182	93	91	93	91
Adjusted R^2	0.01	0.04	0.02	0.03	0.12	0.11

Note: This table reports the estimated effects of the introduction of a CCA extension on the closing price transitory volatility. The parameter estimates correspond to the following difference-in-differences regression:

$Y_{i,j} = \alpha + \beta_1 Post_{i,j} + \beta_2 Treatment_{i,j} + \beta_3 Post_{i,j} Treatment_{i,j} + \gamma \boldsymbol{Controls}_{i,j} + \varepsilon_{i,j}$,

where i is an index for stocks and j can be either Pre or Post, referring to the pre-event window (June 1, 2014 to November 30, 2014) and the post-event window (December 1, 2014 to May 31, 2015), respectively. The dependent variable $Y_{i,j}$ is the excess transitory volatility, *ETV*, defined as the variance ratio of daily returns measured using the closing price and the morning price, respectively, minus 1. We compute the morning prices as either the midprice of the bid–ask spread prevailing at 10:00 a.m. or as the volume-weighted average trade price from 9:30 a.m. to 10:30 a.m. $Treatment_{i,j}$ is a dummy variable indicating whether stock i belongs to the treatment group (NASDAQ Stockholm); $Post_{i,j}$ is a dummy variable indicating the post-event window; and $\boldsymbol{Controls}_{i,j}$ is a matrix of ***control*** variables including *Volatility* and *Volume*. *Volatility* is computed as the average difference between the highest and lowest daily traded prices, divided by the average midpoint, and *Volume* is the average natural logarithm of the daily traded EUR volume. Standard errors are clustered to correct for correlations in the stock cross-section and are reported in parentheses. The analysis is repeated for *Volatile stocks* and *Non-volatile stocks*, with the subsamples defined relative to the median volatility in the pre-event period.

***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

TABLE 4 Descriptive statistics on pre/post volatility

	Pre-event		*Post-event*			
	Mean	Median	Mean	Median	Difference in means	*t*-Statistic
High–Low Volatility						
All stocks	0.027	0.024	0.031	0.027	0.004	3.626***
Treatment	0.030	0.027	0.034	0.029	0.004	2.331***
Control	0.024	0.022	0.029	0.025	0.005	2.839***
Open-to-Close Volatility						
All stocks	0.014	0.013	0.016	0.014	0.002	2.761***
Treatment	0.015	0.014	0.017	0.015	0.002	1.762***
Control	0.014	0.012	0.016	0.013	0.002	2.134***

Note: This table reports descriptive statistics on two alternative volatility measures for 6 months before the introduction of CCA extensions (June 1, 2014 to November 30, 2014) and 6 months after the implementation (December 1, 2014 to May 31, 2015). *High–Low Volatility* is the log difference between the highest and lowest transaction prices of the day. *Open-to-Close Volatility* is the absolute log difference of the opening and closing prices. The mean and the median are computed from the daily observations of each variable. The last two columns show the difference in means pre/post the introduction of the extensions and the significance of the difference in means using a two-tailed Welch *t*-test with heteroskedastic robust standard errors. The analysis is conducted for all the stocks of the sample, as well as separately for the treatment and control groups.
***, **, and * indicate statistical significance at the 1%, 5% and 10% levels, respectively.

To see whether the conclusions from our visual inspection hold up statistically, we benchmark the market integrity variables to the control group. Table 5 presents the results of the difference-in-differences regression analysis on market integrity. The standard errors, reported in parentheses, are double clustered by stock and day (following Petersen, 2009).[17] We find evidence of improved market integrity, consistent with H2. The variable *Late Cancellation Rate*, which captures the cancellation intensity at the end of the batching period, decreases significantly for the treatment group relative to the control group. The *Late Cancellation Rate* for the treatment group before the event is 1.120 (0.921 + 0.199 = 1.120), showing that the amount of late cancellations is, on average, slightly higher than the trading volume in the uncross. Following the introduction of the volatility extension, it falls to 0.968 (1.120 – 0.001 – 0.151 = 0.968), which is a drop of 14%. At the same time, the control group remains unchanged. The drop in cancellations in the last seconds of the auction indicates that volatility extensions improve the CCA integrity.

