When bigger is better: The impact of a tiny tick size on undercutting behavior

Anne H. Dyhrberg [a,1] Sean Foley [a] Jiri Svec [a]

[a] *University of Sydney*

Abstract

We exploit a cryptocurrency market structure setting with an infinitesimal tick size to quantify undercutting behavior and assess how it impacts liquidity provision and market quality. We find that increasing tick sizes in this market enhances overall market quality by reducing the instances of undercutting, encouraging traders to post more and larger limit and market orders. Increased liquidity provision lowers quoted, effective and realized spreads for both institutional and retail-sized trades and decreases short-term volatility. These findings corroborate theoretical predictions of a convex relationship between relative tick size and spread and confirm a non-zero optimal tick size. This evidence provides support for raising minimum trading increments in tick-unconstrained markets.

JEL classification: G14 G15 C580

Keywords: Market Microstructure, Tick Size, Trading Behavior, Undercutting, Cryptocurrency

[1] Anne Haubo Dyhrberg acknowledges financial support from the Capital Markets Cooperative Research Centre.
Send correspondence to Anne Haubo Dyhrberg, email: Anne.dyhrberg@sydney.edu.au.

1. Introduction

High overall market quality is critical for trading venues to attract traders in increasingly fragmented markets, with almost thirty percent of all US equity volume executed in off-exchange venues (O'Hara and Ye, 2011). While there is no single metric to measure market quality, the minimum tick size is one aspect of market quality that is controlled by an exchange. Empirical studies show that optimal tick size must be small to minimize the indirect trading costs associated with bid-ask spread, but theoretical models assert that it is non-zero to enforce time and price priority, incentivizing traders to provide liquidity with limit orders (Harris, 1991; Cordella and Foucault, 1999; Foucault, Kadan, and Kandel, 2005). Creating incentives for market participants to supply liquidity is a key issue in market design and a non-zero tick size is essential for time priority to have a meaning (Harris, 1991, 1996).

In order driven markets without a designated market maker, which primarily rely on Endogenous Liquidity Providers (ELPs) who supply liquidity because it is profitable, a selection of an appropriate tick size is vital. Since ELPs have no obligations to maintain markets, they can withdraw when liquidity provision becomes risky or unprofitable, adversely impacting market quality (Anand and Venkataraman, 2016). Inventory is one of the primary sources of risk for liquidity providers and inventory averse ELPs mitigate this risk by reducing their participation in markets during periods of high inventory risk (Aït-Sahalia and Sağlam, 2017a; 2017b). Exchanges with a fine trading increment that encourages aggressive quoting of prices that undercut existing orders by an economically insignificant amount create significant inventory risk for ELPs. Undercutting causes ELPs to lose execution priority and hinders rapid offload of potential inventory. High prevalence of undercutting is thus likely to reduce ELPs participation in the market leading to reduced depth of the limit order book and lower market quality.

In this paper, we propose new measures of undercutting to quantify undercutting behavior and assess how it impacts liquidity provision and market quality. While the literature is replete with theoretical predictions on the detrimental value of undercutting on market quality (see for example, Werner et al., 2019), empirical evidence is lacking. One of the key empirical issues is that pricing grids on most equity exchanges are too coarse to facilitate cheap undercutting and spreads are too constrained without sufficient room to undercut existing limit orders.

We aim to fill this gap in literature using high frequency trade and quote data from the Kraken cryptocurrency exchange, where tick sizes are orders of magnitude smaller than equity markets and the relative tick size (tick size relative to the stock price) is virtually zero. Trading on Kraken is comparable to trading on an equity exchange and its market structure resembles modern equity markets with continuous trading in a non-intermediated order driven market. Traders can either execute immediately with a market order or wait for a better execution price with a limit order. Limit orders are stored in the limit order book and are executed according to price and time priority. Aware of the damaging impact of undercutting on market quality, Kraken significantly increased its tick size for all currency pairs in August and September 2017.

"Reducing the price precision will help reduce extraneous activity in the order books as traders continually jump in front of each other by a very small fraction. We have received many requests from clients for this reduction and it will help reduce load on the trade engine with more efficient order books." (Kraken Press Release, August 26, 2017)

We use these two tick size increases with explicit references to the reduction of undercutting as natural experiments to analyze the relation between undercutting, liquidity provision and market quality. Specifically, we examine whether increasing the infinitesimal tick size leads to reduction in undercutting, increased liquidity provision and improvement in market quality for six currency pairs between Bitcoin (BTC), Ethereum (ETH), Ethereum classic (ETC), Litecoin (LTC) and the US dollar (USD).

Our results show that, consistent with its stated objective, widening the tick size leads to a change in traders' behavior, with a significant reduction in undercutting. Lower instances of undercutting boost the number and size of limit orders, increasing the overall depth of the limit order book. Limit orders posted at the same price point increase, implying that liquidity providers are clustering limit orders at the same price levels, restoring the relevance of time priority. The improved liquidity environment also increases the size of liquidity demanding orders.

An analysis of spreads confirms that the increased liquidity provision leads to lower transaction costs with a 12.98 basis points (bps) reduction in quoted spread, 10.04 bps reduction in effective spread and 11.22 bps reduction in realized spreads, respectively. We provide evidence in support of the theoretical predictions of Foucault et al. (2005) and Werner et al. (2015; 2019) that increasing the tick size for stocks with unconstrained spreads in very fine pricing grids improves market quality and increases market resiliency.

Our study contributes to the optimal tick size debate, which has received considerable attention recently with the US Securities and Exchange Commission (SEC) Tick Size Pilot Program. Commissioned in 2016, the program assesses whether widening the trading increment from one cent to five cents for a subset of mainly small-cap stocks enhances the market quality of these stocks (Bartlett and McCrary, 2017; Chung, Lee and Rosch, 2018; Griffith and Roseman, 2018; Rindi and Werner, 2017). Werner et al. (2015) model a dynamic limit order book and predict that tick size increase will improve market quality for illiquid books, but liquid books will be worse off. Early evidence by Rindi and Werner (2017) is consistent with these predictions with a small decline in spreads for stocks with unconstrained spreads in the pre-pilot period and potential benefits for institutional-sized trades. A similar study on the increase in tick size for a subset of stocks listed on Euronext by Bourghelle and Declerck (2004) fails to observe any significant change in market quality using relative, quoted and effective spreads.

By using a finer pricing grid with less constrained spreads than found in conventional markets, we are able provide a more conclusive result. Consistent with existing literature, our findings demonstrate that when tick sizes are close to zero and spreads are unconstrained, a larger tick size improves liquidity provision. This is likely driven by ELPs' increased participation in the markets. Increased liquidity provision enhances market quality by reducing spreads and volatility. However, in contrast to the SEC Tick Size Pilot Program stocks analyzed by Rindi and Werner (2017) where benefits in tick size increases mainly accrue to institutional traders, we find a reduction in spreads across both retail and institutional sized trades. Moreover, as predicted by theory, the currency pair with the highest (smallest) relative tick size increase exhibits the largest (smallest) reduction in spreads. Finally, we show that the increased tick size also improves market quality by reducing the midpoint return volatility.

More broadly, our results provide empirical evidence in support of a non-zero optimal tick size and are consistent with a convex relationship between the relative tick size and quoted spread hypothesized by literature. Kraken's similarity with conventional equity exchanges enhance the generalizability of our result.

Our findings have implications for equity market design and the setting of minimum tick sizes by exchanges. We provide support for a dynamic minimum tick size based on the share price and liquidity of the stock rather than constant tick size for all stocks. While many exchanges already set the minimum tick size according to a step function linked to the share price, US exchanges await the outcome of the Pilot Program to make any decisions regarding minimum increments, the first since decimalization. Our results also highlight the issues faced by traders in the cryptocurrency markets at a critical point in their development, by showing how trader behavior impacts liquidity provision and market quality. Our work also has wider potential implications for other markets with an environment of exceedingly granular tick sizes, such as foreign exchange markets, where order flow is the primary determinant of daily price fluctuations (Baillie & Bollerslev, 1990; Breedon & Ranaldo, 2013; Ranaldo, 2009).

The remainder of this paper is structured as follows. Section 2 provides a literature review on the link between tick size, undercutting, liquidity provision and market quality. Section 3 describes the data collection. The results and discussion are presented in section 4 whilst section 5 concludes.

