Need for Speed: An Empirical Analysis of Hard and Soft Information in a High Frequency World

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Abstract

Speed matters for the processing of market relevant information and for stock price discovery. We measure and compare the impact of different types of information events on high-frequency trading (HFT) and non-HFT (NHFT) based on a NASDAQ high-frequency dataset. Information events are categorized into hard quantitative information shocks and soft qualitative shocks. We find that HFT reaction to hard information is stronger and faster than for soft information while NHFT reaction is stronger and slower for soft information. The HFT reaction is also reflected in trading profits: HFT profits after futures shocks are short-lived and highest in the short run. On the contrary, VIX and news shocks lead to increasing HFT profits. Furthermore, initiating traders and passive traders complement one another in price discovery: Initiating HFT have a higher influence on short-term price discovery than initiating NHFT and increasingly after hard information shocks. Passive NHFT on the other side have a higher influence in the long run and increasingly after soft information shocks.

Keywords: High-Frequency Trading, Algorithmic Trading, Information, News Trading, Price Discovery

JEL G10, G14

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June 21, 2012
1. Introduction

Due to the ever increasing possibilities of technological innovations on financial markets, speed has become a competitive edge for trading participants, especially for high-frequency traders (HFT; also used for high-frequency trading). HFT is a subcategory of algorithmic trading (AT) which is commonly defined as the use of computer algorithms to support the trading process (cf. Hendershott et al., 2011). HFT distinguish themselves from other algorithms by their sophisticated trading strategies and their high trading volume and speed. The most commonly used strategies are market making strategies which provide liquidity and make profits from bid-ask spreads and liquidity rebates (rewards provided by trading venues to liquidity providers). In practice, a new generation of news processing algorithms seems to have arrived to the market and more investments are being made in the area of machine-readable news.\footnote{See “Computers that trade on the news”, \textit{New York Times}, December 22nd, 2010. Recent investments have been made by NASDAQ and Deutsche Börse in 2011 to integrate machine-readable economic news into their line of services offered for trading firms and specifically automated traders (cf. “NASDAQ pushes into machine-readable news”, \textit{Wall Street Journal}, December 19th, 2011).} One may infer a development of HFT from the domain on hard quantitative information to the processing of soft qualitative information (cf. Jovanovic and Menkveld, 2011). However, the question remains whether computers are sufficiently sophisticated to actually trade on news and market sentiment. Furthermore, does speed (and thus HFT technology) matter for the processing of different types of financial information?

The goal of this paper is to analyze whether their competitive edge in speed helps HFT to react to specific types of information events faster than to other events and to subsequently lead price discovery and realize trading profits. Our contribution is threefold: Firstly, we measure the impact of hard and soft information shocks and their duration on HFT and non-high-frequency traders (NHFT). Hard quantitative information shocks are proxied by abnormally high market futures returns and market volatility changes. Soft qualitative information shocks are represented by news arrivals. Secondly, the influence
of HFT and NHFT on market returns and thus the contribution to price discovery is measured and compared. Thirdly, we characterize information events with respect to their profitability for HFT and NHFT. We distinguish between influence in the short and long run and periods with and without specific information shocks. The results show that HFT reaction to hard information is stronger and faster than for soft information. Results on trading profits confirm that HFT profits after hard futures return shocks are highest in the short run and decreasing afterwards. NHFT on the other side react more to soft news ticker information and contribute to long-term price discovery. Furthermore, we find that initiating traders and passive traders complement each other: On one side, HFT that initiate trades using marketable orders have a higher influence on market returns and thus price discovery in the short run. Their influence increases after hard information shocks. On the other side, passive NHFT that use limit orders lead price discovery in the long run and increasingly after soft information shocks.

We contribute to the HFT and price discovery literature by analyzing different reactions of HFT and NHFT to hard and soft information events. The analyses are based on a NASDAQ high-frequency dataset from 2008 to 2009 that identifies HFT and NHFT as initiating and passive part of the trade. We apply and extend vector autoregressive (VAR) models that are rooted in the market microstructure model by Hasbrouck (1991). Firstly, our results show the influence of information events on trading based on an extension of the model by Chaboud et al. (2009). Secondly, an adaption of the model of Tookes (2008) illustrates the informational flow between HFT, NHFT and returns.

The remainder of the paper is structured as follows. Section 2 presents related research on HFT, its impact on market quality and price discovery, and information related literature. Section 3 describes our data and the sample on which the analyses are based. Section 4 presents correlation results. Section 5 and presents results on the impact of different information events on HFT and NHFT. Section 6 discusses the role HFT and NHFT play in price discovery in general and after information events. Section 7 presents results on HFT profits after information events. Section 8 finally concludes.
2. Related Literature

The overview of existing literature is structured into three parts: (1) HFT, Information, and Price Discovery, (2) HFT and Market Quality, and (3) Information events and their impact on stock markets.

With respect to the influence of HFT on price discovery, Hendershott and Riordan (2012b) use a state space model to decompose the market return time series into a transitory component (i.e. pricing errors) and a permanent component (i.e. permanent price changes). They find a positive relationship of HFT initiated trades with permanent price changes and opposite trading of HFT passive trades to permanent price changes and in the same direction as pricing errors. O’Hara et al. (2011) study the contribution of odd-lot trades to price discovery. They show that odd-lot trades account for 30% of price discovery. Chaboud et al. (2009) show that AT withdraw from the market after macroeconomic news announcements. This finding is confirmed by Brogaard (2011b) who shows a decrease in initiating trading volume around news events for some stocks. We help to fill this gap with our analyses on intraday news ticker events and the distinction between different time periods of reaction for HFT and NHFT. The consideration of different time periods is important since literature has shown that latency matters for traders and exchanges in terms of trading activity and market quality (cf. Hendershott and Moulton (2011) among others).

Our paper is closely related to the theoretical findings of Martinez and Rosu (2011). They explicitly assume level aversion for HFT, meaning that HFT rather trade on price changes than on the fundamental value of assets. In the case of extreme level aversion, they show that with increasing news precision, trading volume and the informed variance ratio increases among others. We can empirically confirm the result on trading volume and the assumption of HFT level aversion by the positive correlation of net trading, absolute

3Odd-lot trades are trades below 100 shares. They are often used by AT and HFT as a result of slicing large orders into smaller ones in order to hide trading intentions.
trading, and profits with the hardness of information events. In their theoretical model, Biais et al. (2010) show that HFT increase adverse selection costs for slower traders, which subsequently lowers social welfare. Cartea and Penalva (2011) model a market with liquidity traders, market makers, and HFT. They find that HFT increase price volatility, trade volume, and may decrease liquidity.

