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HFTS AND NON-HFTS ALONG THE LIMIT ORDER BOOK

Xiaoxin W. Beardsley[1] and Zheng He[2]

[1]Associate Professor and Hamilton Family Faculty Fellow in Finance, College of Business and Analytics, Southern Illinois University Carbondale, Rehn 128A, 1025 Lincoln Dr., Carbondale, IL 62901. E-mail: xwang@business.siu.edu
[2]Lecturer, School of Economics and Management, Shanghai Maritime University, 1550 Haigang Ave, Shanghai, China 201306. E-mail: hezheng@shmtu.edu.cn

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ABSTRACT

Using NASDAQ high frequency trading and limit order book data over 120 stocks between 2008 and 2010, we document that HFTs are active in order placement along the book with an average placement at the 5th step, slightly ahead of NHFTs. HFT orders are further ahead during market crisis, though price-wise they retreat. Liquidity provider in trades, not consumer, matters in order placement along the book. Traders becomes more (less) aggressive placing orders when their own (the other) kind provides liquidity in trading. Trades between HFTs (NHFTs) are significantly related with less aggressive orders from NHFTs (HFTs) along the book.

***Keywords*:** High Frequency Trading, Order Placement, Limit Order Book.

***JEL codes*:** G12, G19, G23

1. INTRODUCTION

In the ever-evolving financial markets, the past decade has witnessed a rapid growth of high frequency trading (HFT) conducted by professional traders who use high-speed and sophisticated computer programs to create, modify, and execute orders. Thanks to technological innovation, the increasingly easy access to co-location service and the relaxation of regulations in recent years, these fast traders have cut the latency of trading into nano-seconds (one billionth of a second) and continue to invest heavily in upgrading their technology and infrastructure to speed up further (Budish, Cramton and Shim, 2015). Nowadays, high frequency traders (HFTs) are responsible for the majority of the trading

volume every day (Carrion, 2013; Jones, 2013). The advent of high frequency era brings drastic changes to the trading environment all over the world. In spite of increasing fragmentation of the security markets, there is significant improvement of market quality (Baron, Brogaard, Hagströmer and Kirilenko, 2019; Boehmer, Fong and Wu, 2012; Carrion, 2013; Conrad, Wahal and Xiang 2015; Easley, López de Prado and O'Hara, 2012; Hasbrouck and Saar, 2013; Hendershott, Jones and Menkveld, 2011; Menkveld, 2013, etc.). Evidence shows that many HFTs use speed advantage to serve as market maker (Jovanovic and Menkveld, 2016), voluntarily providing liquidity to slow traders at a relatively lower cost (Hagströmer and Nordén, 2013). Others engage in arbitrage activities which could potentially improve price efficiency.

Not everyone welcomes these fast algorithmic traders. The existence of speed difference means that HFTs can easily surpass slow traders when necessary. In addition, unlike individual traders, HFTs rely on sophisticated computer programs and expensive trading platforms and systems to seek potential trading opportunities. The perfect combination of speed and powerful algorithms gives HFTs superior order processing ability. If such ability is used in abusive or manipulative trading activities, such as front running, spoofing and other predatory trading practices (Lee, Eom and Park, 2013), it will have a disastrous impact on the overall financial market (Angel and McCabe, 2013; Jones, 2013). Therefore, regulators in the U.S. and abroad have discussed a number of policies including excessive order fees, set minimum order exposure times, security transaction taxes and consolidated order-level audit trails (Malinova and Riordan, 2016; O'Hara, 2015) to keep in pace with the new market environment and to relieve the concern of the public. Security exchanges also have tried to reduce the speed difference between HFTs and Non-HFTs (NHFTs) by upgrading their facilities and equipment.

The different attitudes towards HFT by academic researchers vs. regulators and the public document the importance of continuing to study HFT in investment and microstructure research. Past research has focused on the impact of HFTs' trading on market quality, but not so much on HFTs' order placement behind the insides of the market where trading occurs, due to the presumed need for execution speed in high frequency trading. While many financial markets now adopt a limit order book (LOB) in structure, which can extend our understanding of order placements and market quality, existing research on LOB has not paid much attention on HFTs' order placement activities. In this research, we attempt to fill this void by connecting research on HFT with research on LOB. We believe our work is among the first attempts in empirical finance academic research linking HFT research and LOB research together, and we hope to shed further light on both areas of research through this perspective.

We first confirm previous positive findings about HFTs in that HFTs demand less but provide more liquidity in trading than NHFTs, and we note that this effect is somewhat limited to the number of trades, because HFT trading sizes are generally smaller than those

of NHFTs, as shown by previous studies. We also document that the positive finding on HFT liquidity provision is dominated by their trading of large stocks; less traded small and medium stocks see somewhat the opposite result when only trading is considered, especially during the Lehman Brothers crisis week in September 2008. The positive yet limited finding on HFT's liquidity provision in trading prompts us to study the other aspect of HFT activities— their order placement.

We study the order placement activities by HFTs and NHFTs along the LOB, given that a lot of activities go on behind the market insides. We pay special attention to where HFTs and NHFTs place their orders along the book. We show that HFTs are not just active traders by placing orders at the top of the book, they are active behind as well, thus highlighting the importance of examining further along the LOB when studying HFTs. We develop measures of order placement along the depth (step) and the height (price) dimensions of the LOB, and find evidence that HFTs on average place their orders at about the 5th step, slightly ahead of NHFTs who are closer to the 6th step. We project that the reasons for such order placement decisions by HFTs may be to use stale orders to disguise their real trading intention or induce other HFTs or NHFTs to show up (the so-called fishing). It is also possible that certain trading maneuver, such as quote stuffing documented in Egginton, Van Ness and Van Ness (2016) requires HFTs to leave some of the orders in the middle of or even further down the book. Needless to say, when multiple strategies are adopted by HFTs and NHFTs given the book dynamics and market environment, studying the location of their orders along the limit order book can enhance our understanding on the trading strategy of each party and market dynamics in all.

Next, we study how HFTs and NHFTs order placement strategies interact with their trading. Given the fast pace of high frequency trading, the dynamics of the LOB is constantly evolving: at the top of the book due to fast trading, trickling down towards the rest of the book; not to mention order additions, cancellations and modifications at all portions of the book all contribute to the ever-changing LOB, which feeds back to the formation of order placement strategies by HFTs and NHFTs. Depending on who demand and supply liquidity in trades, HFTs and NHFTs may adopt different order placement strategies with regards to order aggressiveness, and the depth of the LOB can provide them ample room for flexible maneuvers with different strategies. We find that indeed who provides liquidity in trading matters in order placement, but not who demands liquidity. At crisis times, when HFTs see HFTs (NHFTs) provide liquidity in trades, they become more (less) aggressive in order placement. NHFTs act similarly when their own kinds provide liquidity in trades and more conservative and cautious when HFTs supply trading liquidity. HFT trades beget more aggressive HFT orders along the book, in that when HFTs trade, either as consumer or supplier of liquidity or both, other HFT orders become more aggressive by moving ahead, step wise and in price. Finally, trades between HFTs (NHFTs) are significantly related with less aggressive orders along the book from NHFTs (HFTs), the other type of traders.

Given the scope of our data provided by NASDAQ, all of our examinations are conducted to compare a normal 9-week period with the 1-week Lehman Brothers crisis period in September 2008. We find that the crisis week saw more trades and more orders placed closer to the top of the book step wise by HFTs, especially with their use of the non-displayed hidden orders, but when considering the price distance towards the top of the LOB, crisis week indeed saw more backward orders by HFTs and NHFTs both, though HFT orders were still ahead of NHFT orders, and there were more aggressive hidden orders by HFTs in crisis than during normal times. Regression analyses on the interactions between HFT/NHFT order placement and trading also yield some statistical significant differences between normal and crisis weeks.

In addition, we document a significant firm-size effect by using subsamples of large-, medium- and small-cap firms and find that HFT orders and NHFT orders populate every portion of the LOB across firm sizes with large firms having the tightest and densest books, in depth and in price. Both HFTs and NHFTs are more aggressive in placing orders for large stocks, along both the depth (step) and the height (price) dimensions of the book, but HFT orders are not missing for small/medium sized companies, especially during market turmoil when liquidity is most needed; though HFTs provide less liquidity to the market then, they do not disappear, consistent with previous finding on trading such as Brogaart (2010). We believe that our research is an important supplement of the current literature on HFT and that on LOB, by adding the depth and height dimensions of the LOB into the study of HFTs vs. NHFTs, in their trading, order placement along the book and the interaction in between, together with the comparison between normal and crisis times while considering the firm-size effect.

2. DISCUSSION ON CURRENT LITERATURE

2.1. Literature on HFT

While some research studies HFT profitability such as Chordia, Green and Kottimukkalur (2018) that finds it to be relatively small, existing theoretical and empirical work on HFT focuses on whether it improves overall market quality. Theoretical work modelling the impact of HFT includes Biais, Foucault and Moinas (2013) that documents the adverse selection and negative externalities generated by fast traders, Aït-Sahalia and Saglam (2013) that predicts HFT reduces market making activities when volatility is high, and the dynamic LOB models in Bongaerts and Van Achter (2016), Hoffmann (2014) and Jarrow and Protter (2012). The latter two both present a stylized model of trading in a limit order market where there are two agents in the market: a fast trader (FT) and a slow trader (ST). Both models predict that fast traders' speed advantage creates a new inefficiency by inducing slow traders to strategically place limit orders with a lower execution probability, which could reduce trading. However, in Hoffmann's model, the presence of FTs could boost

trading as well because their ability to revise some of their quotes after news arrivals reduce the risk of being picked off, thus increasing trading.