2. Market quality, tick size and undercutting

Market quality captures the market's ability to provide liquidity and facilitate price discovery (O'Hara et al., 2018). Markets with lower spreads, increased depths, and higher volume are generally seen as being of higher quality. Minimum tick size is a crucial component of market quality as it determines the price traders pay to gain price priority over a standing limit order and dictates the minimum bid-ask spread, a major component of trading costs. Setting an appropriate minimum tick size is thus one of the most important decisions made by an exchange.

Exchanges have progressively decreased their tick sizes due to historic shift to decimalization and more recent competitive pressure from other trading venues. Extant literature provides ample evidence of enhanced market quality from these tick size reductions in North America (Bacidore, 1997; Goldstein and Kavajecz, 2000; Harris, 1991, 1994; Porter and Weaver, 1997), Europe (Bourghelle and Declerck, 2004; Meling and Odegaard, 2017), and Asia (Aitken and Comerton-Forde, 2006; Lau and McInish, 1995). Similar results are observed in the futures markets (Kurov, 2008) and foreign exchange markets (Mahmoodzadeh and Gencay, 2017).

However, theoretical models show that market quality improvements from tick size reductions cannot occur indefinitely. As the minimum tick size approaches zero, trading costs increase as aggressive traders can improve limit orders by an economically insignificant amount. Biais et al. (1995) show that these improvements on one side of the quotes tend to occur in succession and are more prevalent when the depth at the quotes is large. This reflects competition in the supply of liquidity and the associated tradeoff between the execution probability and price. Large depth at the best quotes reduce the likelihood that new limit orders at that price will be executed, encouraging traders to undercut the best quote to increase the probability of execution at only a marginally less favorable execution price, typically just one tick (Bourghelle and Declerck, 2004; Mahmoodzadeh and Gencay, 2017). This strategic undercutting behavior lowers market quality by dis-incentivizing liquidity provision and encourages traders to cross the spread to get executed leading to lower depth, higher volume and volatility and deterioration in spread (Bessembinder et al., 2009; Buti and Rindi, 2009, 2013; Harris, 1996, 1997, Werner et al., 2019).

Figure 1 provides an example of the undercutting behavior observed on Kraken prior to the tick size increase. It depicts several undercutting runs of the bid quotes on August 2nd 2017 between 04:00:00 AM and 04:07:28. The price graph clearly highlights the tiny price improvements and unconstrained nature of the market, providing ample opportunity for aggressive traders to undercut posted limit orders.

< Figure 1 here >

To combat undercutting, Kraken increased the tick sizes across a wide cross section of currency pairs in August and September, 2017. Wider pricing increment forces traders to undercut by a larger amount, increasing the cost of such a trading strategy and reducing its attractiveness. The reduced threat of undercutting from a coarser pricing grid enforces price-time priority and encourages liquidity provision leading to an increase in depth and decrease in volume (Werner et al., 2019). Imposing a minimum price variation also increases market resiliency, defined as the probability that the spread reverts to the competitive level before the next transaction, as traders are forced to improve the quote by a non-infinitesimal amount (Foucault et al., 2005). This accelerates the tightening of the spread between transactions and leads to a reduction in spread. Provided the tick size remains unconstrained post the increase there is no associated mechanical increase in spread and consequently traders are better off overall (Werner et al., 2015).

Werner et al. (2015; 2019) provide a theoretical model that links market quality with liquidity of the underlying limit order book. They show that tick size reductions decrease depth and improve spread for tick constrained stocks but increase volume and increase spread for unconstrained stocks. Consequently, given the unconstrained nature of spreads on Kraken, a tick size increase is expected to increase liquidity provision, increase depth and reduce spreads and volatility.

To empirically test whether increasing the tick size for markets with unconstrained spreads improves market quality, we measure how traders modify their dynamic order placement strategies as the tick size increases. Specifically, we calculate several new measures of undercutting intensity prior and post the tick size increase, including the length of undercutting runs and the speed of price improvement. We define an "undercutting run" as a sequences of limit orders placed within the best quotes at the same side of the order book as illustrated in figure 2. We consider all uninterrupted runs (panel A), as well as runs interrupted by order cancellations, where the price level reverts back to its previous level (Panel B). Undercutting runs are terminated with either two or more consecutive price movements in the opposite direction (Panel C) or one price movement in the opposite direction in excess of the previously quoted price (Panel D). A run cannot start or finish with a cancellation and terminates with a trade.

< Figure 2 here >

3. Data

The dataset of high-frequency order-level data is obtained directly from Kraken's Application Programming Interface (API). The API is polled twice a second to get a snapshot of the top ten levels of the order book. These snapshots are used to construct a standard trade and quote dataset instead of reported quote updates and trades. Kraken increased the tick size on two occasions on August 30th and September 6th, 2017 at 06:00, see Table 1.[2] However, due to the short period between the two successive tick size changes, we eliminate the week in between the separate tick size changes and collapse them into one event. Since Kraken is subject to "know your customer" regulation which can delay trader registration by up to a week, the sample covers a period of one month either side of the tick size increase, from 1st August, 2017 to 5th October, 2017.

We investigate the currency pairs Bitcoin to US Dollar (BTC-USD), Ethereum to Bitcoin (ETH-BTC), Litecoin to US Dollar (LTC-USD), Ethereum-Classic to US Dollar (ETC-USD), Ethereum-Classic to Ethereum (ETC-ETH) and Ethereum-Classic to Bitcoin (ETC-BTC).[3] The

[2] On each of the days where the tick size was increased, 46 currency pairs were affected. The same currency pairs were not necessarily affected by both changes. The analysis is limited to six currencies due to data availability.

[3] Obvious pricing errors were corrected (eg misplacement of decimal points surrounding the tick size changes). Kraken was offline for one hour on August 25 and an hour and a half on August 26 due to maintenance during which time there are no quotes or trades observed.

relative tick size across currency pairs prior to the tick size increase ranged from 0.0015 bps (LTC-USD) to 0.133 bps (ETH-BTC). After the tick size increase, the relative range increased to between 0.2261 bps (BTC-USD) and 2.6517 bps (ETC-BTC), bringing Kraken into line with competing cryptocurrency venues such as Gemini and Gdax. The tick size increase was significant for all currency pairs with LTC-USD and ETC-ETH increasing by a staggering 99,900%.

< Table 1 here >

Trades and quotes are time stamped to the millisecond and recorded in UTC time, with an indicator provided for trade initiator. Trade aggregation is complicated by Kraken's relatively slow matching engine, resulting in trades not being time stamped with the exact same millisecond when executing as a part of one market order. We find that the central messaging engine delays consecutive interactions of market orders with limit orders by up to 20 milliseconds, with such a filter capturing 80% of the observed trade durations. As such, trades which occur within 20 milliseconds of each other in the same direction (buy or sell) are considered as one market order.[4] Trade volumes are then aggregated and assigned the average price and total volume of the trade.

4. Empirical results

Univariate analysis

Undercutting is one of the central issues of unconstrained markets as liquidity providers do not post orders to the same price step, but rather create new price steps by undercutting the price by a single tick. Table 2 shows that undercutting is quite prevalent on Kraken with 256,213 cases of undercutting runs with an average length of 6.78 undercuts and a longest run of 463 undercuts across the six currency pairs in the month leading up to the tick size change. Undercutting in the cryptocurrency markets is likely exacerbated by no provisions for hiding order size and their limited or no fundamental value (Cheah and Fry, 2015), largely constraining price-moving information to that contained in order flow. This hypothesis is

[4] As with trade and quote data from traditional data sources, each observed trade constitutes a limit order executed against part of a (potentially) larger market order. To calculate the total trade size and price, we aggregate these limit orders into one market order. Due to the relatively slow matching engine on Kraken, we aggregate limit orders which occur within 20 milliseconds of each other in the same trade direction as part of the same market order, resulting in a new volume and volume-weighted average price.

supported by Buti et al. (2015) who argue that undercutting traders do not have strong opinions about the fundamental value, but rather trade opportunistically to profit from small deviations in the price from the average valuation.