A major concern of regulatory authorities, such as the U.S. Securities and Exchange Commission (SEC), is the influence of HFT on market quality (cf. the call of comments of the SEC (2010)). In answer to this call for comments, empirical evidence of positive impact of HFT and AT on liquidity has been provided (e.g. Hendershott et al. (2011), Chaboud et al. (2009), and Hendershott and Riordan (2012a) among others). Menkveld (2011) further analyzes the influence and profitability of a HFT market-maker on Chi-X. Recent events, such as the “Flash Crash” on May 10th, 2010\(^4\), has further drawn the public attention to HFT. Kirilenko and Kyle (2011) find that HFT did not trigger the “Flash Crash”, but exacerbated market volatility during this extreme event. Easley et al. (2010) find that order flow toxicity\(^5\) increases before the “Flash Crash” took place. Zhang (2010) finds a significantly higher contribution of HFT to price volatility after a firm’s fundamental news.\(^6\) On the contrary, HFT does not seem to exacerbate market volatility under normal market conditions. Chaboud et al. (2009) and Brogaard (2011b) find no effect of HFT increasing market volatility. A general overview of the topic HFT, recent discussions and research is provided by Biais and Woolley (2011) and Gomber et al. (2010).

Various types of information events and their effect on financial markets have been analyzed, such as macroeconomic and earnings announcements, news arrivals among others. A general classification of information is provided by Jovanovic and Menkveld (2011) who distinguish between hard and soft information as we also do in our paper. They find a positive relationship between HFT activity and the amount of hard information. Petersen

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\(^4\)On May 10th, 2010, the Dow Jones Industrial Average dropped rapidly by 10% with a similarly rapid recovery within half an hour.

\(^5\)measured by the Volume-Synchronized Probability of Informed Trading, VPIN

\(^6\)Zhang (2010) uses trading activity by hedge funds and small institutional traders as a proxy for HFT.
(2004) characterizes hard information as quantitative and easily processable and storable by computers, such as stock prices and market indices. Soft information on the contrary is qualitative and hard to interpret by computers, e.g. news ticker items, blog posts or even Twitter messages. Though the classification seems intuitive, a clear distinction of both groups is difficult in a lot of cases. In this context, Petersen (2004) mentions the possibility of hardening soft information with the use of algorithms. The automatic transformation of textual information into numbers has made the border between hard and soft information even more blurred and offers opportunities to include this information in trading strategies. Literature on soft information used different information types, such as a Wall Street Journal column (Tetlock, 2007), newswire messages (Tetlock, 2010), and Internet stock messages (Antweiler and Frank, 2004). Current research in computer science is further evolving to use social media, such as Twitter messages, to predict box-office revenues for movies (Asur, 2010) and market returns (Bollen and Mao, 2011). In our paper, we focus on news ticker data. It is professionally processed by algorithms of the Reuters News Sentiment Engine which is used by practitioners and academics. The same news dataset is analyzed by Groß-Klußmann and Hautsch (2011) who find that trading volume and spread measures increase around news events.

3. Data and Sample Selection

There are few datasets available that directly identify AT and HFT. Datasets used in research often use proxies of HFT and AT (such as Hendershott et al. (2011), Hasbrouck and Saar (2010), and Zhang (2010)). Only recently, data with specific AT and HFT identifiers have become available. Hendershott and Riordan (2012a) use data from Deutsche Börse in Germany. The same dataset as in our paper is also used for research by Hendershott and Riordan (2012b), O’Hara et al. (2011), and Brogaard (2011b).

We use high-frequency information datasets and high-frequency trade data. Trade data is tick-by-tick data time-stamped to milliseconds and identifies the liquidity demander and liquidity supplier of a trade as a HFT or NHFT. It is based on a dataset provided
by NASDAQ\textsuperscript{7} and covers the years 2008 and 2009. The information datasets include abnormally high and low S&P 500 future returns and VIX returns as hard information shocks and Reuters news ticker data as soft information shocks.

3.1. Sample Descriptives

We restrict our data sample to 40 stocks listed in the S&P 500 index which provide a sufficiently high number of high-frequency trades and news items. The minimum number of HF trades per day is 125. Therefore we believe that the chosen sample provides sufficient observations for analysis. The final stock sample consists of 40 stocks listed in the S&P 500 index, 20 listed on NYSE and 20 listed on NASDAQ. We distinguish between the HFT group demanding liquidity (\(HFT_{\text{init}}\)) and supplying liquidity (\(HFT_{\text{pass}}\)) as well as the corresponding NHFT group demanding liquidity (\(NHFT_{\text{init}}\)) and supplying liquidity (\(NHFT_{\text{pass}}\)). Only continuous trading is considered in order to measure the direct intra-day reaction after an information event. The first and last five minutes of each trading day are omitted in order to leave out trading on overnight information and biases associated with market opening/closing, i.e. the data spans from 9:35 a.m. to 3:55 p.m. Descriptives of the data sample are shown in Table 1. The complete list of sample stocks and relative portion of HFT can be found in the Appendix A, Table A.1.

3.2. Hard and Soft Information

Information events are manifold and can be categorized based on a number of dimensions. Following Jovanovic and Menkveld (2011), we distinguish between “hard” and “soft” information events as described in Section 2. We present the three chosen proxies for information events, futures return shocks, news events, and VIX return shocks and discuss

\textsuperscript{7}We thank Frank Hathaway and Jeff Smith for providing access to the data as well as Terrence Hendershott and Ryan Riordan for compiling the dataset. For further information on the dataset see Hendershott and Riordan (2012b).
their characteristics in more detail. They are derived from recent literature and fulfill the requirement of exogeneity in order to run a de facto impulse response analysis in Section 5.

For hard information shocks, we choose S&P 500 futures return shocks and volatility index (VIX) price return shocks. S&P 500 futures prices and VIX prices are collected on a tick by tick basis from Thomson Reuters Tick History.\(^8\) Jovanovic and Menkveld (2011) propose the R squared of a capital asset pricing model (CAPM) based on stock returns and market futures returns as a proxy for the relevance of hard information. Hence, we consider market futures returns as a proxy for hard information. We exclude the first and last 5 minutes of the trading day and determine the 1% and 99% percentiles of S&P 500 futures 10 second returns over the whole observation period. Returns above the 99% and below the 1% level are considered as futures return shocks.

We also include VIX prices in our analysis. The VIX is published by the Chicago Board Options Exchange (CBOE) and is constructed from the implied near-term volatility of S&P 500 stock index option prices.\(^9\) Brogaard (2011b) shows in his analysis that VIX is positively related to HFT trading activity. Similar to futures returns, VIX price returns can be easily processed by HFT and therefore qualify as hard information. Similarly with the analysis of futures returns, we also analyze the relationship of abnormally high and low VIX returns and subsequent HFT and NHFT activity.