Unlike many theoretical models that predict a negative impact of HFT on the market, empirical work on HFT such as Brogaard (2010), Brogaard, Hendershott, Hunt and Ysusi (2014), Brogaard, Hendershott and Riordan (2014), Brogaard, Hastromer, Norden and Riordan (2015), Carrion (2013), Hasbrouck and Saar (2013) and Hirschey (2018) overwhelmingly conclude that HFT trading improves, or at least, not deteriorates, market quality. Brogaard (2010) tests eight hypotheses about HFTs and finds no evidence that HFTs front run NHFTs. Though HFTs provide less liquidity to the market when it is volatile, they do not disappear. Hasbrouck and Saar (2013) shows market depth increases with HFT trading and it improves market quality in both normal periods and periods associated with declining prices and heightened uncertainty. Carrion (2013) concludes that HFTs provide liquidity when it is scarce and consume liquidity when it is plentiful, a finding that is echoed by Hendershott and Riordan (2013). Brogaard, Hendershott and Riordan (2014) finds that algorithmic traders' activities improve price efficiency by trading in the direction of permanent price changes and in the opposite direction of transitory pricing errors. Kirilenko, Kyle and Samadi (2014) argues that HFTs are not the culprit of the Flash Crash. HFTs follow the same trading behavior and maintain their inventory levels before and during the crash. Both HFTs and market makers scratch trades although HFTs scratch a little bit more on that day. Subrahmanyam and Zheng (2016) finds that HFTs increase liquidity provision during high volatility periods and do not cancel more orders than NHFTs. Hirschey (2018) suggests that liquidity demand by HFTs predicts liquidity demand by NHFTs a second ahead and such predictability allows HFTs to incorporate information into prices, enhancing the price efficiency. Chakrabarty, Moulton and Wang (2021) find HFT improves price efficiency following earnings announcements.

However, other empirical research does not provide strong positive conclusion on HFT's impact on the market. Ye, Yao and Gai (2013) does not find evidence that HFT activities improve market quality. Van Kervel and Menkveld (2019) suggests that HFTs unknowingly trade against institutional investors at first, but once they detect these orders (may take several hours), they trade in the same direction as these large investors and such trading pattern may deteriorate price efficiency in the long run. Aquilina, Budish and O'neil (2021) also suggest that HFTs constitute into market illiquidity, roughly one-third of price impact and the effective spread.

2.2. Literature on LOB

A strand of earlier literature on the limit order book focuses on order placement by studying the choice of market vs. limit orders. Examples include Foucault (1999), Foucault, Kadan and Kandel (2005), Foucault and Menkvald (2008), Harris and Hasbrouck (1996), Parlour (1998) and Rosu (2009). Another stream of literature on LOB focuses on optimal trade

execution such as Cont, Kukanov and Stoikov (2014), Obizhaeva and Wang (2013) and Predoiu, Shaikhet and Shreve (2011). Several papers study the scheduling of orders such as Almgren and Chriss (2001) and Bertsimas and Lo (1998). Out of existing work that studies HFT on LOB, Avellaneda and Stoikov (2008) derives a dynamic model of HFT trading in a LOB market that focuses on the inventory risk of market makers. Jarnecic and Snape (2014) show that HFT participants submit orders concentrated at or within the quote of the LOB so issues remain surrounding their effect on market depth. Subrahmanyam and Zheng (2016) reconstructs the order book to 50 best price steps and finds that HFTs strategically place more liquidity further away from the top of the book, especially when market is volatile. Goldstein, Kwan and Philip (2021) find that HFTs supply liquidity on the thick side of the order book and demand liquidity on the thin side, especially during high volatility periods. Our work differs from theirs in that in addition to documenting HFTs' presence beyond the top of the LOB, we also study the interaction between trading activities and order placement strategies of HFTs, as compared to those of NHFTs, along the limit order book. Besides the comparison between HFTs and NHFTs, we examine displayed as well as hidden orders, document firm-size effect and conduct all the research contrasting a normal time period with the Lehman Brothers crisis week.

Our paper fits into the current interest level and research scope on HFT by finance academics, industry professionals, the public and regulators, and extends the existing work by studying both the trading activities and order placements of HFTs, as compared to NHFTs, along the limit order book, rather than focusing on the very top of the book, during normal and crisis times (represented by the Lehman Brothers crisis week for comparison), and examine potential firm-size effects. Compared to the amount of work on HFT's impact on market quality and existing research on the limit order book, research on HFTs and NHFTs' order placement activities along the LOB and the interaction between their order placement and their trading is scarce. Our research intends to fill this void.

3. DATA

3.1. Data Description

We use the 2008-2010 NASDAQ HFT database of 120 stocks, divided equally by NASDAQ into large-, medium- and small-cap groups. Trades are timestamped to milliseconds and are provided for each trading day during 2008 and 2009 as well as one week in 2010[2]. NASDAQ also identifies 26 trading firms as HFTs from the observation that unlike NHFTs, HFTs submit and cancel orders frequently in a short period of time, leading to short order duration and high order-to-trade ratio. The inventory level of HFTs is also close to zero at the end of each trading day. NASDAQ creates a variable "Type" to reveal whether the liquidity demand and supply side of a trade is a HFT or a NHFT and assigns 'Type' to be *HH*, *HN*, *NH*, and *NN*. The first letter refers to the liquidity seeking side and the second to

the providing side. For example, *HN* suggests that a HFT firm takes liquidity from a NHFT firm in this trade and the reverse is true for *NH* trades. *HH* (*NN*) indicates that a HFT (NHFT) firm demands liquidity from another HFT (NHFT) liquidity supplier. For the rest of this paper, we denote HFT liquidity demanding trades as the sum of *HH* and *HN* trades and HFT liquidity supplying trades as the sum of *NH* and *HH*. NHFT liquidity demanding and supplying trades are defined accordingly.

NASDAQ also provides the limit order book snapshots at one-minute intervals. For each sample date and security, the available liquidity hidden and displayed, on both the Buy and Sell sides of the book (up to 10 best price levels) is shown minute by minute from 9:30 a.m. to 4:00 p.m.. As a result, we have 391 observations for each stock/date combination. However, unlike the trade report, NASDAQ only provides book information for 10 weeks, including the first full week of the first month of each quarter during 2008 and 2009, the Lehman Brothers crisis week (Sep15-19, 2008), and one week in 2010 (Feb 22-26, 2010). The book data contains the following data field: *Stock symbol*, *Buy/Sell indicator*, *Price*, *HFT flag* (1=HFT; 0=NHFT), *Display flag* (Y=displayed order; N=hidden order), *Time*, *Date* and *Shares*. Though ten best price levels (steps) on each side of the market are provided, it is possible that at times for certain stocks, one type of traders (HFT or NHFT) is missing at some of the price steps.

3.2. The shape of the LOB with HFT and NHFT orders

A limit order book by nature takes the shape of two step functions of the demand (buy) and supply (sell) schedules in the price-quantity space, with each step length representing the depth of the market, in either number of shares or number of orders for example, and step height representing the price dimension. In Figures 1-4, we show the average shares per price step on the LOB provided by HFTs and NHFTs respectively, for the overall sample (Figure 1) and by size groups (Figures 2-4). As we can see, NHFTs (solid, blue) unsurprisingly, provide liquidity by placing orders along the book, while contrary to common presumption that HFTs are primarily active at the market insides, there is a significant amount of liquidity provision by HFTs (dash red) beyond the top of the book. Aggregating the number of shares at each price step, Figure 1 shows that, overall, HFTs provide about 9,000 shares while about 14,000 shares are from NHFTs on the top 10 price steps of each side of the book. In general, the liquidity provided by HFTs is stable on each side of the book from the 1st through the 10th price step. The number of average shares provided by HFTs fluctuates slightly over 800 shares at each price step of the book till the 7th step before increasing a little bit afterwards. Therefore, behind the market insides, HFTs continue to place orders, together with more NHFT shares that are present all along the book. Unlike NHFT orders that are more present towards the 4th-6th steps, HFTs' presence at the 8th-10th steps is more prominent than the other steps. Our finding is consistent with Subrahmanyam and Zheng (2016) that finds HFTs strategically place

orders towards the back of the book through their reconstructed book towards the 50th price step on each side of the market.

Figures 2 to 4 illustrate the significant size effect of the LOB shaped by HFT and NHFT orders. Large firms in Figure 2 have significantly longer books from step 1 to 10 with an average aggregated 13,000+ HFT shares and almost 29,000 NHFT shares, while medium firms in Figure 3 possess shorter books with close to 6,000 HFT shares and close to 8,000 NHFT shares. Small firms in Figure 4 have about the same depth of book as medium firms but with flipped number of shares from HFTs and NHFTs. HFTs provide more shares on the book than NHFTs for small illiquid firms, but no matter what firm size, liquidity provision by HFTs continues beyond the top of the book, though for large liquid stocks, about 70% of the liquidity provided by HFTs is at the top five steps but for the small illiquid stocks, it is only around 20%. The remaining 80% of HFT liquidity for small stocks is all behind step 5. NHFTs on the contrary, provide liquidity with shares mostly evenly spread along the book. HFTs seem to be more active and aggressive in large liquid stocks, though still not all centered at the top of the book, and from our limited data set, we could only speculate that they tend to leave relatively stale orders along the LOB when trading small/medium firms, presumably due to lack of trading in general for these stocks. Large stocks have a top-heavy book while small stocks' books are loaded towards the bottom (with 10 price steps truncated by NASDAQ).

