Tick Size Change in the Wholesale Foreign Exchange Market

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October 1, 2014

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Abstract

This paper studies the changes in the spread, market depth and market efficiency that are due to the lower minimum tick size (which was changed from a pip to a decimal pip) in the Electronic Broking Services (EBS) interbank foreign exchange (FX) market. Coupled with the lower tick size, the composition of the traders and their order placement strategies have given an opportunity to high frequency traders (HFTs) to implement the sub-penny jumping strategy to front-run manual traders. Our analysis shows that the lower tick size enabled HFTs to be more aggressive in the sub-penny jumping strategy. We show by difference-in-difference (DID) regression that the spread as a liquidity cost was reduced after the tick size change. Furthermore, the benefit of the reduction in the spread was mostly absorbed by the HFTs, whereas the manual traders faced wider spreads. More strikingly, the market depth was reduced significantly after the introduction of decimal pip pricing. There was no distinctive change in the arbitrage opportunities as a sign of market efficiency.

JEL classification: F31; G14; G15.

Keywords: Foreign Exchange Market; Tick Size; Market Microstructure

*Corresponding author: Soheil Mahmoodzadeh (smahmood@sfu.ca). We are thankful to Alain Chaboud, Alec Schmidt and the participants in the seminars at Simon Fraser University. Ramazan Gençay (rgencay@sfu.ca) gratefully acknowledges financial support from the Natural Sciences and Engineering Research Council of Canada and the Social Sciences and Humanities Research Council of Canada. The remaining errors are ours.
1. Introduction

We study changes in market quality that are due to the lower minimum tick size in the EBS market and the role of high-frequency traders (HFTs). EBS is the leading interbank FX market, and it is used mainly to trade the major currency pairs EUR/USD, USD/JPY, EUR/JPY, USD/CHF, and EUR/CHF in units of millions. In March 2011, EBS decided to reduce the tick size from a pip to a decimal pip on major currency pairs. The tick size is the minimum price movement which plays an important role in financial markets. As an example, if the tick size is a pip equal to 0.0001 and the EUR/USD best bid is 1.39940, then a buyer could improve this price by placing an order with the price of 1.39950. However, if the tick size is a decimal pip 0.00001, the buyer could also place an order with the price of 1.39941. The decision to shift to decimal pip pricing was mainly driven by the competitive environment to match some smaller trading platforms to attract more HFTs.

To find the minimum tick size changes from 2009 to 2013 in the EBS market, we have analyzed approximately 800 gigabytes of millisecond limit order book (LOB) data. Figure 1 illustrates the tick size changes in this time span. For instance, the tick size was a pip (4 decimal points) for the EUR/USD until March 2011. Then, it was reduced to a decimal pip (5 decimal points), and finally, it changed to a half-pip (4.5) in September 2012. Half-pip pricing is a special case of decimal pip pricing in which the fifth digit could be only “0” or “5”. Figure 1 indicates a general pattern from pip to decimal pip and then reverting back to a half-pip over a two-year period.

The original change to decimal pip pricing on EBS began in September 2010 with the less active currency pairs, presumably to test the reactions of the market participants. In October 2010, EBS reduced the tick size of the next group of most commonly traded currency pairs: EUR/GBP, GBP/USD, and USD/CAD. Finally, EBS reduced the tick size of the five major currency pairs to decimal pip pricing in March 2011. This move caused controversial debates by the two main types of traders. Although decimal pip was welcomed by HFTs, manual traders believed that HFTs already had an unfair advantage, which was enhanced by the smaller tick size. When EBS shifted to decimal pip pricing to attract more HFTs, it took the view that it risked losing more business by continuing it. As a consequence, we observed the reversal to half-pip pricing for most currency pairs in September 2012.

1 On June 2014, the Securities and Exchange Commission (SEC) ordered a plan to implement a targeted one year pilot program that will widen the tick size for certain small capitalization stocks. The SEC plans to assess whether tick size changes would improve market quality.

2 The pip (decimal pip) tick size is 2 (3) decimal points when the local currency is JPY.
Figure 1: EBS Minimum Tick Size Changes, 2009-2013

Notes: This graph illustrates the tick size changes in the EBS market from 2009 to 2013 for different currency pairs. The vertical axis shows the decimal points used in the exchange rates. As an example, the EUR/USD tick size was 0.0001 (one pip) until March 2011. Thus, if the best bid was 1.39940, then a trader could improve it by adding the tick size and placing an order with the price of 1.39950. However, the trader was not allowed to place an order with a price of 1.39941 because the added value of 0.00001 (a decimal pip) was less than the minimum tick size of 0.0001. The pip (decimal pip) tick size is 2 (3) decimal points when the local currency is JPY, as the exchange rates are based on 100 Japanese Yen. The 2.5 and 4.5 decimal points refer to half-pip pricing, which is a special case of decimal pip pricing in which the last digit could only be “0” or “5”. For example, the tick size of 4.5 for the EUR/USD exchange rate means that the tick size is one decimal pip (5 decimal points), and hence, the fifth digit can only be “0” or “5”.
We study how the structure of the EBS market permitted HFTs to implement the sub-penny jumping strategy to take advantage of the lower tick size.\(^3\) In the EBS market, manual traders usually place large orders and do not cancel them very often. HFTs use this information by trading in front and on the same side of the manual traders by improving the price by the smallest possible amount (the tick size). We call this quote matching strategy sub-penny jumping.\(^4\) Sub-penny jumpers try to extract the option values of the manual traders’ orders. Once a sub-penny jumper (these traders are HFTs) trades in front of a manual trader, he is protected from serious losses on his position because in the event of an adverse price movement, the sub-penny jumper limits his losses by trading with the manual trader. However, if there is a favorable price move, the sub-penny jumper profits to the full extent of the price changes. Therefore, the gains of the sub-penny jumper may be unlimited on the upside and bounded on the downside. The sub-penny jumper profits at the expense of the manual trader by taking liquidity that otherwise would have gone to the manual trader. In addition to sub-penny jumping, order anticipation strategies are also used for front-running by HFTs.