In the month following the tick size increase the number of undercutting runs decreases by 26,894 (10.5%) to 229,319, the average run increases slightly to 7.09 undercuts (4.4%) and the longest run of undercuts drops to 285 successive quotes. The average dollar value improvement of each undercut (step size) increases by 8 cents (16.7%). This is consistent with theoretical predictions of Foucault et al. (2005) that increasing very fine price increments leads to increased market resiliency and enhanced market quality as it forces traders to improve the price by a larger amount. Best quotes are displayed for 1.07 seconds (12.8%) longer and the duration of each run lengthens by 10.23 seconds (19.3%).

The tick size increase has little impact on the quoted value per undercut but the cancellation of quotes rises slightly from 24.06% to 25.35%. Dahlström et al. (2018) shows that frequent order cancellations are a common feature of modern market making and an increase in the rate of cancellations is thus consistent with increased presence of ELPs on Kraken following the tick size increase. As the pricing grid becomes coarser the proportion of one tick undercuts increases by 8.48 percentage points to 27.4%.

< Table 2 here >

Table 3 provides descriptive statistics of liquidity and trading behavior metrics around the tick size increase. Since spreads are an insufficient statistic for market quality (Jones and Lipson, 2001), we use a battery of existing measures and a set of novel metrics to capture trading behavior, trading costs and liquidity in the small tick trading environment. All measures are averaged across the six currency pairs. We find a 9.2 second (36.9%) increase in the average order exposure time following the tick size increase, corroborating the observed reduction in the undercutting behavior in Table 2. The average number of trades for each currency pair declines by 16.6 (32.0%) in each 15-minute interval, but the size of individual market and limit orders increases by 13.2% and 9.6%, respectively following the tick size increase, suggesting there are fewer, larger trades in the post period. The ratio of limit orders to market orders also increases slightly, consistent with more passive liquidity and an increase in the number of resting limit orders at each price step.

Overall, these trading behavior metrics indicate that the tick size increase reduces undercutting behavior which attracts more liquidity providers who post larger limit orders, consolidate depth at fewer price steps and stabilize the best quotes by letting them stand for longer. Consistent with prior literature, we observe a significant reduction in total traded volume in each trading period.

To explore the effect of the tick size increase on liquidity, we calculate three measures of spread: quoted spread measures the cost of a small round-trip trade, effective spread captures the cost of liquidity when it is demanded and realized spread captures the returns for liquidity provision. Table 3 shows that all measures of spread decline significantly post the tick size increase. Quoted spread is reduced by 20.5 bps (29.9%), effective spread decreases by 20.9 bps (32.3%) and realized spread declines by 21.7 bps (35.2%). Moreover, the effective spread declines for both small ($500) and large ($200,000) trade sizes. Small trades display a 26.4% decrease while large trades decline by 42.9%.

To estimate the effect of the tick size increase on depth, we employ the metric of Van Kervel (2015) which measures the dollar volume depth available at X bps points on either side of the midpoint. This measure shown in Eq. (1) to (3) is unaffected by the tick size increase and less likely to be impacted by undercutting behavior.

$$Depth\ Ask(X)_{it} = \sum_{i=1}^{I} P_{i,t}^{Ask} Q_{i,t}^{Ask} 1\left(P_{i,t}^{Ask} < m_{it}(1+X)\right) \quad (1)$$

$$Depth\ Bid(X)_{it} = \sum_{i=1}^{I} P_{i,t}^{Bid} Q_{i,t}^{Bid} 1\left(P_{i,t}^{Bid} < m_{it}(1+X)\right) \quad (2)$$

$$Depth\ at\ (X)\ bps_{it} = Depth\ Ask(X)_{it} + Depth\ Bid(X)_{it} \quad (3)$$

where $P_{i,t}^{Ask}$ is the ask price for currency pair i at time t, $Q_{i,t}^{Ask}$ is the ask quantity, m_{it} is the midpoint and X is the basis point cut off. The cutoff varies between currency pairs to reflect their varying levels of liquidity.[5] The bps cutoff (X) is determined by calculating the distance between the midpoint and prices at level 1 and level 9 depth. We then take the average between the 90th percentile of level 1 and 10th percentile of level 9 throughout the sample period to ensure that the cutoff captures level 1 most often and rarely exceeds level 9. Table 3 shows that following the tick size increase the average depth improves by 32.4% indicating a much more resilient limit order book. Volatility, measured as the standard deviation of midpoint returns, decreases by 29.7%.

< Table 3 here >

[5] The currency pairs take the following values for X: ETH-BTC = 22 bps, LTC-USD = 39 bps, BTC-USD = 13 bps, ETC-ETH = 102 bps, ETC-USD = 66 bps, and ETC-BTC = 99 bps.

As expected, a wider tick size increases the proportion of time spreads are constrained by 2.9 percentage points to 8.2%, but spreads are still largely unconstrained relative to other markets. Figure 3 plots the average relative tick size versus the average relative quoted spread for the six pairs pre and post the tick size increase along with the S&P500 index constituents for comparison. The graph illustrates that the relative tick sizes for all six currency pairs in the pre-event period are significantly lower than any of the index constituents. The spreads on Kraken are also lower than in the foreign exchange markets (Mahmoodzadeh and Gencay, 2017). Following the tick size increases, the relative tick sizes become more comparable but the spreads remain largely unconstrained. By contrast, spreads of the S&P500 index constituents become mostly constrained once the relative tick sizes exceed approximately 4 bps. The high level of dispersion around the level of spread constraint of stocks provides a possible explanation of the divergent findings in literature regarding market quality improvements from equity market literature.

While the figure depicts considerable dispersion in relative quoted spreads for unconstrained stocks, it highlights the predicted convex shape between relative tick size and relative spread. The inclusion of cryptocurrency pairs provides additional observations beyond the smallest relative tick size observed in the equity market and indicates that relative quoted spreads increase as relative tick size approaches zero.

< Figure 3 here >

Regression analysis

To analyze the effects of the tick size increase on liquidity provision, spread and volatility whilst recognizing the need to control for other factors that might influence these measures, we estimate the following intraday (15-minute interval) multivariate regression equation.

$$Metric_{it} = \alpha_i + \beta_1 Post_{it} + \beta_2 \$Volume_{it} + \beta_3 Trades_{it} + \beta_4 Volatility_{it} + \varepsilon_t. \qquad (4)$$

where the $Post_{it}$ is an indicator variable that takes the value of one following the tick size increase and zero otherwise, $\$Volume_{it}$ measures the dollar volume traded for currency i during interval t. $Trades_{it}$ is the number of trades i. $Volatility_{it}$ is the currency-time high-low price range divided by the sum over two in bps. The dependent $Metric_{it}$ variables are measures of liquidity for each currency and 15-minute interval in event time. $Quoted\ spread$ is time weighted quoted spread in bps. $Effective\ spread$, $Realized\ spread$ and $Price\ impact$ are volume weighted and in bps. $Depth\ at\ X\ bps$ sums the dollar volume depth at X bps on either side of the midpoint where X varies depending on the currency pair (see previous section). $Short - term\ volatility$ is the average 15-minute midpoint return volatility. $Effective\ spread\ \$500$ and $\$200K$ estimate the effective spread in bps of a hypothetical $500 and $200K trade. We include currency pair fixed effects and use standard errors clustered on currency pair and date.

The multivariate regression results reported in Table 4 largely confirm the univariate results presented in the previous section. Quoted spread declines by 19.85 bps, effective spread decreases by 16.33 bps and realized spread improves by 18.05 bps. All coefficients are significant at the 5% level. Spreads improve for both retail and institutional-sized trades. The effective spread for a hypothetical $500 trade decreases by 23.05 bps, significant at the 5% level, while the effective spreads of a hypothetical $200K trade reduces by 26.96%, significant at the 10% level. Depth at X bps increases by $28,640 in each 15-minute interval, significant at the 5% level. Finally, short-term volatility declines by 44.9%, significant at the 10% level.

Overall these results show that, consistent with the univariate results in the preceding section, the tick size increase on Kraken leads to an improvement in market quality. The depth of the limit order book improves, leading to lower spreads and reduced volatility.