In addition, looking at the vertical price dimension of the height of each step, using price distance between two adjacent steps over that towards the average of the best bid and ask prices (all in %), we find that the larger the stocks, the lower the steps, while small stocks see the steps with over 10 times higher in price. Using the same scale of depth and height across Figures 1 to 4, we can clearly see the significant difference in the shape of the limit order book across firm sizes. Large firms have a LOB much densely populated and tightly packed with depth, while books of small firms are short and loose with large price gaps in between steps; medium firms are somewhere in the middle as far as the height of the book goes, but almost as short as small firms in depth. However, no matter the market caps of the stocks, HFT and NHFT orders are all along the book, at the top and beyond the top. Figures 1-4 document the importance to study HFT order placements, as compared to those of NHFTs, beyond the top of the LOB. Why are they there? What purpose do they serve? What impact can they have? All these are empirical questions that remain to be examined and we attempt to provide some answers and shed some light on these issues in this paper. One point worth noting is that for our overall sample and firm-size subsamples, there is no significant asymmetry between the buy and sell sides of the book. Therefore, in our analyses, we report the average results of buy and sell, but perform robustness checks with buy and sell respectively and find no significant changes in results in general.

We later match the millisecond-level trade data to the minute-level book information using ticker and time indicators. The purpose of the matching is to examine the interaction

and impact of HFTs and NHFTs trading activity on their order placement strategies along the limit order book. We exclude limit orders with negative stock price and number of shares presumably due to report errors.

4. ORDER PLACEMENT ALONG THE LOB IN DEPTH AND HEIGHT

We measure the location of order placement along the buy or sell side of the LOB by $STEP_{HFT,t}$ ($STEP_{NHFT,t}$) as the *weighted average step* of HFT (NHFT) orders at minute *t*:

$$STEP_{HFT,t} = \frac{\sum_{i=1}^{10} V_{i,t}^{HFT} N_{i,t}}{\sum_{i=1}^{10} V_{i,t}^{HFT}} \tag{1}$$

$$STEP_{NHFT,t} = \frac{\sum_{i=1}^{10} V_{i,t}^{NHFT} N_{i,t}}{\sum_{i=1}^{10} V_{i,t}^{NHFT}} \tag{2}$$

As shown by Equations (1) and (2), for buy and sell separately, $V_{i,t}^{HFT}$ refers to the number of shares at step *i* provided by HFTs (*i* is from 1 to 10) at minute *t*, and $N_{i,t}$ represents the step number *i* at minute *t*. The denominator represents the aggregate number of shares provided by HFTs at minute *t*. $STEP_{NHFT,t}$ is defined similarly using NHFT shares. Both are bounded inclusively between step 1 and step 10, the truncation provided by the NASDAQ data. We use these two variables to measure the depth dimension of order placement along the LOB by HFTs and NHFTs, with a smaller value indicating orders placed more aggressively closer to the top of the book.

To further illustrate, assume that the total number of shares available for a stock at minute *t* is 1,000 and 400 comes from HFTs. 300 HFT shares are provided at step 1 and 100 at step 4. Using Equation (1), the *weighted average step* of HFTs is 300/400*1+100/400*4=1.75, showing that HFT orders are placed on average at the 1.75th step at this time. Alternatively, instead of using $\sum_{i=1}^{10} V_{i,t}^{HFT}$ as the denominator, we can use the aggregate number of shares provided by all traders, $\sum_{i=1}^{10} V_{i,t}^{HFT} + \sum_{i=1}^{10} V_{i,t}^{NHFT}$, in the denominator. If so,

the *weighted average step* of HFTs will change to 300/1000*1+100/1000*4=0.7, much smaller than 1.75 from Equation (1) and by the value itself, can be misleading in representing order aggressiveness, since this calculation can yield a result smaller than 1. It may also be confusing to explain and does not carry as direct a meaning as the conditional measure in Equation (1) or (2) which captures the average location of orders when HFTs or NHFTs place them. Therefore, in later analyses, we use the measure in Equation (1) and (2).

The *weighted average step* measure above only captures order placement in the depth dimension along the LOB. We know that the height dimension (the vertical axis of *price*) is the other important feature of any limit order book, as it depicts how close orders are to each other in price competitiveness. To capture the height dimension of order placement by HFTs and NHFTs along the book, we construct $Price_{HFT,t}$ and $Price_{NHFT,t}$ for each of the buy and sell sides of the book, by first calculating the absolute percentage difference of each price step i towards the mid inside quotes m_t at t (the average of the best bid and ask prices).

$$\%\Delta p_{i,t} = \frac{\left|P_{i,t} - m_t\right|}{m_t} * 100\% \tag{3}$$

Because the buy and sell sides have prices move in opposite directions along the LOB, we compute the absolute values between order prices and m_t here. We then define,

$$Price_{HFT,t} = \frac{\sum_{i=1}^{10} (\Delta p_{i,t} * V_{i,t})^{HFT}}{\sum_{i=1}^{10} V_{i,t}^{HFT}} \tag{4}$$

$$Price_{NHFT,t} = \frac{\sum_{i=1}^{10} (\Delta p_{i,t} * V_{i,t})^{NHFT}}{\sum_{i=1}^{10} V_{i,t}^{NHFT}} \tag{5}$$

We use similar weighting method here in the denominator as in Equations (1) and (2). $Price_{HFT(NHFT),t}$ measures the competitiveness of the limit orders placed by HFTs (NHFTs) from the height (price) dimension at time t, with smaller values indicating orders aggressively placed closer in price to the top of the book. The depth-dimension measure in Equations (1) and (2) captures order aggressiveness horizontally along the book, but price gaps between steps can vary, and an order can be on one of the top steps while being distantly far away in

price, so the height-dimension measure adds the vertical price perspective by complementing the horizontal depth-dimension measure and completes the description of order aggressiveness by HFTs and NHFTs.

5. SUMMARY STATISTICS

In this section, we present summary statistics on a group of variables describing HFTs and NHFTs trading and order placement. The *Overall* sample includes ten weeks from 2008 to 2010. *Normal* period includes nine non-crisis weeks (Weeks 1-9) and the *Crisis* week (Week 10) refers to the Lehman Brothers week of Sep 15-19, 2008. To examine the firm-size effect, all firms are subcategorized into three groups: *Large*, *Medium*, and *Small*, each having 40 firms, classified by NASDAQ based on market capitalization. In addition, we test the difference in each variable between HFTs and NHFTs and test the difference in the same variable over the two time periods.

5.1. Number of Trades

Table 1 reports the summary statistics on the *average daily number of trades*. Panel A shows that *NH* trades, where NHFTs demand liquidity and HFTs supply liquidity, count the most for our sample, higher than the opposite *HN* trades (3,366 vs. 2,556), both in normal times and during crisis, indicating HFTs provide liquidity to NHFTs more often than the opposite regardless of market condition, and confirms previous findings in the literature. Both HFTs and NHFTs trade significantly more when market is volatile. The daily number of *NH* trades significantly increases by 87% from 3,090 to 5,791 in the crisis week, contrary to critics of HFTs that these algorithm traders may withdraw from the market when it is volatile, at least in the number of trades. Compared with NHFTs, HFTs engage in less liquidity demanding trading, regardless of market conditions; HFTs demand liquidity in 1,339 trades fewer than NHFTs per day for the normal nine weeks, and 2,509 fewer trades per day in the crisis week. Moreover, examining the difference between *HN* and *NH* trades, we find that HFTs net provide liquidity to NHFTs, especially during the crisis week, as the difference more than doubles from 716 trades to 1,651 trades per day. All are statistically significant at the 1% level. HFTs also engage in more liquidity supplying trades than NHFTs, though statistically insignificant. These results are consistent with previous literature (Brogaard, Hendershott and Riordan, 2014 and Hirschey, 2018) that finds many HFTs serve as market makers who provide liquidity to market participants when necessary.

Firm size may have a significant impact on trades because transaction costs on small illiquid stocks tend to be larger than those on large liquid securities. Results in Table 1 Panel B reflect that most trades are on large firms, especially for HFTs. Looking at trades between HFTs (*HH*), we find that trades on the 40 large sample firms account for 96% (5,252 out of 5,252+225+19=5,496) of the total number of *HH* trades, while that percentage for the *NN* trades is 81%. As expected, HFTs are more reluctant to trade illiquid medium

and small firms, presumably because of liquidity concerns of adverse selection and inventory management issues (Carrion, 2013 and Hirschey, 2018). HFTs tend to hold stocks for a very short period of time and targeting liquid large firms allow them to liquidate quickly.

We continue to find HFTs demand less liquidity and supply more liquidity than NHFTs across firm sizes though the results are dominated by large firms. HFTs net provide liquidity in 2,491 more trades a day than NHFTs for large firms (Panel B), but take liquidity on more trades of illiquid medium and small stocks, 293 and 68 trades respectively. The effect is enlarged during the crisis week (Panel C), when HFTs net provide liquidity to NHFTs in 5,821 more trades a day for large firms, but the medium and small firms see NHFTs provide liquidity to HFTs in 706 and 152 more trades a day. In this sense, this result on the firm-size effect, supports Kirilenko, Kyle, Samadi, and Tuzun (2017) that HFTs slow down in providing liquidity when needed the most (small/ medium firms during crisis).