Then, we discuss the effects of the tick size change on spreads, market depths and arbitrage opportunities. Using the difference-in-difference estimators, we find that as a measure of the liquidity cost, the spread becomes smaller after the introduction of decimal pip pricing. However, we argue that due to the implementation of the sub-penny jumping strategy by HFTs, manual traders would be pushed back in the limit order book and face higher spreads compared to HFTs. Therefore, the spread is not a sufficient criterion for market quality after the tick size change. The analysis of the limit order book indicates that the market depth decreased after the tick size change. Liquidity providers prefer depth because there will be a sufficient volume of pending orders, preventing a large order from significantly moving the price. We also find that there was no strong difference in the number of arbitrage opportunities before and after the tick size change.

The remainder of the paper is organized as follows: Section 2 provides a brief literature review, Section 3 describes the data and the EBS market, Section 4 presents sub-penny jumping, Section 5 provides empirical evidence for the existence of sub-penny jumping, Section 6 discusses the effect of the tick size reduction on market quality, and Section 7 concludes.

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\(^3\) Sub-penny jumping is a type of front-running strategy in which the sub-penny jumper trades in front and on the same side of a large, patient trader.

\(^4\) Quote matching has been called penny jumping after using the decimal format since 2001 in U.S. security markets. We use the term “sub-penny jumping” because the tick size is smaller than a penny in the EBS market.
2. Literature Review

There are only a few papers that study the tick size change in the interbank foreign exchange market. Using confidential data from EBS, Schmidt (2012) documents that manual traders did not use decimal pip pricing very often after the tick size change. He also provides the taxonomy of the types of EBS customers and their order placement features. Lallouache and Frederic (2014) analyze the data distributions of EUR/USD and USD/JPY and report the price clustering at prices ending in “0” and “5” after March 2011. They argue that “automated” traders take price priority by submitting limit orders one tick ahead of clusters. However, they do not provide insight as to why these traders take such a priority. The common observation that emerges from these two papers is that the EBS market’s microstructure changed significantly after the introduction of decimal pip pricing. However, the reasons for this change and the consequences remain unresolved.

The literature on the tick size change in security markets is controversial with respect to the effects of the tick size change. Bessembinder (2000) finds that spreads are reduced when the tick size is lower. The findings of Jones and Lipson (2001) and Goldstein and Kavajecz (2000) reveal that the spread is not a sufficient criterion for market quality. Bessembinder (2003) finds that both spreads and intraday return volatility decreased after decimalization. The reduction for quoted spreads was stronger in the heavily traded large-capitalization NASDAQ stocks. On the Kuala Lumpur Stock Exchange, where the tick size increases with the price, Chung et al. (2005) find that stocks that are subject to greater tick sizes have wider spreads and less quote clustering. Bourghelle and Declerck (2004) show that the tick size change generated neither a lower liquidity provision for large trades nor a change in the spread on the Paris Bourse Ahn et al. (2007) find that the spread declined significantly after the Tokyo Stock Exchange (TSE) introduced a change in tick sizes for stocks traded within certain price ranges. Reductions in spreads are larger for stocks with larger tick size reductions and higher trading activity. Bacidore et al. (2001) show that the quoting intensity and cancellation rates of limit orders increased after switching to decimal pricing. Chung and Chuwonganant (2002) discover that the number of quote revisions increased dramatically after the minimum tick size reduction. Lastly, Cai et al. (2008) conclude that there is no general effect of a tick size reduction on the TSE because the trading volume, the number of shares traded, and the average trade size react differently.\(^5\)

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\(^5\)The controversies have led to theoretical studies about the choice of a suitable minimum tick size, Harris (1994), Anshuman and Kalay (1998), Cordella and Foucault (1999), Alexander and Zabotina (2005), Kadan (2006), and Ascioglu et al. (2010).
3. Data Description and Market Structure

Banks usually trade currencies with each other on two wholesale electronic trading platforms, namely, EBS and Thomson Reuters. The decision whether to use EBS or Reuters is usually driven by the currency pair. In practice, EBS is the leading liquidity provider for EUR/USD, USD/JPY, EUR/JPY, USD/CHF and EUR/CHF, and Reuters is the primary trading venue for commonwealth and emerging market currencies. The data set used in this study is the EBS level 5 limit order book, which includes 10 levels of “Quotes” (buy, sell) and “Deal” records at 100 milliseconds each. Orders are submitted in units of millions of the base currency. Currently, the available transaction data provided by EBS do not have dealer identifications or characteristics. To analyze the effect of the minimum tick size change in March 2011, we have chosen the data from May 2011 to October 2011, as the share of the EBS customers using decimal pips mostly stabilized starting in May 2011. We excluded thin weekend trading periods and holidays because the liquidity may have been extremely limited. We controlled for daylight savings time (summer) and standard time (winter). Similar conventions were adopted by Andersen et al. (2003) and Chaboud et al. (2004).

In this section, we provide information about the EBS market. We explain the structure of the EBS market and our analysis, which is based on the EUR/USD currency pair. The other major currency pairs USD/JPY, USD/CHF, EUR/CHF, and EUR/JPY are mostly similar to EUR/USD. We will discuss the distribution of the EBS customers, their fill ratio, the volume distribution and their reactions to the introduction of decimal pip pricing. The information in this section is necessary to gain an understanding of our analysis of the sub-penny jumping strategy, which we believe changed the EBS market’s microstructure.

There are two main types of traders in the EBS market: automated traders who use an automated interface (AI) to place orders and manual traders who generally trade at the trading desks of the major banks and use GUI-based access for order management. The main component of an AI is the professional trading community (PTC), which typically places orders at very high frequency. Manual traders (slow traders) and the PTC (HFTs) are the main EBS costumers. Our interpretation of Schmidt (2012) leads to the following four stylized facts:

**Stylized Fact 1.** Manual traders are the main EBS customers. They place orders less frequently and are slow in reaction compared to HFTs.

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6The full results are available upon request.
Manual traders compose approximately 75% of all EBS costumers in EUR/USD, for example, whereas the PTC comprises 16.6% of the customers for the same currency pair. Although manual traders are the main EBS costumers, they place only 3.7% of the daily orders for EUR/USD, and the PTC places 61.6% of all orders.