News data serves as a proxy for soft information. The news dataset is provided by Thomson Reuters and contains firm-specific newswire items time-stamped to milliseconds. The dataset is pre-processed by Reuters Newsscope Sentiment Engine (RNSE) which allows a differentiation of news items on the basis of two indicators, Sentiment, and Relevance. Sentiment can be either negative (-1), neutral (0), or positive (+1) depending on the news item. We only consider positive and negative news items during continuous trading hours which are relevant to the specific stock (Relevance = 1). Furthermore, news

\(^8\)We thank SIRCA for providing access to the Thomson Reuters DataScope Tick History.

items with identical news IDs within the same day are deleted.

The distinction between hard and soft information can be ambiguous. Futures returns are quantitative information and can be interpreted relatively easily. VIX is quantitative as well, but also represents market sentiment. The interpretation of such a quantitative measure and its return shocks involves a higher uncertainty about the market reaction to this information event than to futures shocks. Thus, the hardness of financial information should also include the certainty about its interpretation. Newswire items are classically categorized as soft information and can also lead to ambiguous market reactions. The descriptives of the chosen hard and soft information events are presented in Panel B and Panel C of Table 1.

4. Correlation Results

Correlation results on trading variables and information event dummies give us first indications of trading behavior after information events. Trade variables in Panel A are net trading volume, i.e. buyer-initiated minus seller-initiated volume to accurately measure the information flow of different trader groups (e.g. Chaboud et al. (2009), Tookes (2008)). In Panel B, we analyze absolute trading volume and illiquidity after information events. Return and trade variables are standardized by the mean and standard deviation of the respective stock-day which makes results comparable across firms. Results are presented in Table 2.

[INSERT TABLE 2 HERE]

The results in Panel A show positive contemporaneous correlations of HFT initiated volume \( (HFT_{init}) \) and NHFT initiated volume \( (NHFT_{init}) \) with futures shocks and negative correlations with the corresponding passive trade variables \( (HFT_{pass} \) and \( NHFT_{pass} \). VIX returns are positively related to \( HFT_{init} \) and \( HFT_{pass} \) for all lags and negatively to initiating NHFT volume. News sentiment has the highest positive relationship with \( NHFT_{init} \). In order to rule out interrelationships between the information events, we also
compute correlations of futures and VIX returns and news sentiment. Correlations with news sentiment are negative and low, with the maximum correlation being 0.16% for both futures and VIX and the minimum being -0.19%. In conclusion, we find low correlations between the chosen information events and thus low interrelationships between them.

In Panel B, we present results for absolute trading variables. According to findings by Martinez and Rosu (2011), trading volume and illiquidity increases with news precision. Equating news precision with the hardness of information, we can confirm these findings: We see a higher effect on absolute trading volume and on illiquidity after hard futures shocks and a lower effect after soft news shocks.

5. The Impact of Information Events on Net Trading

In order to answer the question what type of impact information events have on trading behavior, we implement a VARX model based on models of Hasbrouck (1991) and Chaboud et al. (2009). Our VARX model includes one stock return time series and one HFT and one NHFT order flow time series. We also control for $k$ lags of stock return, HFT order flow, and NHFT order flow. $W$ denotes the relevant lags after an information shock. The coefficients of interest are $\phi_{i,w}^h$ and $\phi_{i,w}^n$ which represent HFT and NHFT behavior after exogenous information shocks. The subscript $i$ denotes the stock, $w$ denotes lags after an information event. The VARX model is implemented as follows:

$$V_{i,t}^h = \alpha_i^h + \sum_{j=1}^{k} \beta_{i,j}^h V_{i,t-j}^h + \sum_{j=0}^{k} \gamma_{i,j}^h V_{i,t-j}^n + \sum_{j=0}^{k} \delta_{i,j}^h r_{i,t-j} + \sum_{w=0}^{W} \phi_{i,w}^h D_{i,w} + \epsilon_{i,t}^h$$

$$V_{i,t}^n = \alpha_i^n + \sum_{j=0}^{k} \beta_{i,j}^n V_{i,t-j}^h + \sum_{j=1}^{k} \gamma_{i,j}^n V_{i,t-j}^n + \sum_{j=0}^{k} \delta_{i,j}^n r_{i,t-j} + \sum_{w=0}^{W} \phi_{i,w}^n D_{i,w} + \epsilon_{i,t}^n$$

$$r_{i,t} = \alpha_i^r + \sum_{j=0}^{k} \beta_{i,j}^r V_{i,t-j}^h + \sum_{j=0}^{k} \gamma_{i,j}^r V_{i,t-j}^n + \sum_{j=1}^{k} \delta_{i,j}^r r_{i,t-j} + \sum_{w=0}^{W} \phi_{i,w}^r D_{i,w} + \epsilon_{i,t}^r$$

The quoted spread is computed as $Qspread_{i,t} = (AskPrice_{i,t} - BidPrice_{i,t})/Mid_{i,t}$ for stock $i$ and time $t$. $Qspread$ is a measure for execution costs of a trade and thus for market illiquidity.
where \( t \) denotes the respective 10s interval. \( V_{i,t} \) is the signed net order flow (buyer-initiated volume minus seller-initiated volume) of HFT (superscript \( h \)) and NHFT (superscript \( n \)) respectively, standardized by mean and standard deviation of the respective stock-day. The model is applied to HFT and NHFT initiated net order flow (\( HFT_{init}, NHFT_{init} \)) as well as passive net order flow (\( HFT_{pass}, NHFT_{pass} \)). For the VARX model, we choose lag length \( k = 12 \) and \( W = 12 \), i.e. 2 minutes, in order to gain a comprehensive insight into short and long run behavior for HFT. \( r_{i,t} \) is the standardized return. The coefficients are \( \beta_i, \gamma_i, \) and \( \delta_i \), where superscripts \( h, n, \) and \( r \) denote HFT, NHFT, and return respectively. \( \alpha_i \) are intercepts and \( \epsilon_{i,t} \) error terms. \( D_{i,w} \) is a dummy variable and equals one if a positive information shock occurs, -1 if a negative information shock occurs in \( t \) or less than \( W \) 10s intervals before \( t \), and 0 otherwise. Results are reported for the contemporaneous impact in the short run (\( SR; \phi_{i,0}^h \) and \( \phi_{i,0}^n \)), the aggregated impact in the long run (\( LR; \sum_{w=0}^{12} \phi_{i,w}^h \) and \( \sum_{w=0}^{12} \phi_{i,w}^n \)) and the difference, i.e. the long run impact minus the short run reaction (\( LR - SR; \sum_{w=1}^{12} \phi_{i,w}^h \) and \( \sum_{w=1}^{12} \phi_{i,w}^n \)).