Late Order Imbalance captures whether the average order imbalance is larger in the last 10 s than in the rest of the batching period. For the treatment group before the event, this variable is slightly below 1 (0.928 + 0.045 = 0.973), indicating that the order imbalance is, on average, lower late in the auction. After the introduction of the extension, *Late Order Imbalance* decreases relative to the control group, but the effect is statistically significant only at the 10% confidence level. The decrease in auction order book imbalance amounts to about 3% (–0.024/0.973 = –0.025) and indicates a slight improvement in market integrity.

6.3 | Auction attractiveness

We now turn to the investigation of H3, stating that extensions make the CCA more attractive to investors, partially because the increased integrity improves trust in the auction mechanism. Figure 3 depicts the evolution of two measures of auction attractiveness for stocks at NASDAQ Stockholm. Panel a reports the average evolution of the *Indicative Volume* available during the batching period before and after the introduction of volatility extensions. The parallel

[17] For robustness, we compute the two market integrity proxies using alternative times frames. The conclusions are along the lines of the ones obtained when using 10 s and are found in Section C of the Appendix in the Supporting Information.

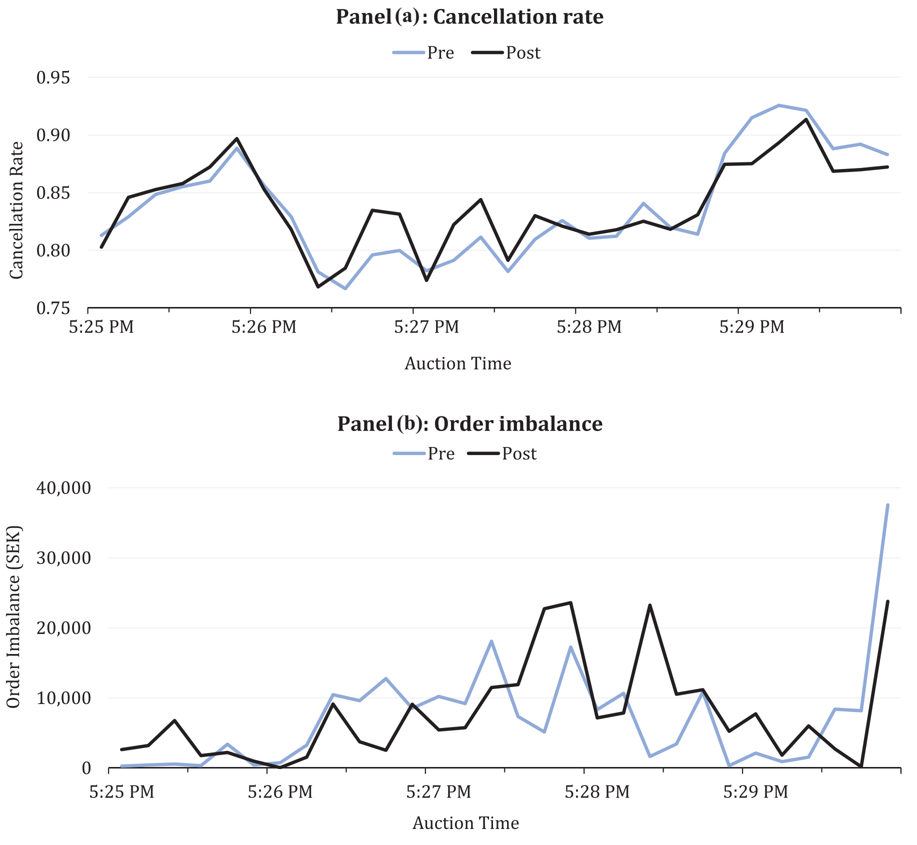

FIGURE 2 Measures of market integrity. This figure shows the cancellation rate and order imbalances during the batching period of the CCA at NASDAQ Stockholm. Panel (a) depicts the SEK value of limit orders (limit price multiplied by the limit quantity) cancelled in a given period, divided by the SEK *Closing Volume* on the same stock-day. The time series is based on a 10-s frequency for the period from 5:25 p.m. to 5:30 p.m. Panel (b) shows the SEK *Order Imbalance* (absolute difference between the bid and ask limit quantities multiplied by their limit prices) at a 10-s frequency for the period from 5:25 p.m. to 5:30 p.m. Both measures are averaged across stock-days for small- and mid-cap stocks at NASDAQ Stockholm. The pre-event period (*Pre*) contains all trading days from June 1 to November 30, 2014. The post-event period (*Post*) contains all trading days from December 1, 2014 to May 31, 2015

upward shift of the volume curve shows that the *Indicative Volume* is higher throughout the batching period after the volatility extension is introduced. In line with our hypothesis, the evidence suggests that the volatility extension succeeds in attracting liquidity to the CCA.

Auction attractiveness can also be assessed by looking at the timing of order submissions. If market participants trust the auction mechanism, they are more likely to submit their orders early in the batching period. Panel b of Figure 3 depicts the cumulative frequency of the time of the first indicative price, $t_{first\ indicative}$. The upward shift of the curve shows that, after the implementation of CCA extensions, the indicative price is established earlier in the batching period. This finding suggests that traders are less concerned about closing price volatility.