< Table 4 here >

For robustness, we also estimate a two stage least squared model, which enables us to use the relative tick size as the shock variable in the model. Traders respond to the relative tick size as it provides more information about the dollar value of the tick size and the relative cost of the tick size to the trade (Aitken & Comerton-forde, 2006; Angel, 1997). However, the tick size has a mechanical effect on liquidity metrics calculated from quotes, as it defines the values of the quotes. Including the relative tick as the independent variable representing the shock will therefore raise endogeneity concerns. To mitigate these issues, we use a two stage least squares model with the percentage change of the tick size as the instrument following Eq. (5). The percentage change of the tick size directly affects the relative tick size but has no direct effect on the trading behavior or liquidity metrics included as dependent variables. The second stage includes the estimated variable $\widehat{Relative\ Tick}_{it}$ as an independent variable which is the variable of interest in Eq. (6).

$$Relative\ Tick_{it} = \alpha_i + \beta_1 PercentChange_{it} + \beta_2 \$Volume_{it} + \beta_3 Trades_{it}$$

$$+\beta_4 Volatility_{it} + \beta_5 MeanPrice_{it} + \varepsilon_t \quad (5)$$

$$Metric_{it} = \alpha_i + \beta_1 \$Volume_{it} + \beta_2 Trades_{it} + \beta_3 Volatility_{it} + \beta_4 MeanPrice_{it}$$

$$+\beta_5 \widehat{RelativeTick}_{it} + \varepsilon_t \quad (6)$$

where $Relative\ Tick_{it}$ is the tick size relative to the price in basis points for currency pair i in 15-minute interval t, α_i is currency pair fixed effects, $PercentChange_{it}$ is the percent change in the tick size which takes the value of zero before the tick size increase and the actual percentage change of the tick size after. $\$Volume_{it}$ is the dollar volume in base currency, $Trades_{it}$ is the number of trades, $Volatility_{it}$ is the currency pair 15-minute high-low price range divided by the sum over two, $MeanPrice_{it}$ is the average price in base currency and ε_t is the error term. Robust standard errors are reported in parentheses and clustered on currency pair and date. We include currency pair fixed effects and use standard errors clustered on currency pair and date.

The first column of Table 5 reports the first stage results which controls for variation in the dollar volume, trading activity, volatility and average price between currency pairs. $PercentChange_{it}$ takes a value of zero prior to the tick size increase, and the percent change in the tick size after. The F-statistic of the regression rejects the null hypothesis of a weak instrument using the critical values by Stock and Yogo (2003).

< Table 5 here >

The remaining columns of Table 5 report the regression results of the impact of tick size increase on trading behavior. Prior to the tick size change it was rare to observe more than two orders at the same price, as traders enjoyed price priority with inconsequential price improvement. Following the tick size increase, we observe price clustering of limit orders as traders disperse their orders across fewer price steps. We find the average limit order increases by just over one unit (column 2) and there are more limit orders being posted at the same price point (column 3). This result indicates an improved average trading price for large volume orders and is consistent with the increased liquidity provision arguments of Harris (1997).

Table 6 shows the impact of Kraken's tick size increase on trading costs over the one-month pre and post event window. While tick size has a mechanical effect on spreads, its direct effect is less certain when spreads are unconstrained. Evidence from stock splits shows that tick sizes increases lead to wider spreads. However, Foucault et al. (2005) and Werner et al. (2015) predict that increasing the tick size of unconstrained stocks will lead to increased liquidity provision and lower spreads. While Rindi and Werner (2017) find that this holds for quoted spreads, effective spreads barely changed when the tick size increased from one cent to five cents in the US pilot study. Similarly, Bourgelle and Declerck (2004) find little effect on spreads from tick sizes increases on the Paris Bourse. In the case of Kraken, none of the currency pairs are tick constrained prior to the tick size increase and the relative tick size is also extremely small.

Consequently, we find the increase in small tick sizes on Kraken provides strong empirical evidence in support of the theoretical models. We observe that quoted, effective and realized spread decrease by 12.98, 10.04 and 11.22 bps, respectively. Furthermore, spreads improve for both retail and institutional-sized trades with the effective spread of a hypothetical $500 and $200K trade decreasing by 16.05 bps and 24.71%, respectively. All coefficients are significant at the 5% percent level or higher. These results confirm that while institutions trading large blocks have a larger optimal tick size than small retail investors (Seppi, 1997), both prefer a tick size strictly greater than zero.

As the incentive to post limit orders is affected by a tick size change, the quoted depth at X is also likely to be affected. Tick size increases have resulted in more depth at the best prices (Conroy et al., 1990; Gray et al., 2003; Schultz, 2000) so a tick size increase on Kraken is expected to have the same effect and consolidate depth at the best prices, reducing execution costs for large trades. Combined with the findings of Goldstein and Kavajecz (2000) that a tick size decrease leads to a reduction in cumulative depth we expect that a tick size increase will increase depth of the limit order book. We find that depth at X increases by 16.71 bps, significant at the one percent level. This finding is consistent with Rindi and Werner (2017).

Finally, tick size changes affect the precision of prices, impacting short-term volatility, but the direction of the effect is unclear. Both Angel et al. (2004) and Koski (1998) find a significant increase in volatility following widening of relative tick sizes from stock-splits as a result of increased participation of small-volume traders in the market. By contrast, we observe a 24.8% decrease in midpoint return volatility, significant at the 5% level. We attribute the greater price stability to the additional depth in the order book coupled with larger order volume and reduction in excessive trading activity from undercutting. Overall, our results suggest that the increase in tick sizes on Kraken improve both market quality and pricing efficiency by encouraging traders to enter more, larger liquidity providing orders.

< Table 6 here >

To assess whether currency pairs which undergo the largest tick size increase deliver the largest reductions in spreads as predicted by theory, Table 7 compares two currency pairs with the smallest and the largest relative tick size increase (BTC-USD vs ETC-BTC). We find that while all measures of spread decrease for both subsamples, the larger tick size change leads to a more pronounced effect with a 11.58 bps reduction in effective spread vs 4.35 bps for the smallest tick size change, consistent with a convex shape relationship between tick size and spread proposed by literature. Both coefficients are significant at the 1% level. As the quoted spreads post the tick size increase are still largely unconstrained, it is likely the spread measures on Kraken could be further reduced by widening the tick size until quoted spreads become more constrained.

< Table 7 here >

5. Conclusion

We investigate the importance of tick sizes in a setting unique to the cryptocurrency market with significantly unconstrained spreads and extremely small tick sizes. We examine how a tick size increase in this market structure affects undercutting behavior and market quality.

Using novel trading behavior metrics, we find a significant improvement in liquidity provision, with more, larger limit orders submitted at each price point. Our results demonstrate that excessively small tick sizes are detrimental to market quality by facilitating undercutting, essentially rendering time priority redundant while larger tick sizes improve depth and reduce volatility.

Since the market structure of Kraken shares many features with conventional markets, we believe our findings have implications for wider market design, especially equity markets, which have witnessed considerable reduction in tick sizes over the last two decades. Our findings also have implications for cryptocurrency and foreign exchange markets, which operate with extremely small tick sizes. As such we add to the debate surrounding optimal tick sizes, particularly focusing on how the change in tick sizes impacts trader behavior.

References

Aitken, M., & Comerton-forde, C. (2005). Do reductions in tick sizes influence liquidity? *Accounting and Finance*, *45*(2), 171–184.

Aït-Sahalia, Y. and Sağlam, M., 2017a. *High Frequency Market Making: Optimal Quoting*. *Working Paper*

Aït-Sahalia, Y. and Sağlam, M., 2017b. *High Frequency Market Making: Implications for Liquidity, Working paper*.

Anand, A. and Venkataraman, K. 2016. Market conditions, fragility, and the economics of market making. *Journal of Financial Economics* 121(2). 327-349

Angel, J. J. (1997). Tick Size , Share Prices , and Stock Splits. *Journal of Finance, LII*(2), 655–681.

Angel, J. J., Brooks, R. M., & Mathew, P. G. (2004). When-issued shares, small trades, and the variance of returns around stock splits. *Journal of Financial Research*, *27*(3), 415–433.

Bacidore, J. M. (1997). The Impact of Decimalization on Market Quality : An Empirical Investigation of the Toronto Stock Exchange. *Journal of Financial Intermediation*, *6*, 92–120.