**Stylized Fact 2.** Manual traders typically place large orders in the order book, whereas HFTs place smaller orders.

Comparisons of the order sizes reveal that the PTC typically uses an order size of one million and almost never uses an order size exceeding four million for the EUR/USD currency pair. In contrast, manual traders place large orders, for example, approximately 5% of the orders submitted by manual traders reach the size of ten million. Such separation in the order sizes permits us to identify the manual traders and the PTC.

**Stylized Fact 3.** Manual traders do not typically cancel their orders, which is in contrast to HFTs; therefore, manual traders have a high fill ratio.

The fill ratio is defined as the ratio of the dealt quotes to the submitted quotes. This ratio is more than 50% for the manual traders and approximately 7% for the PTC. The high fill ratio for the manual traders means that they typically do not cancel their orders, whereas the HFTs do cancel more often, leading to their low fill ratio. All EBS costumers should meet the minimum fill ratio of 3% since July 2012.

**Stylized Fact 4.** Manual traders usually place orders at prices ending in “0”.

In the period under study, manual traders did not widely use decimal pip pricing. Approximately 80% of the manual traders used decimal pip pricing in less than 20% of their orders. Simultaneously, less than 2% of manual traders used decimal pips for more than 80% of their orders. In contrast, AI traders have adopted decimal pip pricing very well: more than 50% of AI traders used decimal pip pricing in more than 80% percent of their orders, and approximately 12% of them used decimal pips in less than 20% of their orders.

The following statement is our first hypothesis regarding the manual traders’ order placement strategy.

**Hypothesis 1.** Manual traders typically place large orders at prices ending in “0” and do not cancel their orders very often.
Notes: Figures 2 and 3 show the limit order book price’s last digit distributions before and after the tick size change, respectively. This distribution was nearly uniform before the tick size change, meaning that traders used all digits equally for the last digit of the price. However, manual traders did not use the decimal pip frequently after the tick size change, which means they often used “0” for the fifth digit. This behavior has created price clustering at prices ending with zero.

Notes: Because manual traders usually use zero for the decimal pip and place large orders, the volume distributions for prices ending in zero and non-zero digits are different. Figures 4 and 5 show that prices ending in non-zero digits are found in smaller volumes, whereas orders with prices ending in zero are found in larger volumes. This pattern indicates that manual traders usually place large orders at prices ending in zero.
There are specific reasons why manual traders were reluctant to use decimal pip pricing. If a manual trader places a large order, for example, ten million, then with pip pricing the value of a tick size would be $1000. However, the value of a tick size with decimal pricing would be $100. Furthermore, manual traders had been accustomed to pip pricing for many years and found it difficult to adapt because using the decimal pip meant adopting new strategies. Considering the smaller dollar value of a tick size with decimal pip pricing, the traditional manual traders who were accustomed to pip pricing did not use the last digit. If manual traders do not use the decimal pip, they place most of their orders such that the fifth digit is equal to “0”. Therefore, there should be price clustering at zero after the tick size change. Figures 2 and 3 show the price’s last digit distributions before and after the tick size change. The last digit distribution was nearly uniform before the tick size change, but there was price clustering at zero after the tick size change. Furthermore, there was another, weaker price clustering at prices ending with “5”. This second clustering could have occurred because some manual traders also used “5” to partially adapt to decimal pip pricing. If manual traders typically use zero for the last digit and place large orders, the volume distribution for prices ending in zero and non-zero digits should be different. Figures 4 and 5 show that the prices ending in non-zero digits come in smaller volumes, whereas the orders with prices ending in zero come in larger volumes.

The described structure of the EBS market creates a setting for HFTs to front-run manual traders by the sub-penny jumping strategy. When a manual trader utilizes a price ending in “0” and a large volume, the HFTs could front-run by improving the price by the amount of the tick size. The patient manual trader almost guarantees that HFTs’ losses are limited by the amount of the tick size. Therefore, this behavior may create an opportunity for HFTs to face a bounded loss and unlimited profit. The HFTs would prefer a lower tick size, as their losses would be smaller. Sub-penny jumping is not the only strategy implemented by HFTs to front-run other traders. There are order anticipation strategies that lead to the occupation of the top of the order book by HFTs.

4. Sub-Penny Jumping

Manual traders are slow traders; they submit large orders at prices ending in zero and they do not cancel their orders very often. In this section, we will explain how HFTs use this information to implement the sub-penny jumping strategy to take advantage of the smaller tick size. Figure 6
depicts the possible sub-penny jumping in the EBS market. Suppose that the manual trader places a 9 million buy order for EUR/USD at the round price 1.39940. A sub-penny jumper, who is able to place an order at very high frequency, would then place a 2 million buy order at 1.39941. The difference between this price and the manual trader’s price is equal to the tick size, i.e., a decimal pip. If the sub-penny jumper buys at his placed order, then he will move to the sell side and can place a sell order at 1.39945. Then, there could be three possibilities. If another trader places a buy market order at 1.39945, the sub-penny jumper’s profit would be $80.7

Figure 6: Sub-Penny Jumping, MT- HFT

If a 2 million buy limit order comes at the price 1.39943 (which is higher than 1.39941), the sub-penny jumper could cancel his order and place a sell market order at 1.39943. If the sub-penny jumper is successful at selling his share, then his profit would be $40. However, if the sub-penny jumper thinks that the market is drifting away from his position, he can sell back to the manual trader at the price of 1.39940, and his loss would be $20.

7Market order is an order to buy or sell immediately at the best available current price.
Let us now consider the general case of sub-penny jumping. Suppose that a manual trader and a sub-penny jumper place buy orders at \( p \) and \( p + \tau \) or sell orders at \( p \) and \( p - \tau \), where \( \tau \) is the minimum tick size. When the sub-penny jumper buys or sells his order, he will move to the other side of the order book. If the manual trader does not cancel or adjust the order and other traders do not fill the manual trader’s order, then the loss is bounded at the rate of return, 
\[
a = \frac{p-(p+\tau)}{p+\tau} = \frac{-\tau}{p+\tau}
\]
for the buying sub-penny jumper and 
\[
b = -\frac{p-(p-\tau)}{p-\tau} = -\frac{\tau}{p-\tau}
\]
for the selling sub-penny jumper. However, if prices move in favor of the sub-penny jumper, there would be profit from such a favorable price change.