In unreported results here (available upon request), we also find that HFT trades are somewhat smaller than NHFT trades, no matter when HFTs demand liquidity or supply liquidity in trades, consistent with Brogaard, Hendershott and Riordan (2014). Therefore, though in general, HFTs provide liquidity in trading more frequently than NHFTs, the size of their liquidity provision is not as large, but when they demand liquidity in trading, the size is not as large either. We do not find economically or statistically significant differences in trade size under different market conditions, implying that no further breaking-down of orders take place by HFTs or NHFTs during market stress. However, if in trading, HFT's liquidity provision is a little reserved and limited by their trade size, what about HFTs' order placements on the limit order book? After all, liquidity provided on the book begets and facilitates trading. We examine this question in the sections below.

5.2. Weighted average step of order placement location along the LOB

Table 2 presents *weighted average step*, a measure that shows the depth dimension of orders submitted by HFTs and NHFTs along the limit order book. It is intuitive to assume HFTs place orders at the very top of the LOB because they aim to be fast and frequent in trading, and the top of the book provides the highest order execution probability. However, Panel A shows that overall, HFT orders are placed at the 5.06th step while those by NHFTs are a little behind at the 5.87th step, both way below the top of the book. A *weighted average step* larger than 1 indicates that HFTs do not submit orders at the very top step of the LOB, suggesting that only focusing on the top of the LOB when studying HFTs is not enough. Therefore, we need to review along the limit order book when examining HFT order placements, and when comparing with NHFTs, the need is more justified as the average location for NHFTs' orders is further behind. This finding reconfirms the results from Figures 1-4.

Univariate test confirms that the *weighted average step* of HFTs is about 1 step (0.82) ahead of that of NHFTs, significant at the 1% level. The crisis week witnesses HFTs move ahead an average 0.66 step with a statistical significance level at 1%, indicating more aggressive liquidity provision by HFTs during crisis, while NHFTs move their orders back an average insignificant 0.03 step. This result verifies that HFT orders overall, do not back off when needed, consistent with previous finding on HFT trading (Brogaard, Hendershoot and Riordan, 2014 and Hirschey, 2018).

We also devote some time studying the usage of displayed vs. non-displayed (hidden) orders by HFTs and NHFTs and find some interesting results in Table 2 Panel A. Comparing to displayed orders, hidden orders are placed more aggressively at steps closer to the top of the book by both HFTs and NHFTs, in both normal and crisis weeks, especially for HFT hidden orders: they are moved from an average 4.42^{th} step to the 2.79^{th} step during crisis, a significant increase in aggressiveness at the 1% statistical level. Understandably, given that they are hidden, they can protect traders from easily being adversely selected by other sophisticated traders, thus by nature can be utilized more aggressively in volatile time periods. Nevertheless, HFTs remain more aggressive in placing their orders, displayed or not, than NHFTs.

In firm-size sub-samples presented by Table 2 panels B and C, we find very similar results in that HFTs do not place orders just at the top of the book as their *weighted average step* remains behind step 4, while NHFTs place orders further behind, especially during the crisis week. In the Lehman Brother crisis week when the market is volatile, as high frequency algorithmic traders frequently revise their orders, those "slow" orders submitted by NHFTs are pushed downward to the middle and bottom of the book. As a result, the average location of HFT orders moves ahead from the 4.32^{th} (5.13^{th}, 5.92^{th}) step to the 4^{th} (4.77^{th}, 4.6^{th}) step for large (medium, small) firms, while NHFTs orders are moved backwards from the 5.77^{th} to the 5.83^{th} step for large firms and 5.88^{th} to 6.02^{th} for medium firms, but slightly ahead for small firms (5.95^{th} to 5.85^{th}). These results reconfirm the finding that HFTs do generally step up when market is in turbulence, shown by their trades in Table 1 and orders in Table 2. In addition, large firms see orders placed further ahead than small or medium firms across market conditions.

In the usage of displayed vs. hidden orders, we continue to find that both HFTs and NHFTs submit non-displayed orders way ahead of displayed orders across market cap, regardless of market conditions with the exception of HFT hidden orders on small firms during normal weeks when displayed orders are about one step ahead (4.92 vs. 5.85). In normal weeks for large firms, HFTs place non-displayed orders at the 2.81^{th} step on average, way ahead than their displayed orders at the 4.57^{th} step; during crisis time, HFT hidden orders are all ahead of step 3 while their displayed orders are all behind step 4 across market caps. Likewise, NHFTs place non-displayed orders significantly ahead of their displayed orders too, no matter the market condition or firm size.

5.3. Weighted average price difference of order placement location along the LOB

While the *weighted average step* measures the depth dimension of order placement along the LOB, it provides us little information on the orthogonal yet important dimension, the price dimension, of order placement along the book. Figures 1 to 4 already show that on the book, step heights can vary extensively depending on firm size, and an order can be close in step number to the top of the book yet still being far away in price gap, so simply knowing the step number of an order's placement along the book lacks a dimension of the whole picture. Therefore, we construct the *weighted average price difference* as defined in Equations (4) and (5) to fulfill this goal. We expect that while HFT orders are not concentrated at the very top of the book as documented earlier, HFTs have the incentives to place orders closer to the top than NHFTs for two reasons. First, current literature documents that many HFTs are obligated to or voluntarily provide liquidity to other market participants, suggesting that in those transactions where HFTs serve as market makers, the prices of their orders need to be very competitive. Second, due to their speed advantage, HFTs revise their orders quickly and frequently. Many stale orders whose prices are far from the top of the book will be deleted or replaced by new ones. Due to speed disadvantage and information asymmetry, NHFTs do not update their orders as frequent as algorithmic HFTs, leaving many orders left in the book potentially being adversely selected by HFTs.

Table 3 Panel A reports the summary statistics of the *weighted average price difference*. HFT and NHFT orders are overall of equal distance in price to the market insides during normal weeks, but HFT orders are ahead of NHFT orders in price during the crisis week, when both HFTs and NHFTs move their orders back price wise, with the exception of HFT's usage of hidden orders, that are actually placed more aggressively in price during crisis (0.66% vs. 1%), consistent with the result in Table 2 Panel A when the average step number significantly decreases. NHFTs as expected, significantly move orders backwards when crisis hits, on both displayed and hidden orders. This finding is reconfirmed in sub-sample analysis in Table 3 Panel B and Panel C. HFTs and NHFTs, understandably, back off their order placement in prices when market is under turbulence across firm sizes, with the only exception being that HFTs step up with their hidden order placements price wise, in crisis time on small and medium firms, when liquidity is much needed. Therefore, in price, HFTs, through the placement of non-displayed hidden orders, stay in the market for small/medium firms when needed, consistent again with Brogaard, Hendershott and Riordan (2014) and Hirschey (2018) that many HFTs provide liquidity when necessary, while inconsistent with Kirilenko, Kyle, Samadi and Tuzun (2017) that HFTs slow down in providing liquidity when needed the most as we would think small/medium firms during crisis times are when liquidity is needed the most. This finding illustrates again the importance of studying order placement by HFTs, as compared to that by NHFTs, in addition to trades, in their overall role in liquidity provision and consumption across market conditions.

Table 3 Panel B and Panel C also document a significant firm size effect in that large firms on average see a significant small price difference in their order placements to the top of the book than small firms, regardless of who submit those orders and whether they are hidden or displayed, consistent with Figures 2 and 4 that show a much more densely populated book with closer price steps of large firms than small firms. For HFTs the *weighted average price difference* to the market insides increases from 0.18% for large firms, to 0.68% for medium firms, and to 2.59% for small illiquid firms, an over 14-time jump and all are statistically significant at the 1% level. NHFTs though generally behind HFTs in prices, demonstrate the same statistically significant trend across firm size.

6. INTERACTION OF HFT AND NHFT ORDER PLACEMENTS AND TRADES

In this section, we examine whether trading activities of HFTs and NHFTs affect their order placements along the LOB. Since HFTs are presumed to have better capability to avoid being adversely selected by other traders (mostly other HFTs) than NHFTs, thanks to their speed advantage in processing orders and persistent presence in the market, responses by these two types of traders in order placement to the presence of each other can be different. When large trades involving HFTs took place moments ago, HFTs may tend to behave cautiously. On the other hand, when HFTs on one side of the market do not engage in trading, HFTs on the other side of the market no longer need to worry about being targeted by them. These scenarios are examples presumed to affect order placement decisions by traders. Our main regression is thus a panel regression of each stock j's (j=1 to 120) order placement along the LOB by HFTs or NHFTs on concurrent number of trades among these traders, aggregated minute by minute over the sample days, with several control variables included:

$$Order\ Placement_{j,t} = \alpha + \beta_1 * HH_{j,t} + \beta_2 * HN_{j,t} + \beta_3 * NH_{j,t} + \beta_4 * NN_{j,t} + Controls_{j,t} + \varepsilon_{j,t} \quad (6)$$

As previously stated, for each stock j at every day-minute t, order placement is examined through the depth and height dimensions of order placement by HFTs and NHFTs respectively, $Step_{HFT,}$ $Step_{NHFT}$, $Price_{HFT}$, and $Price_{NHFT}$, then merged with the aggregated number of trades *HH*, *NN*, *HN* and *NH* within that minute. The first letter represents liquidity demanding party and the latter liquidity supplier, classified by NASDAQ.