5.1. Results for Hard and Soft Information Shocks

The model in Equation (1) is estimated as a dynamic simultaneous equation model using two-step least squares. The model is applied to all three information events and the stated hypotheses are tested. We are specifically interested in the trade reaction in the short and long run. Table 3 presents the aggregated coefficients of the VARX model for S&P 500 futures return shocks in Panel A, VIX shocks in Panel B, and news events in Panel C of the sample from 2008-2009. Results for initiated trades of HFT (\( HFT_{init} \)) and NHFT (\( NHFT_{init} \)) and their difference (\( Diff \)) are on the left hand side and results for passive trades on the right hand side. The last column depicts the results for \( HFT_{alt} \), the sum of \( HFT_{init} \) and \( HFT_{pass} \). The corresponding results for \( NHFT_{alt} \) would be the negative value of \( HFT_{alt} \) since all trades are exhaustively indexed with HFT and NHFT identifiers.

[INSERT TABLE 3 HERE]
The rationale of interpretation is a higher and positive net trading, i.e. more buy than sell orders, after positive information shocks and lower and negative net trading after negative information shocks. The information shocks are represented by directed dummies $D_{i,w}$ as mentioned above, i.e. -1 for negative shocks and +1 for positive shocks. Thus, the coefficients of the model can be interpreted as the impact of a directed information shock on net trading in the same direction.

As shown in Panel A, initiating HFT show a significant and positive reaction to futures shocks in the short run (0.240) and invert their trading behavior within two minutes in the long run (-0.249 in LR-SR). Differently, NHFT exhibit a continuously positive reaction (0.179 in the short run and 0.350 in the long run). As a consequence, the difference of HFT and NHFT initiated trading, $Diff$, results in a positive coefficient in the short run (0.061), but a negative coefficient in the long run (-0.420 in LR-SR). The different reaction of HFT and NHFT can be interpreted that HFT are able to react faster to hard information shocks, such as futures return shocks. In the long run, they trade in the opposite direction of the futures shock. This points to a reduction of their trading positions and thus a realization of their short-term profits.

Panel B presents the aggregated coefficients of the VARX model in Equation (1) for VIX return shocks. Brogaard (2011b) suggests an increase in HFT volume for periods of high volatility as proxied by the VIX. We provide further insight into the trading behavior of HFT for periods of extremely high volatility events, measured by VIX return shocks above the 99% level and below the 1% level. Our results suggest a consistent trading behavior of HFT around VIX return shocks. Initiating and passive HFT demonstrate consistently net trading in the same direction as the specific VIX shock, i.e. positive net trading after positive VIX shocks and negative net trading after negative ones. On the other side, initiating NHFT exhibit a trading behavior in the opposite direction to HFT for VIX shocks. Passive NHFT show a similar behavior though results are not significant. Comparing the results for hard information, we see two different reactions to hard information shocks: While futures return shocks seem to induce a strong short-term
reaction of HFT, positive VIX return shocks lead to more long-term reaction and an increase in net trading of HFT. NHFT reaction is weaker in the short run and increases in the long run for futures shocks. Different to HFT, they increase their net trading in periods of low volatility.

In comparison to hard information, the reaction to soft information is different. Though both initiating HFT and NHFT trade in the right direction, NHFT demonstrate a significantly stronger reaction especially in the long run (0.408 as compared to 0.142 in the long run). Thus we conclude that NHFT are able to process soft information more accurately, but need time for its interpretation. Passive traders get adversely selected and NHFT get less adversely selected than HFT. An explanation for the stronger NHFT reaction can be different trading strategies. Although the news data source is reliable and also used by trading firms\textsuperscript{11}, the actual trading strategies are not known. As proposed by Rich Brown\textsuperscript{12} from Thomson Reuters, news ticker data can be used as a circuit breaker. By interpreting stock specific news arrival as a signal for proximate stock price volatility, a trading halt is triggered on their arrival in order to reduce the risk of uncertainty about the following stock price reaction.

We compare the difference in reaction to hard and soft information in Panel D. The differences are especially high in the short run since HFT react stronger to hard information and get less adversely selected. Differently, they trade in the opposite direction in the long run which indicates that they realized their profits within a short timeframe. We discuss trading profits in Section 7 below.

5.2. Robustness Checks

Results for positive and negative shocks separately can be found in Appendix B, Table B.1, Table B.2, and Table B.3. The results for futures shocks are consistent for both positive and negative shocks. Interestingly, there is a stronger reaction to positive news

\textsuperscript{11}cf. Thomson Reuters News Analytics Fact sheet, \url{http://thomsonreuters.com/content/financial/pdf/enterprise/News_Analytics.pdf}.

events. On the other side, passive order flow gets adversely selected: HFT and NHFT exhibit negatively directed net trading in the short and long run. Passive HFT get less adversely selected than NHFT after futures return shocks in the short run, but differences are not significant. We also account for different ordering of order flows in the VARX model. The model is implemented under the assumption that HFT order flow occurs prior to NHFT order flow. Implementing the model with reverse ordering, we see in Appendix B, Table B.5 that the results are not qualitatively different.

Furthermore, in order to check for robustness of the results for different time periods, we perform the analysis separately for time periods of high uncertainty (during the financial crisis from September 2008 to June 2009) and low uncertainty (pre- and post financial crisis). We choose time periods according to the VIX value which increased to above 30 in September 2008 and decreased again below 30 in July 2009. The results hold for both futures shocks and VIX shocks. We can see a higher reaction of HFT in the financial crisis period.

From these observations we can conclude that processing speed matters especially for hard information. The competitive edge of HFT in speed is needed to react to hard information shocks faster and stronger. We interpret the inverting behavior of HFT shortly after the information shock as a strategy to realize profits from this shock. We discuss trading profits in the Section 7. The NHFT group is slower and also trades on hard information for a longer time period (which might have already become “stale”) or new soft information which is harder to interpret and involves more risk in the interpretation. This leads to the question whether HFT actually do cream-skimming since they trade on information within the first ten seconds after information arrivals and cash in their secure profits directly afterwards. This trading strategy could also cause a stronger overreaction of information events and deteriorate price efficiency.
6. The Influence of Information Events on Price Discovery