We will discuss the case of a buying sub-penny jumper, as selling case is very similar. Suppose that the rate of return has a standard normal distribution: \( x \sim N(\mu, \sigma^2) \). In what follows, \( f, F \) will denote the pdf and cdf, respectively. Similarly, \( \phi, \Phi \) will denote the pdf and cdf of the standard normal distribution. Once the penny jumper trades, the orders he front-runs protect him from serious losses. If prices move in his favor, the sub-penny jumper profits to the full extent of the price changes. The returns are unbounded above and limited below by 
\[
a = \frac{p-(p+\tau)}{p+\tau} = \frac{-\tau}{p+\tau}
\]

The sub-penny jumping leads to higher conditional expectation of returns with smaller conditional variance.\(^8\)

\[
E(x|x > a) > E(x) \quad \text{and} \quad \text{Var}(x|x > a) < \text{Var}(x).
\]

**Proposition 1.** \( E(x|x > a) > E(x) \) and \( \text{Var}(x|x > a) < \text{Var}(x) \). The sub-penny jumping leads to higher conditional expectation of returns with smaller conditional variance.\(^8\)

\[
E(x|x > a) = \mu + \sigma \lambda(\alpha), \quad \text{where} \quad \lambda(\alpha) = \frac{\phi(\alpha)}{1 - \Phi(\alpha)} > 0
\]

\[
\lambda(\alpha) > 0 \rightarrow \mu + \sigma \lambda(\alpha) > \mu \rightarrow E(x|x > a) > E(x)
\]

\[
\text{Var}(x|x > a) = \sigma^2(1 - \delta(\alpha)) \quad \text{where} \quad \delta(\alpha) = \lambda(\alpha)[\lambda(\alpha) - \alpha]
\]

\[
0 < \delta(\alpha) < 1 \rightarrow \text{Var}(x|x > a) < \text{Var}(x).
\]

\(^8\)See the Appendix for details.
**Proposition 2.** \( \frac{da(\tau)}{d\tau} < 0. \) The smaller the tick size is, the higher the loss limit will be.

\[ a = \frac{p - (p + \tau)}{p + \tau} = \frac{-\tau}{p + \tau} \rightarrow \frac{da(\tau)}{d\tau} = \frac{-p}{(p + \tau)^2} < 0. \]

If the tick size decreases from pip \( \tau_1 \) to decimal pip \( \tau_2 \), the loss limit will shift from \( a(\tau_1) \) to \( a(\tau_2) \).

**Proposition 3.** \( \frac{dE(x|x > a)}{d\tau} < 0, \ \frac{dVar(x|x > a)}{d\tau} > 0. \) The lower the tick size is, the higher the conditional expectation of returns will be and the lower the conditional variance of returns will be.

\[
-dE(x|x > a) = dE(x|x > a) \frac{d\lambda(\alpha)}{d\alpha} \frac{da}{d\tau} = \frac{d\lambda(\alpha)}{d\alpha} \frac{-p}{(p + \tau)^2} < 0 \text{ since } 0 < \frac{d\lambda(\alpha)}{d\alpha} = \delta(\alpha) < 1 \quad (1)
\]

\[
-dVar(x|x > a) = dVar(x|x > a) \frac{d\alpha}{d\alpha} \frac{d\lambda(\alpha)}{d\alpha} \frac{d\delta(\alpha)}{d\alpha} = -\sigma \frac{d\delta(\alpha)}{d\alpha} \frac{-p}{(p + \tau)^2} > 0 \text{ since } \frac{d\delta(\alpha)}{d\alpha} > 0 \quad (2)
\]

Equations (1) and (2) show that a smaller tick size makes sub-penny jumping more profitable, as the conditional expected rate of return increases and the conditional variance decreases. With a lower tick size, the sub-penny jumper must improve prices by the smaller price increment to trade ahead of the manual traders. Therefore, the tick size is the price that the sub-penny jumper must pay to front-run the manual traders. However, sub-penny jumpers do not pay this price to the manual traders; instead, they pay it to the traders with whom they trade to establish their positions. These traders would have traded with the manual traders if the sub-penny jumper had not front-run them. A sub-penny jumper will trade profitably only if the standing orders that they front-run do not cancel their orders, adjust them quickly, and other traders do not fill the manual trader’s order. If these options are no longer available, the sub-penny jumper will have difficulty when prices move against him. Based on the EBS market’s structure presented in Section 3, HFTs know that orders with prices ending in zero and large order sizes indicate manual traders to front-run. These orders are not canceled or adjusted very often, and they cannot be filled quickly.
5. Sub-Penny Jumping, Deal and Quote Distributions

Because manual traders were reluctant to use decimal pip pricing, there is a price clustering of quotes in all limit order book levels at prices ending in zero. Furthermore, if a buying manual trader places an order with a price ending with “0” (e.g., 1.39940), then the buying sub-penny jumper who wants to front-run the manual trader should place an order with a price ending with “1” (1.39941). If there are other sub-penny jumpers, they would place their orders with prices ending with “2”, “3” and etc. However, greater distance from “0” means less expected profit; therefore, we would expect a decreasing distribution of the number of orders for the buy side of the limit order book in all levels. Figure 7 shows such distributions for the ten levels of the order book with different last digits. For example, at the level-one buy side of the limit order book, 28% of orders have the last digit “0” and only approximately 2.5% of the orders have the last digit “9”. The shape of the distributions in other levels of the bid side are similar to the shape of the level-one distribution.

If a sub-penny jumper improves upon the order of a manual trader by one tick while bidding, he would place an order with the last digit of “1”. However, if the HFT improves the manual trader’s price (e.g., 1.39940) on the ask side, he should place a price ending with “9” (1.39939). Therefore, we would expect an increasing distribution (excluding “0”) for all levels of the sell side of the limit order book. For example, from Figure 7 we see that approximately 28% of the orders have the last digit “0”, but only approximately 2.7% of the orders have the last digit “1”. This ratio starts to rise and reaches 19.5% for orders with the last digit “9”. The shape of the distributions in other levels of the ask side are similar to the shape of the level-one distribution. As shown in Figure 8, the distributions of orders were almost uniform before the tick size change for both the bid and ask sides. Distributions after the tick size change also show weaker price clustering at prices ending with “5”. It seems that some manual traders placed such orders to adopt decimal pip pricing partially without the complexity of using all digits. However, the volume sizes used with this digit are small and there was no opportunity for HFTs to front-run the digit “5”.