Table 6 presents the results of the difference-in-differences regression analysis for the five measures relating to auction attractiveness with standard errors (reported in parentheses) double clustered by stock and day. We find strong evidence of improved auction attractiveness, consistent with H3. In relative terms, the variable *Relative Closing Volume* for the treatment group increases following the event. According to the coefficient estimates, the closing auction volume for the treatment group falls by one percentage point from 5.56% (0.0855 – 0.0299) to 4.56% (0.0556

TABLE 5 Difference-in-differences analysis of market integrity

	Late Cancellation Rate (1)	*Late Order Imbalance* (2)
Intercept	0.921***	0.928***
	(0.005)	(0.005)
$Treatment_{i,t}$	0.199***	0.045***
	(0.029)	(0.011)
$Post_{i,t}$	−0.001	0.008
	(0.006)	(0.008)
$Treatment_{i,t}\ Post_{i,t}$	−0.151***	−0.032***
	(0.066)	(0.017)
$Volatility_{i,t}$	0.007	0.007***
	(0.005)	(0.002)
$Volume_{i,t}$	0.000***	0.000
	(0.000)	(0.000)
Observations	4101	3564
Adjusted R^2	0.01	0.001

Note: This table reports the estimated effects of the introduction of a CCA extension on market integrity. The parameter estimates correspond to the following difference-in-differences regression:
$Y_{i,t} = \alpha + \beta_1 Post_{i,t} + \beta_2 Treatment_{i,t} + \beta_3 Post_{i,t} Treatment_{i,t} + \gamma \boldsymbol{Controls}_{i,t} + \varepsilon_{i,t}$,
where *i* is an index for stocks and *t* is an index for trading days. The regression is estimated for two different dependent variables that capture market integrity: *Late Cancellation Rate* is the ratio between the EUR volume cancellations occurring in the last 10 s of the auction and the EUR *Closing Volume*. *Late Order Imbalance* is the ratio between the average bid–ask EUR Order Imbalance of the last 10 s of the batching period and the overall average *Order Imbalance* of the batching period (excluding the last 10 s). The independent variables are as follows: $Treatment_{i,t}$ is a dummy variable that indicates whether stock i belongs to the treatment group (NASDAQ Stockholm); $Post_{i,t}$ is a dummy variable that indicates the post-event window (December 1, 2014 to May 31, 2015); and $\boldsymbol{Controls}_{i,t}$ is a matrix of control variables including *Volatility* and *Volume*, defined as in Table 3. Standard errors are corrected by double clustering on stock and day and are reported in parentheses.
***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

– 0.0206 + 0.0106).[18] However, the fall is even greater for the control group, whose closing auction market share decreases significantly by more than two percentage points from 8.55% to 6.49%. This result, consistent with Figure 3, Panel a, indicates that the volatility extension successfully attracts trading volume to the auction.