We discussed different effects of information events on net trading in Section 5. In the following section, we further analyze which group of traders has a stronger influence on price discovery around the studied information events. Our second model takes a closer look on informed trading of different trader groups by incorporating interaction variables according to Tookes (2008). We restrict the models to periods after the information shock and use variables aggregated to ten second intervals. The VAR model is implemented as follows:

\[ V_{i,t}^h = \alpha_{i,t}^h + \sum_{j=1}^{k} \beta_{i,j}^h V_{i,t-j}^h + \sum_{j=0}^{k} \gamma_{i,j}^h V_{i,t-j}^n + \sum_{j=0}^{k} \delta_{i,j}^h r_{i,t-j} \]
\[ + \sum_{w=1}^{W} D_{i,w} \left( \sum_{j=1}^{k} \beta_{i,j}^{h,w} V_{i,t-j}^h + \sum_{j=0}^{k} \gamma_{i,j}^{h,w} V_{i,t-j}^n + \sum_{j=0}^{k} \delta_{i,j}^{h,w} r_{i,t-j} \right) + \epsilon_{i,t}^h \]

\[ V_{i,t}^n = \alpha_{i,t}^n + \sum_{j=0}^{k} \beta_{i,j}^n V_{i,t-j}^h + \sum_{j=0}^{k} \gamma_{i,j}^n V_{i,t-j}^n + \sum_{j=0}^{k} \delta_{i,j}^n r_{i,t-j} \]
\[ + \sum_{w=1}^{W} D_{i,w} \left( \sum_{j=0}^{k} \beta_{i,j}^{n,w} V_{i,t-j}^h + \sum_{j=0}^{k} \gamma_{i,j}^{n,w} V_{i,t-j}^n + \sum_{j=0}^{k} \delta_{i,j}^{n,w} r_{i,t-j} \right) + \epsilon_{i,t}^n \]

\[ r_{i,t} = \alpha_{i,t}^r + \sum_{j=0}^{k} \beta_{i,j}^r V_{i,t-j}^h + \sum_{j=0}^{k} \gamma_{i,j}^r V_{i,t-j}^n + \sum_{j=0}^{k} \delta_{i,j}^r r_{i,t-j} \]
\[ + \sum_{w=1}^{W} D_{i,w} \left( \sum_{j=0}^{k} \beta_{i,j}^{r,w} V_{i,t-j}^h + \sum_{j=0}^{k} \gamma_{i,j}^{r,w} V_{i,t-j}^n + \sum_{j=0}^{k} \delta_{i,j}^{r,w} r_{i,t-j} \right) + \epsilon_{i,t}^r \]

The model specifications in Equation (2) is the same as in Equation (1), only the interaction terms are added. \( D_{i,w} \) is +1 if an information events occurs and 0 otherwise. We test whether in times with information events, HFT order has a significant influence on NHFT order flow and vice versa and whether HFT / NHFT order flow has a significant effect on market returns. We estimate the equations as a dynamic simultaneous equation model using two-step least squares for all three information events. Results of the VAR model in Equation (2) for the respective information events (i.e. futures return shocks, VIX return shocks, and news shocks) are presented in Table 4 for initiated trading volume and Table 5.
for passive trading volume. The upper part of Panel A represents results for All Periods and the lower part the additional influence after the occurrence of a futures return shock. The total influence is the sum of the coefficient for All Periods and after the information shock (Information Periods) for the respective time periods. Panel B represents results for VIX return shocks, and Panel C for news events. Results for all periods for VIX shocks and news events are almost identical in their values. We leave them out for brevity.

[INSERT TABLE 4 HERE]

Results on passive trading are presented in Table 5 and again divided into three panels for the different information events.

[INSERT TABLE 5 HERE]

6.1. Results for All Periods

For all periods, we observe a higher influence of NHFT order flow on HFT order flow in the short-run than the other way round as presented in Panels A of Table 4 and 5. This result is valid for initiating and passive order flow, since the difference between the effect of HFT order flow on NHFT order flow and the opposite effect is statistically significantly negative (around -0.005 for initiating and -0.007 passive trades). From this result, we infer that NHFT are too slow to consider effects of HFT order flow in their trading decisions. This changes in the long run, since the difference becomes positive after 10 seconds, i.e. NHFT order flow has a greater effect on HFT order flow.

Furthermore, HFT contribute more to price discovery in the short run than NHFT, while NHFT contribute more in the long run. This is observed in Panel A of the respective tables, where the difference in the short run is significantly positive (around 0.040 for initiating and 0.081 for passive trades), i.e. HFT have a 4% higher influence on market returns. The difference becomes insignificant or negative in the long run (0.000 for initiating trades and -0.044 for passive trades), i.e. initiating traders of both categories contribute about the same to market return and the influence of passive NHFT becomes higher in
the long run. The results are similar in their magnitude and significance for all three information events. We interpret this observation as the speed advantage of HFT to process information and trade on it faster: There is evidence that HFT trade on price information for a short amount of time and subsequently lead price discovery in this time period. NHFT on the other hand need more time to process information but trade on it for a longer time period, i.e. a higher contribution in the long run.

Our results on price discovery are consistent with previous literature that suggests that trades of HFT are more informed than NHFT in terms of their impulse response (cf. Brogaard (2011a)). In conclusion, we infer a dominance of HFT in short-term price discovery, but a higher contribution by NHFT in the long run. The inclusion of information shocks, i.e. futures return shocks, VIX return shocks, and news shocks, sheds light on the additional influence of information events.

6.2. Results for Periods after Information Shocks

Table 4 presents results for initiating trades. In terms of order flow, we observe that the influence of both HFT and NHFT order flow on each other increases (0.021 for HFT and 0.069 for NHFT order flow), but the influence of HFT increases less than NHFT, especially in the short run. This points again to the fact that NHFT are apparently too slow to incorporate high-frequency information into their decisions. In the long run, the increase of NHFT influence is not as high as for HFT. Positive and negative information events, such as a positive or negative return shock or news, should steer the aggregate order flow into the same direction, i.e. in general more buy orders after positive events and more sell orders after negative events. We observe this result for futures shocks and news events where HFT and NHFT order flow are both positively related. In contrast to this observation, the relationship is negative after VIX shocks, as already seen from the results in Table 3 which shows that HFT and NHFT follow different strategies. The results for the influence on stock returns gives more insight into the actual contribution to price discovery by both groups. The additional influence in the short run after information shocks is
consistently positive for all information events, which indicates a higher information flow from both trader groups. Contributions to price discovery decreases and become negative in the long run for all groups.

With respect to the passive order flow after futures return shocks, both groups of traders get adversely selected in the short run, reflected in the negative influences on market returns. For hard information shocks, HFT influence on stock returns becomes positive in the long run (0.039 for futures shocks and 0.023 for VIX shocks\(^{13}\)), whereas after soft news shocks, passive NHFT invert their trading behavior in the long run (0.063 for news shocks). We thus conclude that passive trading strategies follow the change in order flow and prices after information events in the long run. This is an interesting aspect for the price discovery discussion about the level of information of initiating and passive orders: While previous literature has suggested that passive limit orders are more informed, we can contribute to this statements with a more differenced analysis. While initiating marketable orders, especially by HFT, dominate price discovery in the short run, i.e. within a period of 10 seconds, passive NHFT orders are more informed in the long run. This finding holds for periods without information events as well as for the additional influences after the occurrence of information events.

In summary for all periods, initiating and passive traders complement each other in the price discovery process since initiating traders lead price discovery in the short run, while passive NHFT have a higher influence on market returns in the long run. Furthermore, we can confidently reject the stated null hypotheses for hard information shocks. We find that hard information has significant effects on HFT and NHFT order flow and price discovery in the short and long run. For soft information, effects are significant in the short run, but decrease especially for passive traders in the long run. From this observation, we infer that hard information does actually have a stronger and more long-term effect on prices and order flow than soft information. Soft information might have effects in the short run,

\(^{13}\)A differentiation between high and low VIX shocks does not yield qualitatively different results, though coefficients for positive VIX shocks are generally higher than for negative VIX shocks.
but due to the possible ambiguity in the interpretation and reaction to this information, they do not have a long-term effect on price discovery.