Volume distributions also give us information about the consequences of the sub-penny jumping strategy in the limit order book. When HFTs front-run manual traders, they secure their positions by placing orders of smaller volumes. We know from Section 3 that HFTs typically use one million orders and almost never use an order size exceeding four million. As a result, we should observe
smaller volumes in different levels of the limit order book. The order book volume distributions after and before the tick size change have been given in Figures 9 and 10, respectively. In level-one of the buy side of the order book before the tick size change, 16% of orders had the size of one million and 11% had a size of more than ten million. However, after the tick size change, 61% of orders had a size of one million and only 0.7% of orders had a size of more than ten million. Changes in the other levels are more significant. Before the tick size change and in level-two, 3% of orders had the size of one million and 44% had a size of more than ten million. However, after the tick size change, 62% of orders had a size of one million and only 1% of orders had a size of more than ten million. The reason could be that some manual traders placed orders within one pip price distance from the best prices before the tick size change. Therefore, they had some protection against the price movements in the market. The changes in the sell side of the order book are similar to the bid side.

The same patterns are present in the deal price’s last digits (which makes them similar to the limit order books). When there is a potential buyer in the order book, a seller can place a market order to make a deal. We call such a transaction a seller-initiated deal. A buyer-initiated deal happens when there is a potential seller in the order book and a buyer places a market order to make a deal. We examine the trades and split them into trades initiated by buyers and sellers because penny-jumpers place orders differently in the bid and ask side of the order book, as described above. Figure 11 shows the last digit distribution of the deal price’s last digits for the buyer-initiated and seller-initiated transactions after the tick size change. This distribution is increasing for buyer-initiated trades and decreasing for seller-initiated trades. As shown in Figure 12, the distribution of the deal price’s last digits was nearly uniform before the introduction of decimal pip pricing. There is also insignificant price clustering at prices ending with “5” after the tick size change.

The shape of the order book has also changed the distribution of the deal volumes. Figure 14 shows that in the buyer-initiated trades, 57% of the deals happened with a volume of one million with pip pricing before the tick size change, whereas 72% of deals had a volume of one million after the introduction of decimal pip pricing, as shown in Figure 13. We observe the same pattern in the seller-initiated trades. Because sub-penny jumpers occupied the top of the order book after the tick size change with small orders, more trades happened with smaller volumes.
Figure 7: EUR-USD, LOB Last Digit Distributions after the Tick Size Change

Notes: Figure 7 illustrates the bid and ask prices’ last digit distributions for the ten levels of the limit order book. This pattern provides evidence for the existence of sub-penny jumping in the EBS market after the tick size change. If a sub-penny jumper improves the order of a manual trader by one tick on the bid side, he would place an order with a last digit of “1”. However, if the HFT improves the manual trader’s price (e.g., 1.39940) on the ask side, he should place a price ending with “9” (1.39939).

Figure 8: EUR-USD, LOB Last Digit Distributions before the Tick Size Change

Notes: The price’s last digit distributions were almost uniform for all levels of the bid and ask sides of the order book before the tick size change, as shown in Figure 8. The uniform distribution means that sub-penny jumping was not a common strategy by HFTs before the tick size change.
Figure 9: EUR-USD, LOB Volume Distributions after the Tick Size Change

Notes: The order book volume distributions after the tick size change are given in Figure 9. HFTs occupied the top of the order book after the tick size change and almost never use order sizes exceeding four million. As a result, we observe smaller volumes in different levels of the limit order book after the tick size change.

Figure 10: EUR-USD, LOB Volume Distributions before the Tick Size Change

Notes: Figure 10 illustrates the order book volume distributions before the tick size change. Comparing Figures 9 and 10, we observe that large volumes almost disappeared from the top of the order book after the introduction of decimal pip pricing.
Notes: We examine the trades and categorize them as buyer and seller initiated because penny-jumpers place orders differently on the bid and sell sides of the order book. Figure 11 shows the last digit distribution of the deal price’s last digits for the buyer-initiated and seller-initiated transactions after the tick size change. This distribution is increasing for buyer-initiated trades and decreasing for seller-initiated trades, which is due to the different limit order distributions in Figure 7.

Notes: As shown in Figure 12, the distribution of the deal price’s last digits was nearly uniform before the introduction of decimal pip pricing. This figure comes from the limit order book distributions in Figure 8.
**Figure 13:** EUR-USD, Deal Volume Distributions after the Tick Size Change

Notes: The shape of the order book changed the distribution of the deal volumes after the tick size change, as shown in Figure 13. Because sub-penny jumpers occupied the top of the order book after the tick size change with small orders, more trades happened with smaller volumes.

**Figure 14:** EUR-USD, Deal Volume Distributions before the Tick Size Change

Notes: Figure 14 illustrates that more deals happened with larger volumes before the tick size change, as larger volumes were available at the top of the order book with pip pricing.
6. The Effects of the Lower Tick Size on Market Quality

6.1. Spread

Spread is one of the measures of liquidity costs. Spread is defined as the difference between the best bid and the best asking price in the limit order book. In this section, we study the effects of introduction of decimal pip pricing on the spread. Figure 15 shows the one-hour frequency spread of the EUR/USD exchange rates for 2011. In the graph, each dot is a one-hour average spread and there are 24 observations in each day. We have excluded the weekend, holidays and negative or zero spread.\textsuperscript{9} When EBS changed the tick size from pip pricing to decimal pip pricing in March 2011, there was a significant draw down in the spread. Therefore, we will test the following hypothesis regarding the spread:

**Hypothesis 2.** Decimal pip pricing made the bid-ask spread narrower in EBS market.

To test the effects of the lower tick size on the spread, we use difference-in-difference (DID) estimation. DID is typically used to identify the effects of a specific policy intervention or treatment. The idea behind the DID approach is that if an intervention has an effect, the difference between the unaffected group (the control group) and the group directly affected by the intervention (treatment group) should change after the policy intervention. Then, one compares the difference in outcomes between the two groups before and after the intervention. We chose EUR/USD as the treatment group. The best control group in our case would be the same currency pair in the Reuters market on the condition that the spread for EUR/USD in Reuters was not affected by the tick size change in the EBS market. Unfortunately, we do not have access to this data set. Our next best options for the control group are the busiest non-major currency pairs in the EBS market, namely, EUR/GBP, AUD/USD and GBP/USD. We chose the same number of days before March 2011 (before the tick change) and after May 2011 (after the tick change). The share of the EBS customers using decimal pip mostly stabilized starting in May 2011. Our selected control groups were not affected directly by the tick size change, as the tick size did not change for these currency pairs in the time span under consideration. Moreover, we have not found any evidence that the control groups were affected even indirectly by this change; if they were, they could not be used as control groups.\textsuperscript{10}

\textsuperscript{9}If there is no bilateral credit between a buyer and a seller at the top of the limit order book, the trade does not happen and the spread could be negative or zero.

\textsuperscript{10}If the HFTs moved activities from the control groups to the treatments groups to implement sub-penny jumping, the control groups would have been affected indirectly by the tick size change. We checked the deals and the state of the limit order book of these control groups and did not find significant changes from January 2011 to July 2011.
Assuming that the treatment effect is stationary over time, we define the DID model by

$$S_t = \beta_0 + \beta_1 P + \beta_2 T + \beta_3 PT + \epsilon_t$$  \hspace{1cm} (3)

where $T$ is a binary treatment variable that is equal to one for the EUR/USD and zero for the control group. $P$ is the binary post-treatment indicator, and it is equal to one after the tick size change and zero before the change. $T$ controls for the permanent differences between the treatment and control groups, and $\beta_2$ should capture this variation. Similarly, $P$ controls for trends common to both the control and treatment groups, and $\beta_1$ will capture this variation. The variation that remains is captured by $\beta_3$. Conditional means corresponding to the four combinations of $T$ and $P$ produce Table 1.

| Table 1: Conditional Mean Estimates from the DID Regression Model |
|-------------------------|-------------------------|-------------------------|
| After Tick Size Change | Before Tick Size Change | Difference              |
| Treatment               | $\beta_0 + \beta_1 + \beta_2 + \beta_3$ | $\beta_0 + \beta_2$ | $\beta_1 + \beta_3$ |
| Control                 | $\beta_0 + \beta_1$     | $\beta_0$              | $\beta_1$             |
| Difference              | $\beta_2 + \beta_3$     | $\beta_2$              | $\beta_3$             |

The DID regression results for the one-hour EUR/USD spread average are provided in Table 2 with different control groups. In all cases, using different control groups, the estimates of $\beta_3$ are negative and significant at one percent. Consequently, the spread became smaller after the introduction of decimal pip pricing. We also used the one-minute spread average frequency for robustness checks. The results in Table 3 show that the estimates of $\beta_3$ are all -0.00003 and significant at one percent.

The DID regression results indicate that the spread decreased after the tick size change. At the same time, our findings in Figures 9 and 10 indicate that the manual traders were pushed back in the limit order book. Inasmuch as HFTs occupied the top of the limit order book with the sub-penny jumping strategy, the number of large orders (which is a proxy for manual traders) decreased significantly at the top of the order book after the tick size change. As a result, manual traders may have started facing larger spreads compared to HFTs after the tick size change.
**Table 2: Difference-in-Difference Regressions of EUR-USD Spread**

<table>
<thead>
<tr>
<th>Control Group</th>
<th>EUR-GBP ($T=4,236$), $R^2 = 0.65$</th>
<th>AUD-USD ($T=4,012$), $R^2 = 0.59$</th>
<th>GBP-USD ($T=3,670$), $R^2 = 0.84$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimate</td>
<td>Std. Error</td>
<td>t-value</td>
</tr>
<tr>
<td>$\beta_0$</td>
<td>0.000262</td>
<td>0.000001</td>
<td>175.70</td>
</tr>
<tr>
<td>$\beta_1$</td>
<td>0.000015</td>
<td>0.000002</td>
<td>7.30</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>-0.000113</td>
<td>0.000002</td>
<td>-53.72</td>
</tr>
<tr>
<td>$\beta_3$</td>
<td>-0.000030</td>
<td>0.000003</td>
<td>-10.32</td>
</tr>
</tbody>
</table>

All coefficients are significant at the 1 percent level.

**Table 3: Difference-in-Difference Regressions of EUR-USD Spread**

<table>
<thead>
<tr>
<th>Control Group</th>
<th>EUR-GBP ($T=250,880$), $R^2 = 0.59$</th>
<th>AUD-USD ($T=242,544$), $R^2 = 0.54$</th>
<th>GBP-USD ($T=219,448$), $R^2 = 0.79$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimate</td>
<td>Std. Error</td>
<td>t-value</td>
</tr>
<tr>
<td>$\beta_0$</td>
<td>0.000258</td>
<td>$2 \times 10^{-7}$</td>
<td>1202.23</td>
</tr>
<tr>
<td>$\beta_1$</td>
<td>0.000015</td>
<td>$3 \times 10^{-7}$</td>
<td>50.44</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>-0.000110</td>
<td>$3 \times 10^{-7}$</td>
<td>-363.46</td>
</tr>
<tr>
<td>$\beta_3$</td>
<td>-0.000031</td>
<td>$4 \times 10^{-7}$</td>
<td>-74.51</td>
</tr>
</tbody>
</table>

All coefficients are significant at the 1 percent level.

**Notes:** Table 2 provides the difference-in-difference estimate results for the one-hour EUR/USD spread average. We have used EUR/GBP, AUD/USD and GBP/USD as control groups because they are the busiest currency pairs after the major currency pairs. Activities in other currency pairs are usually sparse which make them improper for the control group. The estimates of $\beta_3$ are negative and significant at one percent, which indicates that the spread became smaller after the introduction of decimal pip pricing. Table 3 shows the DID results for the one-minute EUR/USD spread average. All $\beta_3$ are negative, equal to $-0.00003$ and significant at the one percent level.
Notes: Figures 15 and 16 illustrate the one-hour frequency EUR/USD and EUR/GBP spread averages respectively, for 2011. In the graphs, each dot is the one-hour average spread and there are 24 observations in each day. We have excluded weekends and holidays.