Control variables include $Return_{j,t}$, $Open_t$ and $Close_t$. $Return_{j,t}$ is calculated from the percentage change in the average of the best bid and ask prices for stock j at time t. $Open_t$ ($Close_t$) is a dummy variable which equals to 1 during the first (last) 15 minutes of each trading day, and 0 otherwise, with the same value across the 120 stocks at each day-minute. Due to information asymmetry, HFTs are likely to trade more frequently at the beginning of each trading day (Chordia, Green and Kottimukkalur, 2018 and Van Kervel and Menkveld,

2019). When market is about to close, HFTs may need to imbalance their inventory (Van Kervel and Menkveld, 2019). Both $Open_t$ and $Close_t$ are added to the regression to control for this time-of-the-day effect. In previous tables, we find significant firm-size effect in the dependent and independent variables. To ensure that firm characteristics such as firm size and liquidity do not bias our results, we add firm fixed effects in the panel regressions.

We report how trades initiated and responded by HFTs and NHFTs impact the depth dimension of order placement (*weighted average step*) in Tables 4 (for HFTs) and 5 (for NHFTs) respectively and how they impact order placement in the height dimension (*weighted average price difference*) in Tables 6 (for HFTs) and 7 (for NHFTs). We find for HFT order placements (Tables 4 and 6) during normal weeks when HFTs are involved in either providing or demanding liquidity or both (*HN*, *NH* or *HH*), their trades are related with aggressive HFT order placement (significantly negative coefficients), with lower placement step number or price difference to the market insides, with the exception of slightly positive coefficients (0.001) on *HH* trades on the price dimension of HFT order placement in Table 6. HFT trading in general begets more aggressive HFT orders, in both depth and price dimensions of HFT order placements along the book.

Interestingly, when market is volatile during the crisis week, what really matters is not who demand liquidity but who supply liquidity in trades. In other words, there is an asymmetry in step-wise order placement between when HFTs provide liquidity vs. when NHFTs provide liquidity in trades. When HFTs provide liquidity in trades (*HH* and *NH* trades), we find a -0.006 but insignificant coefficient on *HH* and a significant -0.017 coefficient on *NH* in Table 4, indicating more aggressive orders by other HFTs in moving their orders closer to the top of the book (reducing step number). When NHFTs provide liquidity in trades (*NN* and *HN* trades), more conservative HFT order placements by moving orders to latter steps are noticed, represented by a 0.021 coefficient on *HN* and 0.062 on *NN* in Table 4. Both are statistically significant at the 1% level.

Our interpretation of these results is that when market is not volatile, the risk of being picked off by other HFTs is relatively low, allowing HFTs to be bold in order placement. On the other hand, at crisis time, the adverse selection problem can be severe. When HFTs see other HFTs provide liquidity in trades at this time, they become cautious, perhaps concerned of possible fishing manipulation from the other HFTs, act more conservatively and move their orders backward to reduce adverse selection cost. Whenever HFTs see NHFTs provide liquidity in trading, they are less concerned and become more aggressive in order placement. Given the higher risk involved in market turbulent time, depending on who provide liquidity, it seems that HFTs can adjust their order placement accordingly, all done at a high frequency.

Table 5 reports the results on the *weighted average step* from order placements by NHFTs, which are opposite from those on HFTs (Table 4), but again, who the liquidity

provider is, not consumer, has significantly different effects, no matter during normal times or crisis time. For NHFTs, trades in which HFTs provide liquidity are related with more backward order placements by NHFTs, suggesting that NHFTs adopt a conservative order placement strategy when HFTs provide liquidity in trades. They become aggressive when other NHFTs provide liquidity in trades, represented by all negative coefficients on *HN* and *NN* trades. All coefficients are statistically significant at the 1% level. Our interpretation is that NHFTs may view the liquidity provision activities by HFTs as a proxy for the pick-off risk. A higher number of trades with HFTs serving as liquidity providers may indicate higher adverse-selection risk. These findings generally prevail though are not as prominent when the price dimension of NHFT order placements is examined in Table 7.

Another finding noteworthy of mentioning is that trades between HFTs (NHFTs) are significantly related with less aggressive orders from NHFTs (HFTs), in both step and price dimensions, as the positive and significant coefficients on *NN* in Tables 4 and 6, and those on *HH* in Tables 5 and 7 demonstrate. Trades among HFT themselves, understandably, are related with more conservative order placements by NHFTs with orders more backward in steps, and further away from the market insides (i.e., in both the depth and height dimensions of their order placements), as NHFTs may try to stay out of the way of the more sophisticated and much faster HFT traders when they are actively trading with each other. Trades among NHFT themselves, are related with more conservative order placements by HFTs could be because when NHFTs trade with NHFTs, HFTs sense less risk of adverse selection and decide there is no need to be aggressive. However, that fact that HFTs do not seem to take advantage of the situation by being more aggressive when the supposedly-unsophisticated and slow NHFTs trade is somewhat puzzling.

Finally, we notice that the price-dimension order placement results in Tables 6 and 7 and the depth-dimension order placement results in Tables 4 and 5 are not perfect in line with each other, due to the fact that step number and price difference to the market insides do not have to go in sync, as mentioned earlier. Step number decreases (more aggressive) yet price difference increases (more conservative) can happen at the same time. This feature itself demonstrates the importance of studying both the depth and the height dimensions of order placement along the LOB. One dimension cannot be fully descriptive.

7. CONCLUSION

We use trade and limit order book data on 120 firms categorized by size over 2008 to 2010 provided by NASDAQ to study trades and order placements by HFTs and NHFTs, and how their trading activities and order placement strategies interact. We first reconfirm previous findings (Brogaard, Hendershoot and Riordan, 2014 and Hirschey, 2018 etc.) on HFT and NHFT trading activities that HFTs engage in less liquidity demanding trades and more liquidity supplying trades, with the notice the dominance of large firms in driving this result and on smaller trade sizes by HFTs than NHFTs.

We then document the importance of studying HFT and NHFT order placement along the LOB by showing that there is much liquidity provided by HFTs and NHFTs beyond the top of the book. Across firm sizes, HFT and NHFT orders are present all along the limit order book, with large firms see the book more densely populated in depth and in price steps while smaller firms have books that are much shorter and more sparsely spaced between price steps. Thus, orders along the book as to which steps they are placed (not just the top step) and how far away in price they are from the best bid and ask prices cannot be neglected. For both HFTs and NHFTs, we construct two measures of order placement along the LOB: *weighted average step* to capture the depth dimension of orders placed on the book in terms of step number, and *weighted average price difference* from the mid-inside quotes (average of the best bid and ask prices), to capture the height dimension of order placement. We show that HFTs are active not only at the top of the LOB, but their orders are placed along the LOB with an average around the 5th step, slightly ahead of NHFTs who on average are close to the 6th step. Compared with normal times, HFT orders are moved towards the top of the book during the Lehman Brother's crisis week of 2008, especially for small and medium-sized firms whose liquidity is not plentiful at the time. As to the price dimension of order placements, NHFTs place orders further away than HFTs and moved even further down the book during the crisis week, more so than the backward movement of HFTs. Therefore, not only in trades, but also in order placements, HFTs seem to stay when liquidity is needed the most during crisis times, an impressive showing of the positive impact HFTs project to the market.

Both HFTs and NHFTs use displayed and non-displayed hidden orders to provide liquidity. Comparing to displayed orders, hidden orders are placed more aggressively at steps closer to the top of the book by both HFTs and NHFTs across firm size. Price wise, HFT and NHFT orders are overall of equal distance to the market insides during normal weeks, but HFT orders are ahead of NHFT orders in price during the crisis week, when both HFTs and NHFTs move their orders back price wise, with the exception of HFT's usage of hidden orders, placed more aggressively in terms of price during crisis, especially for small and medium firms, when liquidity is much needed. Therefore, though step number wise, HFT and NHFT orders are placed backwards during crisis, in price, HFTs, through the placement of non-displayed hidden orders, stay in the market for small/medium firms when needed. This result, again, documents the importance of studying both the depth (step) and the height (price) dimensions of order placements along the LOB and together with the results on order placements in depth along the book, confirms the previous finding that HFTs do not disappear when market is under stress, contrary to Kirilenko, Kyle Samadi, and Tuzun (2017), but consistent with Brogaard, Hendershoot and Riordan (2014) and Hirschey (2018) etc..

Next, we examine the interactions of trading and order placement by HFTs and NHFTs along the LOB and find some interesting results. HFT trading in general begets more

aggressive HFT orders, in both depth and price dimensions along the book. When market is volatile during the crisis week, what really matters is not who demand liquidity but who supply liquidity in trades. In other words, there is an asymmetry in order placement between when HFTs provide liquidity vs. when NHFTs provide liquidity in trades during market turmoil. Whenever HFTs see other HFTs provide liquidity in trading, they become more aggressive in order placement. However, when NHFTs provide liquidity in trades, HFTs become conservative in moving their orders backward. Similarly, it is the liquidity supplier, not who demand liquidity that are significantly related with the aggressiveness of NHFT order placements, no matter during crisis or not. Like HFTs, NHFTs are more aggressive when their own kinds provide liquidity in trades, and more relaxed when HFTs supply liquidity. Finally, trades between HFTs (NHFTs) are significantly related with less aggressive orders from NHFTs (HFTs), in both step and price dimensions.

Not only is the importance of studying HFT *along* the limit order book, not simply at the market insides, noted in this paper, the importance of both the depth (step) and the height (price) dimensions of order placement is also stressed due to sometimes seemingly contradicting yet possibly complementary results between the two dimensions of order placement measurements. We believe that our research complements existing work on HFT and that on LOB by combining the two streams of study together. As markets around the world adopt electronic limit order book in their structure, as high frequency trading becomes more predominant in security trading with the assist of rapid technology breakthroughs, and as HFTs are indeed active not only at the top of the limit order book, but beyond the top, we hope to shed some light on the joint research into HFT on LOB, and await further work from this perspective. One possible area to extend our research is to study HFT on LOB during the 2020 COVID-19 pandemic, when market witnesses tremendous swings and under unprecedented stress. We intend to pursue this study as data becomes available.