7. The Influence of Information Events on Trading Profits

In this section, we use trading profits to characterize different information events and provide insight into different HFT and NHFT reaction to information events. We adapt revenue measures based on Menkveld (2011) and Hendershott and Riordan (2012b). Specifically, we assume that HFT start with zero inventory at the occurrence of the information shock \((t = 0)\) and cumulate revenues after the shock \((t = 1, \ldots, 12)\). This measure is denoted \(\text{Real}\) in the results in Table 6. In the spirit of Menkveld (2011) and Hendershott and Riordan (2012b), \(\text{Real}\) can be further decomposed into a “positioning” profit and a cash flow profit:

\[
\text{Real}_t = \sum_{i=0}^{t} IMB_{HFT_i} \cdot P_T + \sum_{i=0}^{t} HFT_i
\]

where \(t\) denotes the 10 second interval, \(IMB_{HFT_i}\) is the closing imbalance (number of shares bought minus number of shares sold) of HFT trades in number of shares at the end of \(t\), \(P_T\) is the closing quote midpoint at the end of \(t\) in $, and \(HFT_i\) is HFT net trading in $ (buy volume minus sell volume). We distinguish between initiated and passive trades for HFT imbalance \((IMB_{HFT_{init,t}}, IMB_{HFT_{pass,t}})\) and net trading \((HFT_{init,t}, HFT_{pass,t})\). Since participants of a trade are exhaustively indexed as either HFT or NHFT, this also implies that the NHFT revenue is the negative amount of HFT revenue.

We further compute fictitious revenues that would have been realized from trading only in the ten second interval in which the information shock occurs \((Fast)\), in the time interval 10 seconds after the shock occurs \((Slow)\) and 20 seconds after the shock occurs \((VSlow)\). The computed formulas are presented in Figure 1 below and the values are aggregated per stock-day and tested using robust standard errors clustered by stock and trading day (cf. Thompson, 2011).
Figure 1: Calculation of fictitious revenues

We account for NASDAQ trading fees and rebates in our analysis.\(^\text{14}\) Results in Table 6 present the profits yielded after information shocks from the closing imbalances \(IMB_{HFT_0}\), \(IMB_{HFT_1}\) and \(IMB_{HFT_2}\) and net trading \(HFT_0\), \(HFT_1\) and \(HFT_2\) in $\$. The left hand side presents results for initiating HFT and the right hand side for passive HFT.

\[\text{[INSERT TABLE 6 HERE]}\]

The profit results support results on trading reaction. In terms of the characterization of the different information shocks, we can see clear differences: Futures shocks imply a strong and decreasing reaction in realized trading profits. In terms of HFT reaction, speed is vital: Profits from fast reaction ($556.15) would deteriorate by more than 30% if realized after 10 seconds and would only yield one sixth of the actually realized profit after two minutes. Compared to profits from slower reaction to information events ($261.19 for \(Slow\) and $200.20 \(VSlow\)), the profits are less than half of the profits of fast HFT. On the other side, passive HFT get adversely selected which is also reflected in their profits. In total, HFT gain their highest profits in the short run directly after the shock and their profits monotonously decrease. VIX shocks yield similar results to futures shocks, but differently to futures shocks, the initiating profits as well as the total profits are increasing.

\(^{14}\) Analyses without trading fees and rebates do not yield qualitatively different results.
News shocks induce weaker reactions in realized trading profits in absolute terms, but profits are increasing in the long run. The interesting result here is that despite high adverse selection losses of passive trades, HFT are able to gain positive profits in total. Additionally, profits of slower trades are higher than those of fast trades which can be explained that HFT wait for the market reaction before actually trading on soft information.

In terms of profits, NHFT experience disadvantages for both hard and soft information: They do not realize short-term profits on hard information since HFT are faster in processing this type of information. Furthermore, they do not seize profit opportunities available in periods of high volatility, but increase their net trading in periods of low volatility when profits are low. Additionally, for soft information shocks, HFT are able to interpret market reaction comparably fast and gain positive profits within the twenty second period after the news event.

A differentiation between crisis, pre-crisis, and post-crisis periods (for a definition of the periods see Section 5) gives insight into profit opportunities in the respective time period. Results are presented in Table C.1. Profit opportunities after futures shocks are higher during the financial crisis and more short-lived. In the crisis period, realized as well as fictitious trading profits are decreasing within two minutes while they are increasing in the other time periods. Similar to the total results, Fast yields the highest profit compared to Slow and VSlow. Apart from the fact that profit opportunities are short-lived in the crisis period, the results do not yield qualitatively different results.

8. Conclusion

Recent trends have shown an evolution of HFT to more sophisticated algorithms that might be able to incorporate soft textual information in their trading strategies. In addition to existing concerns associated with HFT, these algorithms might give rise to even greater concerns than traditional HFT algorithms due to misinterpretation of and overreaction to events. Our results might ease some of these concerns, but also point to an edge of
HFT over NHFT in the speed of information processing. We analyze the reaction and profitability of HFT and NHFT after information events and further study the difference in their contribution to price discovery. We find that HFT use their competitive edge in trading speed and information processing to instantly react to hard information events. The reaction to futures return shocks is higher than for VIX shocks and news and leads to high realized profits, but deteriorates quickly while trading reaction and profits to other information events are increasing in the long run. Furthermore, a certain increase in volatility, as measured by the VIX, implies more profit opportunities for HFT and causes them to build up trading positions while the contrary is observed for NHFT. Finally, initiating HFT lead price discovery in the short run and especially after hard information events, which implies that HFT actually have a positive effect on price discovery, but this effect is short-lived. Despite the sophistication of HFT algorithms, NHFT have an advantage in the processing of soft information. Subsequently, they also have a higher influence on long-term price discovery than corresponding HFT.

There are limitations to our study that have to be considered before making inferences to regulatory and practical issues. We do not test for causality in our analyses. Therefore, our results are restricted to the influence of specific trade variables after controlling for autoregressive parts. We consider only intraday events and use a relatively short time period after the information events. Our applied models are robust to different time lags. Furthermore, we discuss possible correlations between information events in Section 3 and do not find any relevant interrelationships.