Notes: Figures 17 and 18 illustrate the one-hour frequency AUD/USD and GBP/USD spread averages respectively, for 2011. In the graphs, each dot is the one-hour average spread and there are 24 observations in each day. We have excluded weekends and holidays.
6.2. Market Depth

Market depth is the amount available in the limit order book. This quantity could also be interpreted as the size an order must reach to move the market’s best available price by a given amount. Generally, traders prefer a deep market because a large order is needed to move the best price. We have analyzed both the bid and ask sides of the market to find the EUR/USD market depth of 0.0001 and 0.0002 for 2011. Figure 19 shows the daily averages of the buy side depth. Each circle shows which order size is necessary to move the best price by 0.0001, and each triangle shows a market depth of 0.0002. For example, orders of $15-$20 million were necessary to move the best bid by 0.0001 before the tick size change in March 2011. However, an overall order size of $10-$15 million was sufficient after the introduction of decimal pip pricing. Figure 19 shows that the introduction of decimal pip pricing reduced the market depth after the tick size change. Figure 20 reveals similar results for the ask side of the order book.

There are two reasons why the market depth worsened after the introduction of decimal pip pricing. Firstly, the HFTs implemented the sub-penny jumping strategy and occupied the top of the order book with smaller volumes. Furthermore, because manual traders have not welcomed the decimal pip, if they were not successful in placing an order in an available price ending in zero, they would move to the next price ending in zero. As a result of this order placement strategy, manual traders have not used the best available slots of the limit order book. These changes have led to less deep order books.

6.3. Arbitrage Opportunities

If markets were perfectly efficient, there would be no arbitrage opportunities. In this section, we study the EBS market’s efficiency based on the daily number of arbitrage opportunities. The minimum tick size changed for the five major currencies in March 2011. The combinations of these currency pairs could create two opportune situations for triangular arbitrage, namely, \((\text{EUR} \to \text{USD}, \text{EUR} \to \text{JPY}, \text{USD} \to \text{JPY})\) and \((\text{EUR} \to \text{USD}, \text{EUR} \to \text{CHF}, \text{USD} \to \text{CHF})\). EBS defines the currencies based on the base and local currencies, and \(C_1/C_2\) denotes the amount of local currency \(C_2\) required to buy (or sell) one unit of the base currency \(C_1\). If we consider triangular arbitrage with profit greater than 1 basis point (0.0001), then we need to check Equations (4a) to (5b) to find the arbitrage opportunities. Superscript \(b\) denotes the buy (bid) quote and superscript \(s\) denotes the sell (offer) quote. For example, in Equation (4a), an arbitrageur could initially sell USD and buy EUR. At the next step, the arbitrageur could sell
his EUR to buy JPY and finally, the arbitrageur would buy USD and sell JPY. Figure 21 shows
the daily number of arbitrage opportunities for the EUR/USD, EUR/JPY, and USD/JPY in 2011.
There is no strong difference between the daily number of arbitrage opportunities before and after
the tick size change. We observe the same situation for the EUR/USD, EUR/CHF, and USD/CHF
exchanges in Figure 22.

\[
\left( P_b^{EUR/USD} \times P_b^{USD/JPY} \right) / P_s^{EUR/JPY} \geq 1.0001 \quad (4a) \\
\frac{P_b^{EUR/JPY}}{(P_s^{EUR/USD} \times P_s^{USD/JPY})} \geq 1.0001 \quad (4b) \\
\left( P_b^{EUR/USD} \times P_b^{USD/CHF} \right) / P_s^{EUR/CHF} \geq 1.0001 \quad (5a) \\
\frac{P_b^{EUR/JPY}}{(P_s^{EUR/CHF} \times P_s^{USD/CHF})} \geq 1.0001 \quad (5b) 
\]

Overall, the minimum tick size change had no significant effect on the market efficiency. In
addition, the structure of the EBS market makes it very difficult to take advantage of any arbitrage
opportunity. In the EBS market, orders are usually submitted in units of millions of the base
currency. The minimum volume size is the smallest amount \( V \) of the base currency that can be
traded. Orders must have a size of \( KV \), where \( K \) is a positive integer. As a result of this structure,
an arbitrageur faces the problem of leftovers if he wants to engage in triangular arbitrage. In the
second step of our previous example, the arbitrageur should buy \( KV \) units of JPY, which are not
necessarily equal to the exact amount of his EUR holdings.
**Figure 19**: EUR-USD, Bid Side Market Depth

**Figure 20**: EUR-USD, Ask Side Market Depth

**Notes**: Figure 19 shows the EUR/USD daily average of the buy side depth. Each circle shows which order size is necessary to move the best price by 0.0001, and each triangle shows a market depth of 0.0002. Figure 20 illustrate the sell side depth.

**Figure 21**: Arbitrage Opportunities, EUR-USD-JPY

**Figure 22**: Arbitrage Opportunities, EUR-USD-CHF

**Notes**: Figure 21 shows the daily number of arbitrage opportunities for EUR/USD, EUR/JPY, and USD/JPY in 2011. Figure 22 shows the daily number of arbitrage opportunities for EUR/USD, EUR/CHF, and USD/CHF in 2011.
7. Conclusions

EBS is the main interdealer market for the currency pairs EUR/USD, USD/JPY, EUR/JPY, USD/CHF, and EUR/CHF. EBS decided to change the tick size, i.e., the minimum price improvement, from pip pricing (four decimal points) to decimal pip pricing (five decimal points) for quoted prices in March 2011. This decision has changed the EBS market’s microstructure significantly. Our analysis shows that the EBS market’s structure enabled the high frequency traders to front-run manual traders by the sub-penny jumping strategy. Manual traders typically place large orders in the order book at prices ending in “0”, and they usually do not cancel their orders. Using this information, HTFs place orders in front of manual traders by improving prices by the amount of the minimum tick size. Once the sub-penny jumper trades, the orders he front-runs protect him from serious losses on his position. If the price moves in his favor, the sub-penny jumper profits to the full extent of the price changes. Therefore, the returns are unbounded for HFTs on one side and limited on the other side.