Baillie, R. T., & Bollerslev, T. (1990). Intra Day and Inter Market Volatility in Foreign Exchange Rates. *Review of Economic Studies*, *58*(3), 565–585.

Bartlett, R. P., and McCrary, J. (2017). Subsidizing Liquidity with Wider Ticks: Ecidence from the Tick Size Pilot Study. *Working Paper*

Biais, B., Hillion, P. & Spatt, C. (1995). An Empirical Analysis of the Limit Order Book

and the Order Flow in the Paris Bourse. Journal of Finance 50(5), 1655-1689.

Bourghelle, D., & Declerck, F. (2004). Why markets should not necessarily reduce the tick size. *Journal of Banking and Finance*, *28*(2), 373–398.

Breedon, F., & Ranaldo, A. (2013). Intraday patterns in FX returns and order flow. *Journal of Money, Credit and Banking*, *45*(5), 953–965.

Buti, S., Consonni, F., Rindi, B., Wen, Y., & Werner, I. M. (2015). *Sub-Penny and Queue-Jumping*.

Cheah, E. T., & Fry, J. (2015). Speculative bubbles in Bitcoin markets? An empirical investigation into the fundamental value of Bitcoin. *Economics Letters*, *130*, 32–36.

Chung, K. H., Lee, A. J., and Rosch, D. (2018). Tick Size, Liquidity for Small and LArge Orders, and Price Informativeness: Evidence from the Tick Size Pilot Program, *Working Paper*.

Conroy, R. M., Harris, R. S., & Benet, B. A. (1990). The effects of stock splits on stock liquidity. *Journal of Finance*, *45*(4), 1285–1295.

Cordella, T., & Foucault, T. (1999). Minimum Price Variations, Time Priority, and Quote Dynamics. *Journal of Financial Intermediation*, *8*(3), 141–173.

Dahlström, P, Hagströmer, B., Nordén, L. L., 2018. *Determinants of Limit Order Cancellations. Working Paper, Stockholm Business School*

Foucault, T., Kadan, O., & Kandel, E. (2005). Limit order book as a market for liquidity.

Review of Financial Studies, *18*(4), 1171–1217.

Goettler, R. L., Parlour, C. A., & Rajan, U. (2005). Equilibrium in a Dynamic Limit Order Book Market. *Journal of Finance*, *60*(5), 2149–2193.

Goldstein, M. A., & A. Kavajecz, K. (2000). Eighths, sixteenths, and market depth: Changes in tick size and liquidity provision on the NYSE. *Journal of Financial Economics*, *56*(1), 125–149.

Gray, S. F., Tom, S., & Whaley, R. E. (2003). Stock splits: implications for investor trading costs. *Journal of Empirical Finance*, *10*, 271–303.

Griffith, T. and Roseman B. (2018). Making Cents of Tick Sizes: An Investigation of the 2016 U.S. SEC Tick Size Pilot on Limit Order Book Liquidity. *Working Paper*.

Harris, L. (1991). Stock Price Clustering and Discreteness. *Review of Financial Studies*, *4*(3), 389–415.

Harris, L. (1994). Minimum Price Variations, Discrete Bid-Ask Spreads, and Quotation Sizes. *Review of Financial Studies*, *7*(1), 150–178.

Harris, L. (1996). *Does a Large Minimum Price Variation Encourage Order Exposure ?*

Harris, L. (1997). *Order Exposure and Parasitic Traders Order Exposure and Parasitic Traders Abstract*.

Hasbrouck, J. & Saar, G. (2013). Low-latency trading, *Journal of Financial Markets*, 16, 646–679

Jones, C. M., & Lipson, M. L. (2001). Sixteenths: Direct evidence on institutional execution costs. *Journal of Financial Economics*, *59*(2), 253–278.

Koski, J. L. (1998). Measurement effects and the variance of returns after stock splits and stock dividends. *Review of Financial Studies*, 11(1), 143–162.

Kurov, A. (2008). Tick Size Reduction, Execution Costs, and Infomrational Efficiency in the Regular and E-mini Nasdaq-100 Index Futures Markets. *The Journal of Futures Markets* 28(9), 871–888.

Lau, S. T., & McInish, T. H. (1995). Reducing tick size on the Stock Exchange of Singapore. *Pacific-Basin Finance Journal*, *3*(4), 485–496.

Mahmooddzadeh, S. and Gencay, R. (2017). Human vs. High-frequency Traders, Penny Jumping, and Tick Size, Journal of Banking nad Fiannce 85, 69-82.

Meling, T. G., & Odegaard, B. A. (2017). Tick Size Wars, High Frequency Trading, and Market Quality. *SSRN Electronic Journal*, (June).

O'Hara, M., Ye, M. (2011). Is Market Fragmentation Harming Market Quality? *Journal of Financial Economics* 100(3), 459-474.

O'Hara, M., Saar, G., & Zhong, Z. (2018). Relative Tick Size and the Trading Environment. *Review of Asset Pricing Studies, Forthcoming*

Porter, D. C., & Weaver, D. G. (1997). Tick Size and Market Quality. *Financial Management*, *26*(4), 5–26.

Ranaldo, A. (2009). Segmentation and time-of-day patterns in foreign exchange markets. *Journal of Banking and Finance*, *33*(12), 2199–2206.

Rindi B. and Werner, I. M. (2017). U.S. Tick Size Pilot. *Working Paper*.

Schultz, P. (2000). Stock splits, tick size, and sponsorship. *Journal of Finance*, *55*(1), 429–450.

Seppi, D. J. (1997). Liquidity provision with limit orders and strategic specialist. *The Review of Financial Studies*, *10*(1), 103–150.

Stock, J. H., & Yogo, M. (2003). Testing for weak instruments in linear IV regression, (February).

Van Kervel, V. (2015). Competition for Order Flow with Fast and Slow Traders. *Review of Financial Studies*, *28*(7), 2094–2127.

Van Ness, B. F., Van Ness, R. A., & Pruitt, S. W. (2000). The Impact of the Reduction in Tick Increments in Major U.S. Markets on Spreads, Depth, and Volatility. *Review of Quantitative Finance and Accounting*, *15*(2), 153–167.

Werner, I. M., Wen, Y., Rindi, B., Consonni, F., & Buti, S. (2015). *Tick Size : Theory and Evidence*. *Fisher College of Business Working Paper Series*.

Werner, I. M., Wen, Y., Rindi, B., Consonni, F., & Buti, S. (2019). *Tick Size, Trading Strategies and Market Quality, Fisher College of Business Working Paper Series*.

Figure 1
Undercutting example

The bid and ask quote and trade price for BTC-USD on August 2nd 2017 from 04:00:00 AM to 04:07:28 AM. Triangles represent transaction prices, the dashed line represents the ask quote, and full line indicates the bid quote.