Turning to the batching period activity, the metric *First Indicative Time to Uncross* captures whether investors submit orders earlier in the CCA. We find that the metric increases by 3.08 s (from 223.86 to 226.94 s) for the treatment group, a statistically significant improvement relative to the control group (which moves significantly in the opposite direction). This result is consistent with the idea that CCA volatility extensions increase trader confidence in the auction mechanism.

The conjecture of increased auction attractiveness is reinforced by the positive and significant results for *Indicative Volume Time to Uncross* (which captures whether traders submit orders earlier and of greater volume), *Early Trading Interest* (which reflects if a greater fraction of the final traded volume is concentrated at the beginning of the batching period), and the significantly negative coefficient on *Indicative Price Volatility* (which indicates the auction's sensitivity to liquidity shocks).

Overall, our results show strong support for H3. They are consistent with Domowitz and Madhavan's (2001) point that market participants value the possibility of modifying or cancelling orders in the batching period, particularly in

[18] We exclude *Volume* as a control variable for *Relative Closing Volume* in order to avoid a mechanical relation between the two variables.

TABLE 6 Difference-in-differences analysis of auction attractiveness

	Relative Closing Volume (1)	*First Indicative Time to Uncross* (2)	*Indicative Volume Time to Uncross* (3)	*Early Trading Interest* (4)	*Indicative Price Volatility* (5)
Intercept	0.0855***	249.56***	161.22***	0.685***	0.009***
	(0.0062)	(3.77)	(5.84)	(0.0102)	(0.0006)
$Treatment_{i,t}$	−0.0299***	−25.70***	18.97***	0.014	0.002***
	(0.0071)	(5.13)	(6.87)	(0.0145)	(0.0009)
$Post_{i,t}$	−0.0206***	−4.21***	−9.22***	−0.014***	0.001***
	(0.0035)	(1.57)	(2.42)	(0.0066)	(0.0007)
$Treatment_{i,t}$ $Post_{i,t}$	0.0106***	7.29***	8.78***	0.026***	−0.002***
	(0.0043)	(3.42)	(3.96)	(0.0120)	(0.0008)
$Volatility_{i,t}$	0.0003	−0.43	−1.21***	−0.002	−0.001
	(0.0005)	(0.60)	(0.55)	(0.0020)	(0.0006)
$Volume_{i,t}$		0.00***	0.00***	0.000	0.000
		(0.00)	(0.00)	(0.0000)	(0.0000)
Observations	31,999	34,839	30,964	31,215	15,224
Adjusted R^2	0.02	0.02	0.02	0.002	0.002

Note: This table reports the estimated effects of the introduction of a CCA extension on auction attractiveness. The parameter estimates correspond to the same difference-in-differences regression as in Table 4; only the dependent variables differ. Five different dependent variables that capture auction attractiveness are considered: *Relative Closing Volume* is the ratio between the *Closing Volume* and the daily traded volume; *First Indicative Time to Uncross* is the distance, in seconds, between the time the first indicative price was disseminated in the auction and the time of the auctions' uncross, $t_{uncross}$; *Indicative Volume Time to Uncross* is the distance, in seconds, between the time when a volume at least equal to the *Closing Volume* is recorded in the batching period and $t_{uncross}$; *Early Trading Interest* is a time-weighted ratio between the EUR volume associated with the first indicative price and the EUR *Closing Volume*; and *Indicative Price Volatility* is the log difference between the highest and lowest *Indicative Price*. The independent variables are defined as in Table 4. Standard errors are corrected by double clustering on stock and day and are reported in parentheses.