We also show that the lower tick size helped HFTs be more aggressive in sub-penny jumping. There is evidence from the data that supports our analysis of sub-penny jumping in the EBS market. The distribution of the deal prices’ last digit is increasing for buyer-initiated deals and is decreasing for seller-initiated deals. Using difference-in-difference regression, we find that the spread as a liquidity cost decreased after the introduction of decimal pip pricing. However, due to the implementation of the sub-penny jumping strategy by HFTs, manual traders were pushed back in the order book and might face larger spreads. The market depth decreased after the tick size change on both the bid and ask sides. HFTs use sub-penny jumping with smaller orders, and manual traders have not used decimal pip pricing. These factors have led to shallower market depth. Furthermore, there was no distinctive impact of the tick size change on the market efficiency through triangular arbitrage opportunities.
Appendix A. Appendix

Suppose that the rate of return that the sub-penny jumper faces has a standard normal distribution: 

\[ x \sim N(\mu, \sigma^2). \]

In what follows, \( f, F \) will denote the pdf and cdf, respectively. Similarly, \( \phi, \Phi \) will denote the pdf and cdf of the standard normal distribution.

\[
f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2\sigma^2}(x-\mu)^2}, \quad \phi(z) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}z^2}
\]

\( \phi'(z) = -z\phi(z) \) and \( \phi(-z) = \phi(z) \). The associated cumulative distribution function is

\[
\Phi(z) = Pr(Z \leq z) = \int_{-\infty}^{z} \phi(t)dt
\]

Note that \( \Phi'(z) = \phi(z) \) and \( \Phi(-z) = 1 - \Phi(z) \). Once the penny jumper trades, the orders he front-runs protect him from serious losses on his position. If prices move in his favor, the sub-penny jumper profits to the full extent of the price changes. The returns are unbounded on one side and limited on the other side at 

\[ a = \frac{p-(p+\tau)}{p+\tau} = \frac{-\tau}{p+\tau}. \]

\[
f(x| x > a) = \frac{f(x)}{Prob(x > a)} = \frac{f(x)}{1 - F(a)} = \frac{\phi(\alpha)}{1 - \Phi(\alpha)} \text{ where } \alpha = \frac{a - \mu}{\sigma}
\]

Moments of the truncated normal distribution (see Greene (1997)): 

\[ E(x|x > a) = \mu + \sigma \lambda(\alpha), \text{ where } \lambda(\alpha) = \frac{\phi(\alpha)}{1 - \Phi(\alpha)} > 0 \]

\[ \lambda(\alpha) > 0 \rightarrow \mu + \sigma \lambda(\alpha) > \mu \rightarrow E(x| x > a) > E(x) \]

\[ Var(x| x > a) = \sigma^2(1 - \delta(\alpha)) \text{ where } \delta(\alpha) = \lambda(\alpha)[\lambda(\alpha) - 1] \]

\[ 0 < \delta(\alpha) < 1 \rightarrow Var(x| x > a) < Var(x). \]
If the minimum tick size decreases from pip pricing \( \tau_1 \) to decimal pip pricing \( \tau_2 \), the loss limit will shift from \( a(\tau_1) \) to \( a(\tau_2) \) since

\[
a = \frac{p - (p + \tau)}{p + \tau} = \frac{-\tau}{p + \tau} \rightarrow \frac{da(\tau)}{d\tau} = \frac{-p}{(p + \tau)^2} < 0.
\]

\[
\frac{dE(x|x > a)}{d\tau} = \frac{dE(x|x > a)}{d\alpha} \frac{d\alpha}{d\tau} = \frac{d\lambda(\alpha)}{d\alpha} \frac{-p}{(p + \tau)^2}
\]

\[
\lambda(\alpha) = \frac{\phi(\alpha)}{1 - \Phi(\alpha)} \rightarrow \frac{d\lambda(\alpha)}{d\alpha} = \frac{-\alpha \phi(\alpha) [1 - \Phi(\alpha)] + \phi(\alpha) \phi(\alpha)}{[1 - \Phi(\alpha)]^2} = \lambda(\alpha) [\lambda(\alpha) - \alpha] = \delta(\alpha)
\]

\[
\frac{d\lambda(\alpha)}{d\alpha} = 0 < \delta(\alpha) < 1 \rightarrow \frac{dE(x|x > a)}{d\tau} < 0
\]

\[
\frac{d\delta(\alpha)}{d\alpha} = \frac{d\lambda(\alpha)}{d\alpha} [\lambda(\alpha) - \alpha] + [\frac{d\lambda(\alpha)}{d\alpha} - 1] \lambda(\alpha) = \lambda(\alpha) [(\lambda(\alpha) - \alpha)^2 + \lambda(\alpha)(\lambda(\alpha) - \alpha) - 1]
\]

\[
\rightarrow \frac{d\delta(\alpha)}{d\alpha} = \lambda(\alpha) [(\lambda(\alpha) - \alpha)(\lambda(\alpha) - \alpha + \lambda(\alpha)) - 1]
\]

Case 1: \( \lambda(\alpha) \geq 1 \)

\[
\rightarrow \lambda(\alpha) - \alpha > 1 \text{ and } \lambda(\alpha) - \alpha + \lambda(\alpha) > 1 \text{ since } \alpha < 0 \rightarrow \frac{d\delta(\alpha)}{d\alpha} > 0
\]

Case 2: \( 0 < \lambda(\alpha) < 1 \)

\[
\delta(\alpha) = \lambda(\alpha)(\lambda(\alpha) - \alpha) < 1 \rightarrow (\lambda(\alpha) - \alpha) > \frac{1}{\lambda(\alpha)} > \frac{1}{\lambda(\alpha) - \alpha + \lambda} \rightarrow \frac{d\delta(\alpha)}{d\alpha} > 0
\]

\[
\frac{d\delta(\alpha)}{d\alpha} > 0 \rightarrow \frac{d\text{Var}(x|x > a)}{d\tau} > 0 \quad \Box
\]
References


Bacidore, J., R. Battalio, and R. Jennings (2001). Changes in order characteristics, displayed liquidity and execution quality on the NYSE around the switch to decimal pricing. Working paper, NYSE.