Our results have several implications for the public discussion on HFT. We can refute concerns about HFT that overreact to soft information events. HFT seem to rather withdraw from the market than actively trade on soft information events. For hard information, concerns could be raised whether HFT might lead to overreactions in the short run, but in the long run, they rather mitigate volatility due to the inversion of their trading behavior. The question arises whether HFT do cream-skimming in information processing, since the short-term reaction to information involves lower risks than the
longer term strategies of NHFT. On the other side, the decrease of latency might have also reduced the valid lifetime of an information event. Thus a long-term strategy based on short information shocks might also distort prices and lead to overreaction and market bubbles in the long run. Furthermore, our results also strengthen previous literature on HFT contribution to price discovery (cf. Hendershott and Riordan, 2012b), but restrict this positive contribution to only a short time period. We cannot draw a consistently positive or negative image for HFT overall, but provide a more differenced insight with respect to differentiation of initiating and passive trading, the effect on different time frequencies, and hard and soft information. Further research should be done to include other information events.
References


Table 1: Summary Descriptives

This table provides descriptives of the final sample of 40 stocks and information events for the years 2008 and 2009. Panel A depicts the descriptives of the stock sample based on averages per stock-day. *MarketCap* denotes the average market capitalization of the stocks and *Price* the average stock price. *TradedShares* is the average total number of shares traded, *TradeVolume* is the traded volume. *HFT_{init}* and *HFT_{pass}* is net trading (buyer-initiated minus seller-initiated trade volume) initiated by HFT and with HFT on the passive side respectively. Trade variables are aggregated into ten seconds intervals and standardized by mean and standard deviation of the respective stock-day. *Return* is the average 10 second-logreturn of the stock price. *VIX* is the average daily price for the Chicago Board Options Exchange (CBOE) Volatility Index and *Future* the average daily price for the S&P 500 future. Panel B depicts descriptives of the chosen information time series, i.e. S&P 500 future returns and VIX returns, and Panel C the total number of information events in the sample. Future and VIX shocks are return above the 99% and below the 1% percentile.

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<tr>
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<td>Price</td>
</tr>
<tr>
<td>Traded Shares</td>
</tr>
<tr>
<td>Traded Shares</td>
</tr>
<tr>
<td>Traded Volume</td>
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<tr>
<td><em>HFT_{init}</em></td>
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<tr>
<td><em>HFT_{pass}</em></td>
</tr>
<tr>
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<tr>
<td>Future</td>
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<td>VIX</td>
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<table>
<thead>
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<th>Panel B: Information Descriptives</th>
</tr>
</thead>
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<tr>
<td><strong>Information</strong></td>
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<tr>
<td>Future Returns</td>
</tr>
<tr>
<td>VIX Returns</td>
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<table>
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<th>Panel C: Information Events</th>
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<tr>
<td><strong>Information</strong></td>
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<td>News</td>
</tr>
<tr>
<td>Future Return Shocks</td>
</tr>
<tr>
<td>VIX Return Shocks</td>
</tr>
</tbody>
</table>
Table 2: Correlations

This table presents the correlations of return and trade variables and lagged information variables. In Panel A, trade variables are net trading (buy minus sell volume) aggregated into ten seconds intervals and standardized by mean and standard deviation. $HFT_{init}$ denotes net trading of HFT demanding liquidity, $HFT_{pass}$ denotes HFT supplying liquidity, NHFT variables correspond ($NHFT_{init}$, $NHFT_{pass}$). $fut$ is the S&P 500 future 10 second return, $vix$ is the VIX return. $news$ is the sentiment of a news event (-1, 0, or 1). The indices 1, 6, and 12 denote the lagged variables after 10, 60, and 120 seconds. In Panel B, trade variables are absolute trading volume (buy plus sell volume) and $Qspread$ denotes the quoted spread. $fut$, $vix$, and $news$ are dummies for information events in a time interval (equals 1 if information shock occurs, 0 otherwise). Correlation results are reported in %, aggregated per stock-day and tested using robust standard errors clustered by stock and trading day. Significant results below the 5% level are bold.

### Panel A: Net Trading

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<th>fut6</th>
<th>fut12</th>
<th>vix</th>
<th>vix1</th>
<th>vix6</th>
<th>vix12</th>
<th>news</th>
<th>news1</th>
<th>news6</th>
<th>news12</th>
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<td>0.15</td>
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Table 3: Impact of Information Shocks on Net Trading

This table presents coefficients of HFT and NHFT net trading after an information shock. A VARX model is implemented with the dependent variables as the respective trading variables. The independent variables are lagged and contemporaneous HFT and NHFT order flow and returns. All variables are aggregated into ten second intervals and standardized using mean and standard deviation for each stock and each trading day. Panel A reports aggregated impact on initiating and passive net trading for HFT ($HFT_{init}$, $HFT_{pass}$) and NHFT ($NHFT_{init}$, $NHFT_{pass}$) as well as their respective difference ($Diff$). Panel B reports result for VIX shocks and Panel C for news events. Panel D presents differences between reaction to future shocks and news events. $SR$ denotes the contemporaneous impact in the short run, $LR$ denotes the aggregated impact for the following 12 ten second intervals, i.e. 2 minutes after the information shock, $LR - SR$ denotes the long-run impact minus the short-run impact. Variables are aggregated per stock-day and tested using robust standard errors clustered by stock and trading day (cf. Thompson, 2011). T-statistics are in parentheses. ***, **, and * denotes significance at the 1%, 5%, and 10% level respectively.

### Panel A: Future Shocks

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<th>Passive Order Flow</th>
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<td>$NHFT_{init}$</td>
<td>$Diff$</td>
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<tr>
<td>SR</td>
<td>0.240***</td>
<td>0.179***</td>
<td>0.061**</td>
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<tr>
<td>(t-value)</td>
<td>(9.06)</td>
<td>(13.40)</td>
<td>(2.51)</td>
</tr>
<tr>
<td>LR</td>
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<td>0.350***</td>
<td>-0.359***</td>
</tr>
<tr>
<td>(t-value)</td>
<td>(-0.22)</td>
<td>(5.26)</td>
<td>(-5.04)</td>
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<td>LR-SR</td>
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<tr>
<td>(t-value)</td>
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<td>(2.69)</td>
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### Panel B: VIX Shocks

<table>
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<td>(-7.49)</td>
<td>(7.91)</td>
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<tr>
<td>LR-SR</td>
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<td>-0.146***</td>
<td>0.195***</td>
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<tr>
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<td>(-7.21)</td>
<td>(6.71)</td>
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</table>
### Panel C: News Shocks

<table>
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<tr>
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<th>Passive Order Flow</th>
<th>Init+Pass</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>( H_{\text{init}} )</td>
<td>( N H_{\text{init}} )</td>
<td>( \text{Diff} )</td>
</tr>
<tr>
<td>SR</td>
<td>0.027</td>
<td>0.080**</td>
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<td>0.408**</td>
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</table>