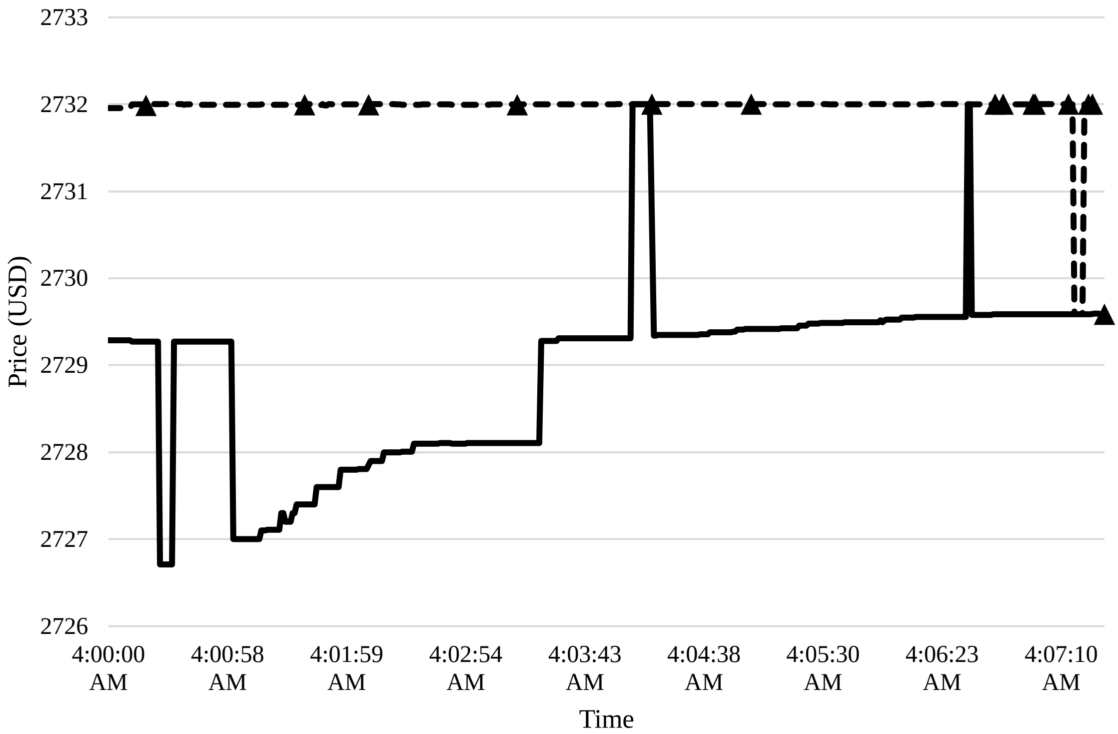

Figure 2
Definition of undercutting runs

The figures illustrate simplified price movements of a bid order. Undercutting run begins with a successive increase in price (Panel A). The run continues if an order is cancelled and the price level drops to the previous level and then rises again (Panel B). The run is terminated by two consecutive decreases in the price (Panel C) or a decrease greater than the previously quoted price (Panel D). A run cannot start or finish with a cancellation and is terminated by a trade.

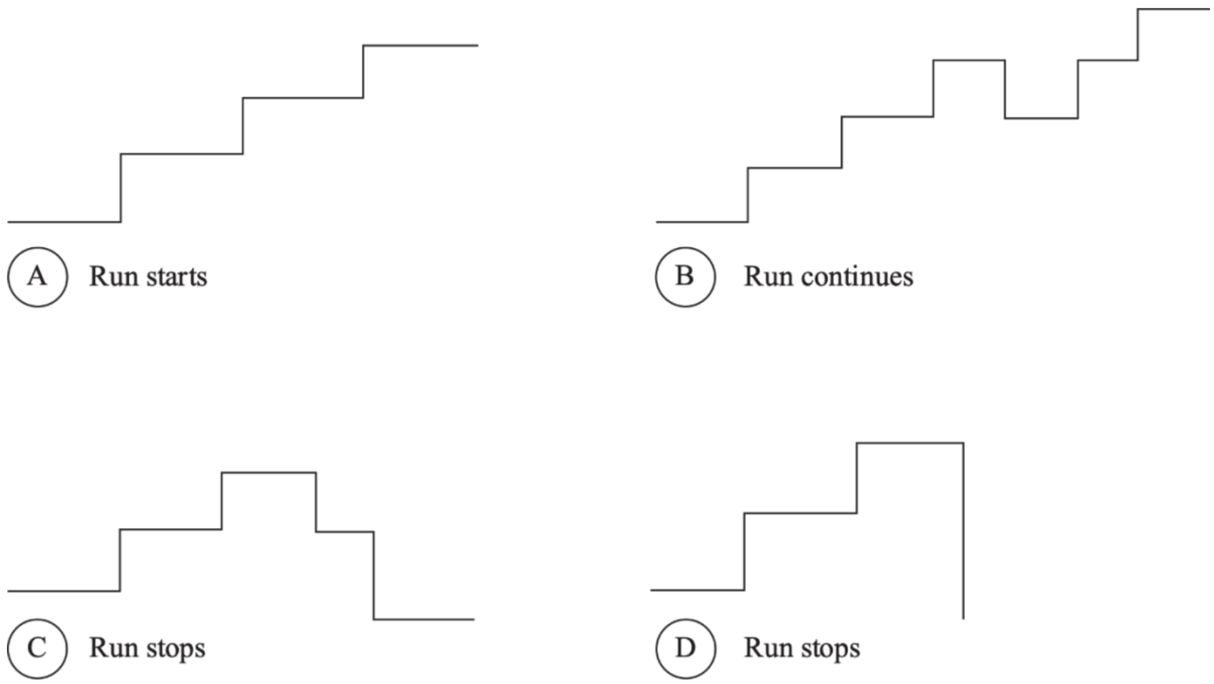

Figure 3

Comparison of relative tick sizes and relative quoted spreads across Kraken and S&P500 stocks

Relative quoted spread and the relative tick size in basis points (log scale) for the constituents of the S&P 500 index on August 30th 2017 and the currency pairs on Kraken pre and post the tick size increases.

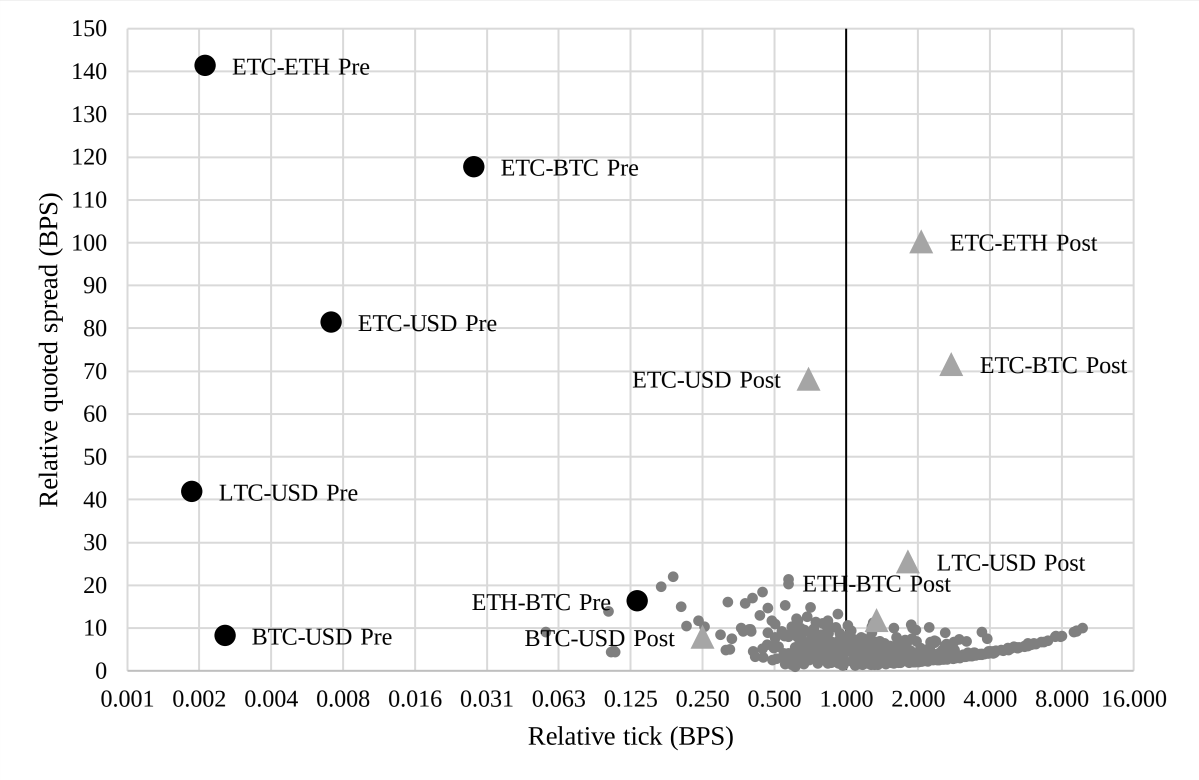

Table 1
Currency pairs and tick sizes at Kraken

The tick sizes are presented in decimal places and in bps relative to the average daily price in the sample period 1st August to 5th October 2017. The tick size increases were implemented at 06:00 UTC time on 30 August and 6 September 2017.