***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

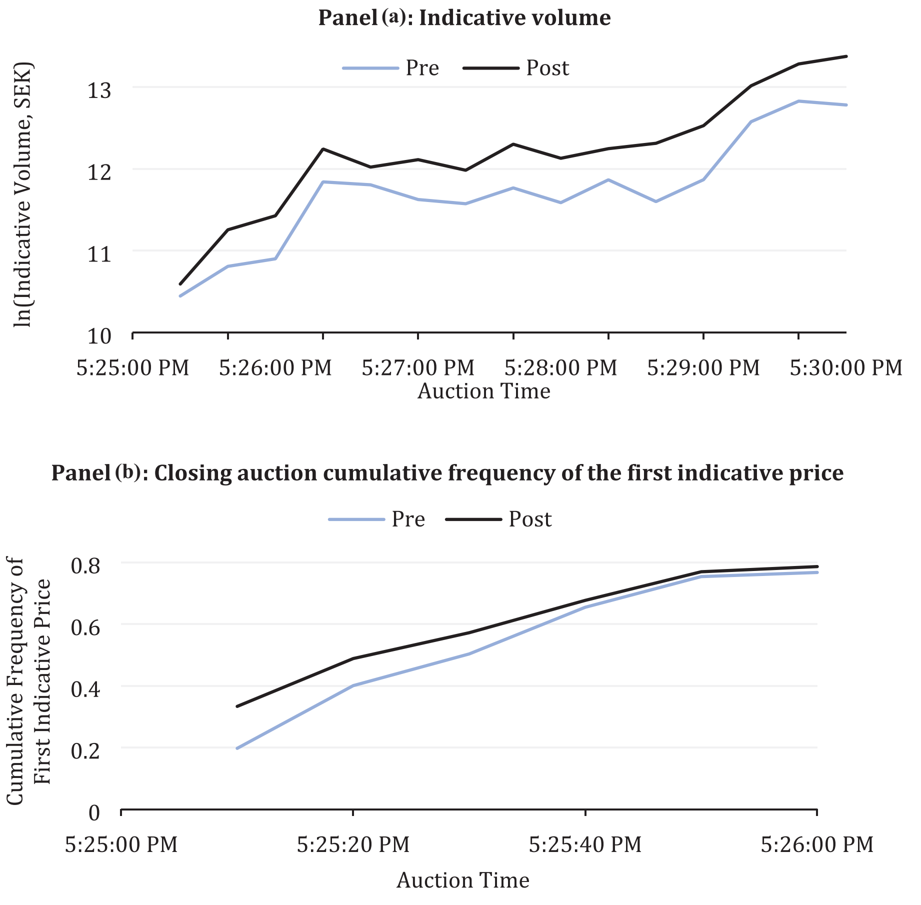

FIGURE 3 Measures of auction attractiveness. This figure reports auction attractiveness measured during the batching period of the CCA. Panel (a) depicts the log SEK *Indicative Volume* at a 20-s frequency for the period from 5:25 p.m. to 5:30 p.m. The measure is averaged across stock-days for small- and mid-cap stocks at NASDAQ Stockholm. Panel (b) shows the cumulative frequency of the time of the first indicative price. The time series has a 10-s frequency for the first minute of the batching period. The pre-event period (*Pre*) contains all trading days from June 1 to November 30, 2014. The post-event period (*Post*) contains all trading days from December 1, 2014 to May 31, 2015

times of high volatility. The finding that investors post orders earlier in the batching period, that the early orders are of greater volume, and that the indicative price becomes less volatile indicates that investors become less wary of auction manipulation, as argued by Comerton-Forde and Putniņš (2014).

7 | CONCLUSION

This paper analyzes the effects of introducing a volatility extension in the CCA. We use a quasi-natural experiment setup based on the introduction of a volatility extension at NASDAQ Stockholm to examine the effects of CCA volatility extensions. Our results show that the (threat of) CCA volatility extensions reduce the incidence of extraordinary closing price volatility and that transitory volatility at the close is mitigated. Our analysis of the order entry phase indicates that the underlying mechanism for the effect is an improvement in CCA market integrity, which makes the mechanism more attractive to investors.

Volatility extensions have been implemented for closing and reopening auctions following trading halts at US equity markets in 2017. Furthermore, call auction volatility curbs are strongly advised for all EU exchanges since January 2018. Given the regulatory agenda, we expect increasing interest in volatility extensions. Understanding the effects of this feature is hence increasingly relevant to regulators and policy makers.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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