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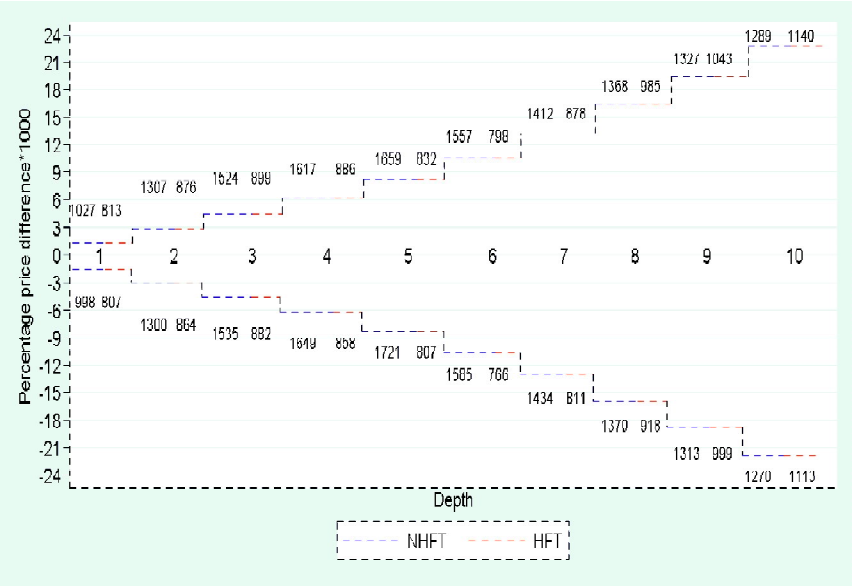

Figure 1: Average shares per step — overall sample

This figure illustrates the average liquidity provision (as measured by average shares per price step) by HFTs and NHFTs along the limit order book over 10 weeks from 2008 to 2010, including 9 non-crisis weeks and a week 10, the Lehman Brother's crisis week of Sep 15-19, 2008. The sample stocks include 120 stocks listed on NASDAQ and NYSE. The X axis shows the average number of shares on each price step of the book. The Y axis shows the percentage price difference of each step to the average of the best bid and ask prices, multiplied by 1000. The solid blue line (dash red line) represents number of shares from orders placed by NHFTs (HFTs).

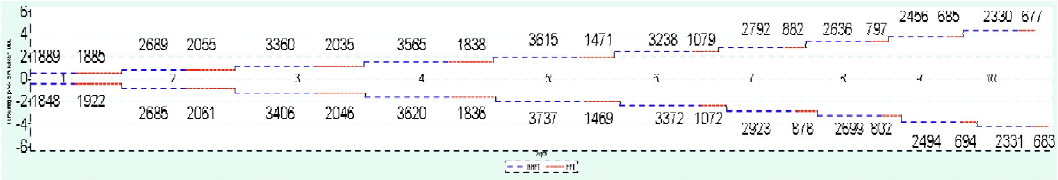

Figure 2: Average shares per step —- large firms

This figure illustrates the average liquidity provision (as measured by average shares per price step) by HFTs and NHFTs of 40 large sample stocks along the limit order book over 10 weeks from 2008 to 2010, including 9 non-crisis weeks and a week 10, the Lehman Brother's crisis week of Sep 15-19, 2008. The X axis shows the average number of shares on each price step. The Y axis shows the percentage price difference of each step to the average of the best bid and ask prices multiplied by 1000. The solid blue line (dash red line) represents number of shares from orders placed by NHFTs (HFTs).

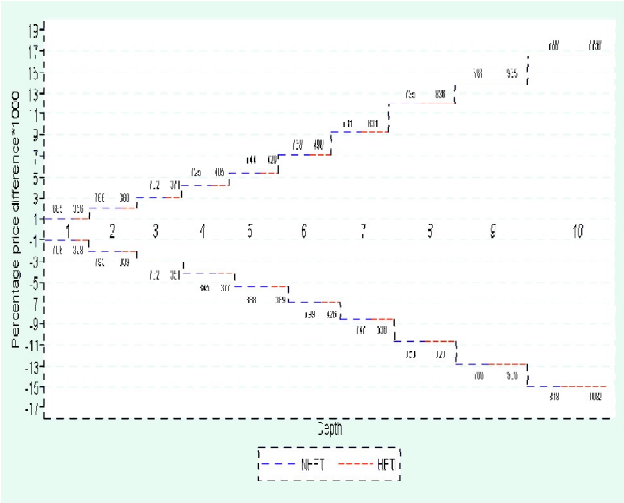

Figure 3: Average shares per step —medium firms

This figure illustrates the average liquidity provision (as measured by average shares per price step) by HFTs and NHFTs of 40 medium-sized sample stocks along the limit order book over 10 weeks from 2008 to 2010, including 9 non-crisis weeks and a week 10, the Lehman Brother's crisis week of Sep 15-19, 2008. The X axis shows the average number of shares on each price step. The Y axis shows the percentage price difference of each step to the average of the best bid and ask prices multiplied by 1000. The solid blue line (dash red line) represents number of shares from orders placed by NHFTs (HFTs).

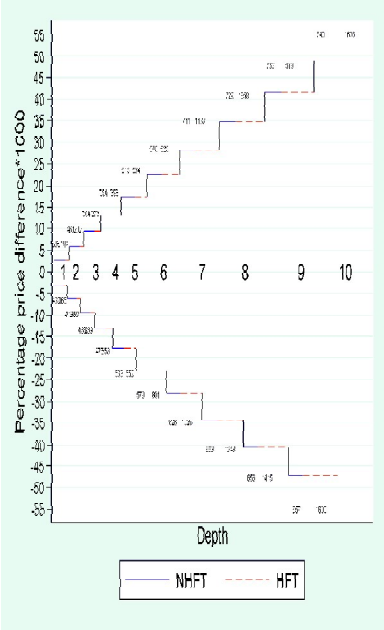

Figure 4: Average shares per step —small firms

This figure illustrates the average liquidity provision (as measured by average shares per price step) by HFTs and NHFTs of 40 small sample stocks along the limit order book over 10 weeks from 2008 to 2010, including 9 non-crisis weeks and a week 10, the Lehman Brother's crisis week of Sep 15-19, 2008. The X axis shows the average number of shares on each price step. The Y axis shows the percentage price difference of each step to the average of the best bid and ask prices multiplied by 1000. The solid blue line (dash red line) represents number of shares from orders placed by NHFTs (HFTs).

Table 1: Summary statistics on daily number of trades

This table presents the summary statistics on the number of trades of the 120 sample stocks listed on NYSE and NASDAQ over 10 weeks from 2008 to 2010, including 9 non-crisis weeks and a week 10, the Lehman Brother's crisis week of Sep 15-19, 2008. HN refers to a trade where HFT demands liquidity from NHFT, and NH is vice versa; HH is a trade between HFTs, and NN is between NHFTs. All liquidity demands and supplies are classified by NASDAQ. The sample is further divided into three sub samples by firm size, according to NASDAQ's classification. T statistics are in ( ) and ***/**/* indicates significance at the 1%/5%/10% level.

Panel A: Overall sample					
	Weeks 1-10	*Weeks 1-9*	*Week 10*	*Weeks1-9*	*Week10*
HH	2,067	1,921	3,356	-1,434***	(-4.53)
HN	2,556	2,376	4,140	-1,765***	(-6.64)
NH	3,366	3,090	5,791	-2,700***	(-4.54)
NN	2,632	2,462	4,131	-1,672***	(-6.74)
liquidity demand: HFT- NHFT	-1,459***	-1,339***	-2,509***	1,170***	(3.6)
	(-23.15)	(-22.4)	(-7.84)		
liquidity supply: HFT-NHFT	162*	88	807	-719	(-1.31)
	(1.69)	(1.02)	(1.49)		
HN-NH	-812***	-716***	-1,651***	937**	(2.32)
	(-6.33)	(-5.88)	(-2.58)		
Panel B: Firm size effect —Normal weeks 1-9					
	Large	*Medium*	*Small*	*Small-Large*	
HH	5,252	225	19	-5,232***	(-31.09)
HN	6,209	710	132	-6,076***	(-45.5)
NH	8,703	418	67	-8,636***	(-31.95)
NN	6,000	978	387	-5,613***	(-45.55)
liquidity demand: HFT- NHFT	-3,245***	-462***	-304***	2,941***	(17.42)
	(-19.25)	(-21.59)	(-33.55)		
liquidity supply: HFT-NHFT	1,745***	-1,047***	-436***	-2,181***	(-8.61)
	(6.89)	(-39.34)	(-33.88)		
HN-NH	-2,491***	293***	68***	2,565***	(14.37)
	(-8.27)	(12.47)	(12.08)		
Panel C: Firm size effect —Crisis week 10					
	Large	Medium	Small	Small-Large	
HH	9,501	314	26	-9,479***	(-12.96)
HN	10,864	1,301	234	-10,629***	(-21.13)
NH	16,696	595	84	-16,612***	(-11.21)
NN	9,971	1,764	659	-9,313***	(-18.28)
liquidity demand: HFT- NHFT	-8,087***	183***	367***	8,454***	(9.95)
	(-9.52)	(3.07)	(13.7)		
liquidity supply: HFT-NHFT	-6,302***	-744***	-482***	5,820***	(6.47)
	(-7.01)	(-9.49)	(-14.26)		
HN-NH	-5,831***	706***	152***	5,983***	(5.24)
	(-3.73)	(6.87)	(6.18)		

Table 2: Weighted average step of order placement

This table presents the *weighted average step* of orders of the 120 sample stocks listed on NYSE and NASDAQ over 10 weeks from 2008 to 2010, including 9 non-crisis weeks and a week 10, the Lehman Brother's crisis week of Sep 15-19, 2008. *Weighted average step* is calculated as:

$$STEP_{HFT,t} = \frac{\Sigma_{i=1}^{10} V_{i,t}^{HFT} N_{i,t}}{\Sigma_{i=1}^{10} V_{i,t}^{HFT}} \qquad STEP_{NHFT,t} = \frac{\Sigma_{i=1}^{10} V_{i,t}^{NHFT} N_{i,t}}{\Sigma_{i=1}^{10} V_{i,t}^{NHFT}}$$

For buy and sell separately, $V_{i,t}^{HFT}$ refers to the number of shares at step *i* provided by HFTs (*i* is from 1 to 10) at minute *t*, and $N_{i,t}$ represents the step number *i* at minute *t*. $STEP_{NHFT,t}$ is defined similarly using NHFT orders. The sample is further divided into 3 sub samples by firm size, according to NASDAQ's classification. T statistics are in ( ) and ***/**/* indicates significance at the 1%/5%/10% level.