	Pre 30 August		Post 30 August		Post 6 September	
Currency pair	Tick	Tick (bps)	Tick	Tick (bps)	Tick	Tick (bps)
BTC-USD	1E-03	0.0025	1E-02	0.0250	1E-01	0.2497
ETH-BTC	1E-06	0.1337	1E-06	0.1337	1E-05	1.3367
LTC-USD	1E-05	0.0018	1E-04	0.0182	1E-02	1.8187
ETC-ETH	1E-08	0.0021	1E-06	0.2065	1E-05	2.0655
ETC-USD	1E-05	0.0070	1E-04	0.0695	1E-03	0.6954
ETC-BTC	1E-08	0.0276	1E-06	2.7560	1E-06	2.7560

Table 2
Undercutting runs pre and post tick size increase

The average pre and post undercutting metrics across currency pairs. $Number\ of\ runs$ is the number of runs with at least two undercuts, $Number\ of\ undercuts$ and $Maximum\ undercuts$ is the mean and maximum number of undercuts per run, respectively, $Step\ size$ is the mean dollar value improvement of each undercut in the run in USD, $Quote\ value$ is the mean dollar volume of each undercut in the run, $Seconds\ between\ undercuts$ indicates the mean number of seconds between undercuts in a run, $Run\ duration$ is the duration of the run in seconds, $Proportion\ of\ cancellations$ is the mean proportion of cancellations in a run, $One\ tick\ undercuts$ is the proportion of undercuts of one tick size per run. The significance for the number of runs is based on the total number of runs by date and 15-minute bucket pre and post. The last column reports the difference in means pre and post tick size increase and the significance based on a two-tailed t-test. ***, ** and * indicate the statistical significance at 1%, 5% and 10% levels, respectively.

	Pre	Post	Difference
$Number\ of\ runs$	256,213	229,319	-26,894***
$Number\ of\ undercuts$	6.78	7.09	0.30***
$Maximum\ undercuts$	463	285	-178
$Step\ size$ ($)	0.48	0.56	0.08***
$Quote\ value$ ($)	3,300	3,310	0.10**
$Seconds\ between\ undercuts$	8.35	9.42	1.07***
$Run\ duration\ (seconds)$	53.01	63.24	10.23***
$Proportion\ of\ cancellations$ (%)	24.06	25.35	1.29***
$One\ tick\ undercuts$ (%)	18.93	27.40	8.48***

Table 3
Market quality metrics pre and post tick size increase

Mean liquidity and trading behavior measures for each currency pair in 15-minute intervals in the month pre and post the tick size increase averaged across currency pairs. *Order exposure* is the number of seconds the best bid or ask order is exposed. The *number of trades* is the 15-minute interval total. *average market order* and *limit order volume* shows the volume in in currency units. *Limit order / market order* shows the proportion of limit orders to market orders. The *average price steps* is the number of price steps a market order goes through on average. The *number of resting limit orders* shows how many limit orders are resting at the same price step on average. *Dollar volume* is the daily total displayed in 10,000 USD. *Quoted spread* is time weighted and in basis points. *Effective and realized spread* are volume weighted and in basis points. *Effective spread* \$500 and \$200*K* estimates the effective spread in bps of a hypothetical trade of a dollar volume. *Depth at X bps* sums the depth at X bps on either side of the midpoint where X varies by currency pair. *Short − term volatility* is the average 15-minute midpoint return volatility *Constrained* is the percent of the day where the spread is equal to one tick. ***, ** and * indicate the statistical significance at 1%, 5% and 10% levels respectively using a t-tailed test.

Variable	Pre	Post	Difference
Order exposure (seconds)	24.9	34.1	9.2***
Number of trades	51.8	35.1	-16.6***
Average market order volume	18.9	21.4	2.5**
Average limit order volume	10.4	11.4	1.0**
Limit order / market order	1.6	1.7	0.1***
Average price steps	1.4	1.4	-0.0*
Number of resting limit orders	1.2	1.3	0.1***
Dollar volume (\$10,000)	7.5	5.8	-1.7***
Quoted spread (bps)	67.9	47.6	-20.3***
Effective spread (bps)	65.9	44.6	-21.3***
Realized spread (bps)	61.9	40.0	-21.8***
Effective spread \$500 *(bps)*	92.1	67.9	-24.3***
Effective spread \$200*K (bps)*	5,938.5	3,391.7	-2,546.8***
Price impact (bps)	4.0	4.6	0.5*
Depth at X bps (\$1,000)	107.6	142.5	34.9***
Short − term volatility	3.7	2.6	-1.2***

Table 4
Multivariate regression

The intraday estimates of the multivariate regression: $Metric_{it} = \alpha_i + \beta_1 Post_{it} + \beta_2 \$Volume_{it} + \beta_3 Trades_{it} + \beta_4 Volatility_{it} + \varepsilon_t$. The model has currency pair fixed effects. The control variables are $Post_{it}$ which is a dummy variable which takes the value of one after the tick size increase and zero otherwise, $\$Volume_{it}$ which measures the dollar volume in 10,000 USD traded for currency i in 15-minute interval t. $Trades_{it}$ is the number of trades. $Volatility_{it}$ is the currency-time high-low price range divided by the sum over two in basis points. The dependent variables $Metric_{it}$, are measures of liquidity for each currency and 15-minute interval in event time. $Quoted\ spread$ is time weighted and in basis points. $Effective\ and\ realized\ spread\ and\ price\ impact$ are volume weighted and in basis points. $Constrained$ is the percent of the day where the spread is equal to one tick. $Depth\ at\ X\ bps$ sums the dollar volume depth at X bps on either side of the midpoint where X takes different values (see section 5.3) and is calculated in 1,000 USD. $Short-term\ volatility$ is the average 15-minute midpoint return volatility. $Effective\ spread$ \$500 and \$200K estimates the effective spread in bps of a hypothetical trade of a dollar volume. Standard errors are clustered on currency pair and date and reported in parentheses. ***, ** and * indicate the statistical significance at 1%, 5% and 10% levels respectively.

Variable	*Quoted* $spread_{it}$	*Effective* $spread_{it}$	*Realized* $spread_{it}$	*Price* $impact_{it}$	*Effective spread \$500*	*Effective spread \$200K*	*Depth at X* bps_{it}	*Short-term* $volatility_{it}$
$Post_{it}$	-19.85**	-16.33**	-18.05**	1.724	-23.05**	-2,696*	28.64**	-0.449*
	(6.319)	(5.703)	(5.951)	(0.900)	(7.546)	(1,149)	(7.693)	(0.184)
$\$Volume_{it}$	0.136	0.158	0.174	-0.0159	0.0527	20.45	1.609***	-0.0233
	(0.180)	(0.200)	(0.210)	(0.0182)	(0.184)	(25.87)	(0.308)	(0.0161)
$Trades_{it}$	-0.281	-0.320*	-0.342*	0.0222*	-0.315	-19.88	-0.285**	0.0119
	(0.147)	(0.149)	(0.155)	(0.00877)	(0.162)	(14.50)	(0.104)	(0.00809)
$Volatility_{it}$	0.222***	0.376***	0.348***	0.0279**	0.291***	6.702	-0.185**	0.0249***
	(0.0396)	(0.0400)	(0.0489)	(0.0103)	(0.0560)	(7.759)	(0.0709)	(0.00104)
Constant	62.75***	48.71***	48.24***	0.471	83.65***	6,252***	126.2***	1.219***
	(6.541)	(6.391)	(6.635)	(0.690)	(7.473)	(1,076)	(6.326)	(0.292)
Observations	33,120	30,013	30,013	30,013	33,120	33,120	32,622	33,120
Adjusted R^2	0.546	0.510	0.427	0.020	0.565	0.076	0.014	0.511
Currency pair fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 5
Impact of relative tick size on trading behavior

This table reports the estimates of the two stage least squares regression: $Metric_{it} = \alpha_i + \beta_1 \$Volume_{it} + \beta_2 Trades_{it} + \beta_3 Volatility_{it} + \beta_4 \widehat{RelativeTick}_{it} + \varepsilon_t$ where relative tick is the estimate of the first stage regression $Relative\ Tick_{it} = \alpha_i + \beta_1 \$Volume_{it} + \beta_2 Trades_{it} + \beta_3 Volatility_{it} + \varepsilon_t$. $Relative\ Tick_{it}$ is the tick size in cents scaled by the price, multiplied by 10,000 and averaged within the 15-minute bucket. The control variables are $PercentChange_{it}$ which takes the value of zero before the tick size change and the value of the percent change in tick size after. $\$Volume_{it}$ measures the dollar volume in 10,000 USD traded for currency i in 15-minute interval t. $Trades_{it}$ is the number of trades. $Volatility_{it}$ is the currency-time high-low price range divided by the sum over two in basis points. In the second stage the dependent variables capture different measures of trading behavior for each currency and 15-minute interval in event time. There are fewer observations as not all 15-minute buckets had changes in the best prices. The $average\ market\ order\ volume$ and $limit\ order\ volume$ is the volume in units. The $average\ price\ steps$ is how many price steps a market order goes through on average. The $number\ of\ resting\ limit\ orders$ shows how many limit orders are resting at the same price step on average. Robust standard errors are reported in parentheses and clustered on currency pair and date. ***, ** and * indicate the statistical significance at 1%, 5% and 10% levels respectively. The trading behavior measures have fewer observations as not all 15-minute intervals observe trades. Resting limit orders per price steps exclude trades that only interact with one depth level and excludes the last limit orders on the last price step the market order interacted with to ensure that all price steps are filled.