Panel A: Overall sample

	Weeks 1-10	*Weeks 1-9*	*Week 10*	*Weeks1-9*	*Week 10*
HFT	5.06	5.12	4.46	0.66***	(11.3)
NHFT	5.87	5.87	5.9	-0.03	(-1.19)
HFT (Displayed)	4.77	4.78	4.7	0.08	(1.13)
NHFT(Displayed)	6.03	6.03	6.02	0.02	(0.79)
HFT (Non-displayed)	4.26	4.42	2.79	1.64***	(33.43)
NHFT(Non-displayed)	4.86	4.86	4.91	-0.05	(-0.81)
NHFT-HFT	0.82***	0.75***	1.44***	-0.69***	(-10.87)
	(37.43)	(32.26)	(24.47)		
(Displayed) NHFT-HFT	1.26***	1.25***	1.31***	-0.05	(-0.8)
	(59.76)	(56.46)	(19.6)		
(Non-displayed) NHFT-HFT	0.6***	0.43***	2.12***	-1.68***	(-21.35)
	(17.24)	(11.59)	(30.32)		

Panel B: Firm size effect—Normal weeks 1-9

	Large	*Medium*	*Small*	*Small-Large*	
HFT	4.32	5.13	5.92	1.6***	(36.56)
NHFT	5.77	5.88	5.95	0.18***	(8.46)
HFT (Displayed)	4.57	4.85	4.92	0.35***	(7.01)
NHFT(Displayed)	5.98	6	6.12	0.15***	(6.73)
HFT (Non-displayed)	2.81	4.61	5.85	3.06***	(50.34)
NHFT(Non-displayed)	4.62	4.96	4.97	0.36***	(8.19)
NHFT-HFT	1.45***	0.75***	0.03	-1.42***	(-30.09)
	(69.08)	(18)	(0.75)		
(Displayed) NHFT-HFT	1.4***	1.15***	1.2***	-0.2***	(-3.76)
	(53.95)	(29.69)	(25.49)		
(Non-displayed) NHFT-HFT	1.82***	0.35***	-0.88***	-2.69***	(-37.65)
	(53.34)	(5.32)	(-13.21)		

	Panel C: Firm size effect — Crisis week 10				Normal - Crisis		
Variable	*Large*	*Medium*	*Small*	*Small-Large*	*Small-Large*		
HFT	4	4.77	4.6	0.59***	(4.73)	1.00***	(6.53)
NHFT	5.83	6.02	5.85	0.02	(0.31)	0.16*	(1.76)
HFT (Displayed)	4.32	5	4.78	0.46***	(2.95)	-0.11	(-0.52)
NHFT(Displayed)	6.21	5.92	5.92	-0.3***	(-6.06)	0.45***	(5.88)
HFT (Non-displayed)	2.89	2.71	2.76	-0.13	(-1.49)	3.17***	(15.3)
NHFT(Non-displayed)	3.83	5.62	5.27	1.44***	(11.4)	-1.08***	(-7.24)
NHFT-HFT	1.82***	1.24***	1.25***	-0.58***	(-4.13)	-0.84***	(-4.38)
	(32.34)	(12.08)	(9.97)				
(Displayed), NHFT-HFT	1.89***	0.92***	1.12***	-0.78***	(-5.13)	0.56**	(2.39)
	(24.01)	(8.42)	(7.76)				
(Non-displayed), NHFT-HFT	0.94***	2.91***	2.51***	1.57***	(10.32)	-4.26***	(-18.5)
	(12)	(26.93)	(19.13)				

Table 3: Weighted average price difference of order placement

This table presents the *weighted average price difference* of orders of the 120 sample stocks listed on NYSE and NASDAQ over 10 weeks from 2008 to 2010, including 9 non-crisis weeks and a week 10, the Lehman Brother's crisis week of Sep 15-19, 2008. *Weighted average price difference* is calculated by using:

$$\%\Delta p_{i,t} = \frac{|P_{i,t} - m_t|}{m_t} * 100\% \quad in \quad Price_{HFT,t} = \frac{\Sigma_{i=1}^{10}(\Delta p_{i,t} * V_{i,t})^{HFT}}{\Sigma_{i=1}^{10} V_{i,t}^{HFT}} \quad and \quad Price_{NHFT,t} = \frac{\Sigma_{i=1}^{10}(\Delta p_{i,t} * V_{i,t})^{NHFT}}{\Sigma_{i=1}^{10} V_{i,t}^{NHFT}}$$

$p_{i,t}$ is the price at step i at minute t; m_t is the average of the best bid and ask prices at minute t; $V_{i,t}^{HFT}$ refers to the number of shares at step i provided by HFTs (i is from 1 to 10) at minute t; $V_{i,t}^{NHFT}$ refers to that from NHFTs. The sample is further divided into 3 sub samples by firm size, according to NASDAQ's classification. T statistics are in ( ) and ***/**/* indicates significance at the 1%/5%/10% level.

Panel A: Overall sample					
	Weeks1-10	*Weeks 1-9*	*Week 10*	*Weeks1-9*	*Week10*
HFT	1.17%	1.15%	1.32%	-0.18%	(-1.51)
NHFT	1.19%	1.14%	1.58%	-0.45%***	(-4.22)
HFT (Displayed)	1.03%	1.00%	1.32%	-0.35%***	(-2.73)
NHFT (Displayed)	1.27%	1.22%	1.74%	-0.53%***	(-4.3)
HFT (Non-displayed)	0.96%	1.00%	0.66%	0.33%***	(8.18)
NHFT (Non-displayed)	0.83%	0.81%	1.00%	-0.2%***	(-4.17)
NHFT-HFT	0.03%	0.00%	0.26%*	-0.26%***	(-2.99)
	(0.57)	(-0.02)	(1.69)		
NHFT-HFT (Displayed)	0.26%***	0.24%***	0.43%**	-0.18%**	(-2.05)
	(5.54)	(4.97)	(-2.53)		
NHFT-HFT (Non-displayed)	-0.13%***	-0.18%***	0.34%***	-0.54%***	(-14.92)

Panel B: Firm size effect —Normal weeks 1-9					
Variable	*Large*	*Medium*	*Small*	*Small-Large*	
HFT	0.18%	0.68%	2.59%	2.37%***	(21.94)
NHFT	0.25%	0.73%	2.45%	2.18%***	(33.29)
HFT (Displayed)	0.17%	0.56%	2.27%	2.01%***	(17.8)
NHFT (Displayed)	0.25%	0.75%	2.66%	2.38%***	(30.9)
HFT (Non-displayed)	0.14%	0.75%	2.11%	1.95%***	(55.28)
NHFT (Non-displayed)	0.20%	0.59%	1.65%	1.43%***	(38.25)
NHFT-HFT	0.07%***	0.05%**	-0.13%	-0.20%***	(-2.62)
	(14.61)	(2.55)	(-1)		
NHFT-HFT (Displayed)	0.08%***	0.2%***	0.45%***	0.34%***	(4.84)
	(16.36)	(9.75)	(3.30)		
NHFT-HFT (Non-displayed)	0.06%***	-0.16%***	-0.46%***	-0.56%***	(-14.45)
	(10.90)	(-8.32)	(-8.96)		

	Panel C: Firm size effect — Crisis week 10				Normal-Crisis		
Variable	*Large*	*Medium*	*Small*	*Small-Large*	*Small-Large*		
HFT	0.19%	0.96%	2.81%	2.62%***	(8.41)	-0.21%	(-0.98)
NHFT	0.28%	1.30%	3.17%	2.89%***	(11.87)	-0.69%***	(-2.82)
HFT (Displayed)	0.18%	0.95%	2.85%	2.65%***	(8.11)	-0.58%**	(-2.5)
NHFT (Displayed)	0.29%	1.29%	3.64%	3.35%***	(11.36)	-0.94%***	(-4)
HFT (Non-displayed)	0.16%	0.46%	1.35%	1.18%***	(13.72)	0.78%***	(4.93)
NHFT (Non-displayed)	0.20%	0.95%	1.85%	1.65%***	(19.15)	-0.20%**	(-2.38)
NHFT-HFT	0.09%***	0.33%**	0.36%	0.27%	(1.13)	-0.48%*	(-1.92)
	(5.41)	(2.26)	(0.92)				
NHFT-HFT (Displayed)	0.12%***	0.34%**	0.82%*	0.68%***	(2.75)	-0.48%	(-1.01)
	(6.72)	(2.37)	(1.86)				
NHFT-HFT (Non-displayed)	0.04%**	0.49%***	0.5%***	0.47%***	(5.8)	-0.99%***	(-7.06)
	(2.28)	(7.39)	(4.18)				

Table 4: HFT/NHFT trading on weighted average step by HFT order placement

This table reports the panel regression results on *weighted average step by HFT* order placement of the 120 sample stocks listed on NYSE and NASDAQ over 10 weeks from 2008 to 2010, including 9 non-crisis weeks and a week 10, the Lehman Brother's crisis week of Sep 15-19, 2008. All the variables are stock specific. *Weighted average step by HFT* is the share-weighted average step from HFT orders each minute, defined in Table 2. HH measures the average number of transactions between HFTs per minute, and NN is that between NHFTs. HN measures the average number of trades per minute in which an HFT firm demands liquidity from a NHFT firm, and NH is vice versa. All liquidity demands and supplies are classified by NASDAQ. RETURN is the minute-level return of m_t, the average of the best bid and ask prices at minute t. OPEN (CLOSE) is a time dummy variable which equals to one for the first (last) fifteen minutes of each trading day. T statistics are in ( ) and ***/**/* indicates significance at the 1%/5%/10% level.