Variable	$RelativeTick_{it}$	Limit order $volume_{it}$	Resting limit $orders_{it}$	Market order $volume_{it}$	Price $steps_{it}$
$PercentChange_{it}$	2.18e-05***				
	(2.46e-06)				
$\widehat{RelativeTick}_{it}$		1.025*	0.0435***	1.694	-0.0165
		(0.423)	(0.00760)	(1.047)	(0.00847)
$\$Volume_{it}$	0. 00239	0.144	0.00250**	0.359	0.00432*
	(0. 00223)	(0.137)	(0.000716)	(0.356)	(0.00172)
$Trades_{it}$	-0. 00197	-0.0317	0.000449**	-0.114	-0.00233**
	(0. 00124)	(0.0270)	(0.000158)	(0.0841)	(0.000849)
$Volatility_{it}$	-0. 00118	0.0116*	0.000133	0.0576**	0.000753***
	(0. 00093)	(0.00548)	(7.96e-05)	(0.0154)	(0.000108)
Observations	33,120	30,447	25,065	30,447	30,447
Adjusted R^2		0.004	0.022	0.009	0.044
Currency pair fixed effects	Yes	Yes	Yes	Yes	Yes
Gragg-Donald Wald F-statistic	29007				

Table 6

Impact of relative tick size increase on liquidity

This table reports the estimates of the two stage least squares regression: $Metric_{it} = \alpha_i + \beta_1 \$Volume_{it} + \beta_2 Trades_{it} + \beta_3 Volatility_{it} + \beta_4 \widehat{RelativeTick}_{it} + \varepsilon_t$ where relative tick is the estimate of the first stage regression $Relative\ Tick_{it} = \alpha_i + \beta_1 \$Volume_{it} + \beta_2 Trades_{it} + \beta_3 Volatility_{it} + \varepsilon_t$. The model has currency pair fixed effects. The control variables are $\$Volume_{it}$ which measures the dollar volume in 10,000 USD traded for currency i in 15-minute interval t. $Trades_{it}$ is the number of trades. $Volatility_{it}$ is the currency-time high-low price range divided by the sum over two in basis points. The dependent variables $Metric_{it}$, are measures of liquidity for each currency and 15-minute interval in event time. $Quoted\ spread$ is time weighted and in basis points. $Effective\ and\ realized\ spread\ and\ price\ impact$ are volume weighted and in basis points. $Constrained$ is the percent of the day where the spread is equal to one tick. $Depth\ at\ best$ is the dollar volume depth at the best prices in 1,000 USD. $Depth\ at\ X\ bps$ sums the dollar volume depth at X bps on either side of the midpoint where X takes different values (see section 5.3) and is calculated in 1,000 USD. $Short-term\ volatility$ is the average 15-minute midpoint return volatility. $Effective\ spread$ \$500 and $\$200K$ estimates the effective spread in bps of a hypothetical trade of a dollar volume. Robust standard errors are reported in parentheses and clustered on currency pair and date. ***, ** and * indicate the statistical significance at 1%, 5% and 10% levels respectively. The number of observations for effective and realized spread is lower as not all 15-minute intervals have trades and any trades with negative effective spreads due to sequencing error is excluded. Depth X has fewer observations as the exchange was offline for a few hours on August 25 and August 26.

Variable	*Quoted spread$_{it}$*	*Effective spread$_{it}$*	*Realized spread$_{it}$*	*Price impact$_{it}$*	*Effective spread \$500*	*Effective spread \$200K*	*Depth at X bps$_{it}$*	*Short-term volatility$_{it}$*
$\widehat{RelativeTick}_{it}$	-12.98***	-10.04***	-11.22**	1.186	-16.05***	-2,471**	16.71***	-0.248**
	(1.591)	(2.016)	(2.794)	(0.830)	(3.227)	(676.6)	(1.707)	(0.0666)
\$Volume$_{it}$	0.128	0.145	0.160	-0.0151	0.0484	23.17	1.631***	-0.0238
	(0.177)	(0.202)	(0.215)	(0.0194)	(0.174)	(22.77)	(0.287)	(0.0161)
Trades$_{it}$	-0.256	-0.297	-0.317*	0.0201*	-0.288	-18.40	-0.327**	0.0126
	(0.145)	(0.148)	(0.155)	(0.00936)	(0.161)	(14.07)	(0.103)	(0.00804)
Volatility$_{it}$	0.209***	0.367***	0.338***	0.0289**	0.274***	3.735	-0.169*	0.0247***
	(0.0392)	(0.0381)	(0.0460)	(0.00964)	(0.0526)	(6.986)	(0.0683)	(0.000902)
Observations	33,120	30,013	30,013	30,013	33,120	33,120	32,622	33,120
Adjusted R^2	0.213	0.332	0.259	0.011	0.207	0.005	0.006	0.481
Currency pair fixed effects	Yes	Yes	Yes		Yes	Yes	Yes	Yes

Table 7
Large versus small relative tick regression

This table shows the coefficient and t-statistic on the post dummy or $\widehat{RelativeTick}_{it}$ variable. Model (1) presents the results from the second stage regression shown in Table 8. Model (2) estimates the effect for the currency pair which after the change has a larger relative tick size, specifically ETC-BTC. Model (3) considers the currency pair which after the tick size change have a smaller relative tick size, specifically BTC-USD. Model (1) has currency pair fixed effects and clustered standard errors. Model (2) and (3) have robust standard errors clustered on datetime. The dependent variables are measures of market quality for each currency and 15-minute interval in event time. $Quoted\ spread$ is time weighted and in basis points. $Effective\ and\ realized\ spread\ and\ price\ impact$ are volume weighted and in basis points. $Constrained$ is the percent of the day where the spread is equal to one tick. $Depth\ at\ best$ is the dollar volume depth at the best prices in 1,000 USD. $Depth\ at\ X\ bps$ sums the dollar volume depth at X bps on either side of the midpoint where X takes different values (see section 1.3) and is calculated in 1,000 USD. $Short-term\ volatility$ is the average 15-minute midpoint return volatility. $Effective\ spread$ \$500 and \$200K estimates the effective spread in bps of a hypothetical trade of a dollar volume. Robust standard errors are reported in parentheses. ***, ** and * indicate the statistical significance at 1%, 5% and 10% levels respectively.

	2SLS	Large relative tick	Small relative tick
$Quoted\ spread\ (bps)$	-12.98***	-12.32***	-4.746***
	(1.591)	(0.547)	(0.503)
$Effective\ spread\ (bps)$	-10.04***	-11.58***	-4.351***
	(2.016)	(0.759)	(1.326)
Realized spread (bps)	-11.22**	-11.21***	-9.328***
	(2.794)	(0.808)	(1.612)
$Depth\ at\ X\ bps\ (1{,}000\ USD)$	16.71***	8.711*	58.37***
	(1.707)	(5.044)	(20.49)
$Short-term\ volatility$	-0.248**	-0.0714*	-0.938***
	(0.0666)	(0.0382)	(0.120)
$Effective\ spread$ \$500 (bps)	-16.05***	-12.84***	-6.412***
	(3.227)	(0.609)	(0.586)
$Effective\ spread\ \$200K\ (bps)$	-2,471**	-644.2***	4,802
	(676.6)	(44.08)	(4,868)