	(1) *Weeks1-10*	*(2)* *Weeks1-9*	*(3)* *Week10*	*(2) VS (3)* *P-value*
HH	-0.008***	-0.008***	-0.006	0.82
	(-4.58)	(-4.63)	(-1.45)	
HN	-0.020***	-0.021***	0.021***	0.00
	(-11.86)	(-11.85)	(5.16)	
NH	-0.035***	-0.040***	-0.017***	0.00
	(-33.93)	(-35.21)	(-6.20)	
NN	0.047***	0.056***	0.062***	0.59
	(28.24)	(31.09)	(15.00)	
RETURN	-6.778	-13.620	44.292**	
	(-0.87)	(-1.60)	(2.53)	
OPEN	1.954***	2.138***	-0.364*	
	(28.56)	(29.87)	(-1.79)	
CLOSE	0.973***	0.742***	0.695***	
	(15.78)	(11.53)	(3.68)	
CONSTANT	47.471***	47.857***	43.437***	
	(2715.19)	(2628.74)	(724.15)	
N	1,579,683	1,400,280	179,403	
r^2	0.00	0.00	0.00	
r^2_adjusted	0.00	0.00	0.00	
r^2_between panel	0.14	0.13	0.13	
r^2_within panel	0.00	0.00	0.00	

Table 5: HFT/NHFT trading on weighted average Step by NHFT order placement

This table reports the panel regression results on *weighted average step by NHFT* order placement of the 120 sample stocks listed on NYSE and NASDAQ over 10 weeks from 2008 to 2010, including 9 non-crisis weeks and a week 10, the Lehman Brother's crisis week of Sep 15-19, 2008. All the variables are stock specific. *Weighted average step by NHFT* is the share-weighted average step from NHFT orders each minute, defined in Table 2. HH measures the average number of trades between HFTs per minute, and NN is that between NHFTs. HN measures the average number of trades per minute in which an HFT firm demands liquidity from a NHFT firm, and NH is vice versa. All liquidity demands and supplies are classified by NASDAQ. RETURN is the minute-level return of m_t, the average of the best bid and ask prices at minute *t*. OPEN (CLOSE) is a time dummy variable which equals to one for the first (last) fifteen minutes of each trading day. T statistics are in ( ) and ***/**/* indicates significance at the 1%/5%/10% level.

	(1) *Weeks 1-10*	*(2)* *Weeks 1-9*	*(3)* *Week 10*	*(2) VS (3)* *P-value*
HH	0.080***	0.076***	0.096***	0.03
	(65.45)	(57.39)	(29.23)	
HN	-0.051***	-0.046***	-0.105***	0.00
	(-42.25)	(-34.75)	(-33.93)	
NH	0.054***	0.057***	0.042***	0.01
	(71.49)	(70.17)	(19.78)	
NN	-0.138***	-0.139***	-0.144***	0.58
	(-114.44)	(-106.12)	(-45.62)	
RETURN	-13.104**	-8.332	-30.169**	
	(-2.33)	(-1.35)	(-2.30)	
OPEN	0.797***	0.975***	-0.634***	
	(16.11)	(18.73)	(-4.14)	
CLOSE	-0.375***	-0.322***	-0.624***	
	(-8.42)	(-6.88)	(-4.50)	
CONSTANT	60.169***	60.041***	61.608***	
	(4767.44)	(4541.41)	(1382.87)	
N	1,614,177	1,427,616	186,561	
r^2	0.02	0.02	0.03	
r^2_adjusted	0.02	0.02	0.03	
r^2_between panel	0.15	0.15	0.01	
r^2_within panel	0.02	0.02	0.03	

Table 6: HFT/NHFT trading on weighed average price difference by HFT order placement

This table reports the panel regression results on *weighted average price difference by HFT* order placement of the 120 sample stocks listed on NYSE and NASDAQ over 10 weeks from 2008 to 2010, including 9 non-crisis weeks and a week 10, the Lehman Brother's crisis week of Sep 15-19, 2008. All the variables are stock specific. *Weighted average price difference by HFT* is the share-weighted price difference of HFT orders each minute, defined in Table 3. HH measures the average number of trades between HFTs per minute, and NN is that between NHFTs. HN measures the average number of trades per minute in which an HFT firm demands liquidity from a NHFT firm, and NH is vice versa. All liquidity demands and supplies are classified by NASDAQ. RETURN is the minute-level return of m_t, the average of the best bid and ask prices at t. OPEN (CLOSE) is a time dummy variable which equals to one for the first (last) fifteen minutes of each trading day. T statistics are in ( ) and ***/**/* indicates significance at the 1%/5%/10% level.

	(1) *Weeks 1-10*	*(2)* *Weeks 1-9*	*(3)* *Week 10*	*(2) VS (3)* *P-value*
HH	0.001**	0.001*	0.001	0.99
	(1.99)	(1.93)	(0.51)	
HN	-0.003***	-0.002***	-0.007***	0.05
	(-4.62)	(-2.92)	(-2.92)	
NH	-0.007***	-0.006***	-0.008***	0.24
	(-15.76)	(-14.13)	(-4.77)	
NN	0.010***	0.008***	0.016***	0.05
	(14.45)	(11.04)	(6.31)	
RETURN	-19.175***	-28.288***	22.692**	
	(-5.86)	(-8.46)	(2.13)	
OPEN	4.185***	3.950***	6.266***	
	(145.50)	(140.96)	(50.46)	
CLOSE	-0.768***	-0.912***	0.509***	
	(-29.61)	(-36.19)	(4.41)	
CONSTANT	5.743***	5.626***	6.674***	
	(781.20)	(789.33)	(182.33)	
N	1,579,683	1,400,280	179,403	
r^2	0.01	0.02	0.02	
r^2_adjusted	0.01	0.02	0.01	
r^2_between panel	0.01	0.03	0.00	
r^2_within panel	0.01	0.02	0.02	

Table 7: HFT/NHFT trading on weighted average price difference by NHFT order placement

This table reports the panel regression results on *weighted average price difference by NHFT* order placement of the 120 sample stocks listed on NYSE and NASDAQ over 10 weeks from 2008 to 2010, including 9 non-crisis weeks and a week 10, the Lehman Brother's crisis week of Sep 15-19, 2008. All the variables are stock specific. *Weighted average price difference by NHFT* is the share-weighted price difference of NHFT orders each minute, defined in Table 3. HH measures the average number of trades between HFTs per minute, and NN is that between NHFTs. HN measures the average number of trades per minute in which an HFT firm demands liquidity from a NHFT firm, and NH is vice versa. All liquidity demands and supplies are classified by NASDAQ. RETURN is the minute-level return of m_t, the average of the best bid and ask prices at *t*. OPEN (CLOSE) is a time dummy variable which equals to one for the first (last) fifteen minutes of each trading day. T statistics are in ( ) and ***/**/* indicates significance at the 1%/5%/10% level.

	(1) *Weeks 1-10*	*(2)* *Weeks 1-9*	*(3)* *Week 10*	*(2) VS (3)* *P-value*
HH	0.005***	0.005***	0.005**	0.96
	(8.23)	(7.93)	(2.34)	
HN	-0.004***	-0.002***	-0.017***	0.00
	(-6.63)	(-3.70)	(-7.88)	
NH	-0.002***	-0.000	-0.002	0.28
	(-5.36)	(-1.15)	(-1.64)	
NN	0.001**	-0.003***	0.002	0.30
	(1.99)	(-4.99)	(-1.02)	
RETURN	-10.603***	-23.665***	26.414***	
	(-3.61)	(-7.87)	(2.97)	
OPEN	5.640***	4.980***	11.497***	
	(217.56)	(196.93)	(110.66)	
CLOSE	-1.173***	-1.164***	-0.632***	
	(-50.34)	(-51.21)	(-6.71)	
CONSTANT	6.581***	6.264***	9.152***	
	(995.70)	(975.54)	(302.73)	
N	1,614,177	1,427,616	186,561	
r^2	0.03	0.03	0.06	
r^2_adjusted	0.03	0.03	0.06	
r^2_between panel	0.24	0.21	0.15	
r^2_within panel	0.03	0.03	0.06	