### Panel D: Future - News Shocks

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</tr>
</thead>
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<td>( H_{\text{init}} )</td>
<td>( N H_{\text{init}} )</td>
<td>( \text{Diff} )</td>
</tr>
<tr>
<td>SR</td>
<td>0.213***</td>
<td>0.099***</td>
<td>0.114***</td>
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<td>( t )-value</td>
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<td>(3.35)</td>
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<td>LR-SR</td>
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<td>-0.156</td>
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<td>( t )-value</td>
<td>(-3.13)</td>
<td>(-1.17)</td>
<td>(-1.44)</td>
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</table>
Table 4: Influence of Information Shocks on Price Discovery of Initiated Trades

This table presents regression results of the VAR model in Equation (2) for initiating trades. The dependent variable is the respective trading variable. The independent variables are lagged and contemporaneous HFT and NHFT order flow and returns as well as interaction variables of the independent variables and a dummy for the respective information shock. The full set of equations are estimated separately by OLS. Panel A reports results for initiating net trading of HFT \((HFT_{init})\) and NHFT \((NHFT_{init})\) for all periods and periods after S&P 500 future return shocks, Panel B periods of VIX return shocks and Panel C periods of news arrivals. All variables are aggregated into ten second intervals and standardized using mean and standard deviation for each stock and each trading day. \(SR\) denotes the contemporaneous influence in the short run, \(LR\) denotes the aggregated influence for the next 12 ten second intervals, i.e. 2 minutes after news arrival, \(LR - SR\) denotes the long-run influence minus the short-run influence. Variables are tested with Wald test. ***, **, and * denotes significance at the 1%, 5%, and 10% level respectively.

### Panel A: Influence of Future Shocks

<table>
<thead>
<tr>
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<th>Effect on Return</th>
</tr>
</thead>
<tbody>
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<td>(NHFT_{init}) on (HFT_{init})</td>
</tr>
<tr>
<td>All Periods</td>
<td></td>
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</tr>
<tr>
<td><strong>SR</strong></td>
<td>0.170***</td>
<td>0.175***</td>
</tr>
<tr>
<td><strong>LR</strong></td>
<td>0.201***</td>
<td>0.123***</td>
</tr>
<tr>
<td>LR-SR</td>
<td>0.031***</td>
<td>-0.052***</td>
</tr>
<tr>
<td>Information Periods</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SR</strong></td>
<td>0.021***</td>
<td>0.069***</td>
</tr>
<tr>
<td><strong>LR</strong></td>
<td>0.040***</td>
<td>0.083***</td>
</tr>
<tr>
<td>LR-SR</td>
<td>0.019***</td>
<td>0.014***</td>
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</table>

### Panel B: Influence of VIX Shocks

<table>
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<td>(HFT_{init}) on (NHFT_{init})</td>
<td>(NHFT_{init}) on (HFT_{init})</td>
</tr>
<tr>
<td>Information Periods</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SR</strong></td>
<td>-0.014***</td>
<td>0.003***</td>
</tr>
<tr>
<td><strong>LR</strong></td>
<td>-0.024***</td>
<td>-0.001</td>
</tr>
<tr>
<td>LR-SR</td>
<td>-0.010***</td>
<td>-0.004</td>
</tr>
</tbody>
</table>

### Panel C: Influence of News Events

<table>
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</tr>
</thead>
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<td>(NHFT_{init}) on (HFT_{init})</td>
</tr>
<tr>
<td>Information Periods</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SR</strong></td>
<td>0.118***</td>
<td>0.050***</td>
</tr>
<tr>
<td><strong>LR</strong></td>
<td>0.226***</td>
<td>0.181***</td>
</tr>
<tr>
<td>LR-SR</td>
<td>0.108**</td>
<td>0.131***</td>
</tr>
</tbody>
</table>

30
Table 5: Influence of Information Shocks on Price Discovery of Passive Trades
This table presents regression results of the VAR model in Equation (2) for passive trades. The dependent variable is the respective trade variable. The independent variables are lagged and contemporaneous HFT and NHFT order flow and returns as well as interaction variables of the independent variables and a dummy for the respective information shock. The full set of equations are estimated separately by OLS. Panel A reports results for passive net trading of HFT ($HFT_{pass}$) and NHFT ($NHFT_{pass}$) for all periods and periods after S&P 500 future return shocks, Panel B periods of VIX return shocks and Panel C periods of news arrivals. All variables are aggregated into ten second intervals and standardized using mean and standard deviation for each stock and each trading day. $SR$ denotes the contemporaneous influence in the short run, $LR$ denotes the aggregated influence for the following 12 ten second intervals, i.e. 2 minutes after news arrival, $LR - SR$ denotes the long-run influence minus the short-run influence. Variables are tested with Wald test. ***, **, and * denotes significance at the 1%, 5%, and 10% level respectively.

### Panel A: Influence of Future Shocks

<table>
<thead>
<tr>
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<th>Effect on Return</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$HFT_{pass}$ on $NHFT_{pass}$</td>
<td>Diff</td>
</tr>
<tr>
<td><strong>All Periods</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR</td>
<td>0.312***</td>
<td>0.319***</td>
</tr>
<tr>
<td>LR</td>
<td>0.213***</td>
<td>0.164***</td>
</tr>
<tr>
<td>LR-SR</td>
<td>-0.099***</td>
<td>-0.154***</td>
</tr>
<tr>
<td><strong>Information Periods</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR</td>
<td>-0.068***</td>
<td>-0.083***</td>
</tr>
<tr>
<td>LR</td>
<td>-0.074***</td>
<td>-0.049***</td>
</tr>
<tr>
<td>LR-SR</td>
<td>-0.007***</td>
<td>0.034***</td>
</tr>
</tbody>
</table>

### Panel B: Influence of VIX Shocks

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
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<td></td>
<td>$HFT_{pass}$ on $NHFT_{pass}$</td>
<td>Diff</td>
</tr>
<tr>
<td><strong>Information Periods</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR</td>
<td>-0.061***</td>
<td>-0.048***</td>
</tr>
<tr>
<td>LR</td>
<td>-0.068***</td>
<td>-0.049***</td>
</tr>
<tr>
<td>LR-SR</td>
<td>-0.007***</td>
<td>-0.002</td>
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### Panel C: Influence of News Events

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<td>Diff</td>
</tr>
<tr>
<td><strong>Information Periods</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR</td>
<td>0.033***</td>
<td>0.101***</td>
</tr>
<tr>
<td>LR</td>
<td>0.015</td>
<td>0.073**</td>
</tr>
<tr>
<td>LR-SR</td>
<td>-0.018</td>
<td>-0.028</td>
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</table>
This table presents HFT profits after information events. Panel A shows profits after future shocks, Panel B for VIX shocks, and Panel C for news shocks. \textit{Real} denotes the total realized trading profit of initiating and passive HFT under the assumption that they start with zero inventory at the occurrence of the information shock. \textit{Fast}, \textit{Slow}, and \textit{VSlow} are fictitious profits under the assumption that HFT: (1) start at occurrence of an information shock with 0 inventory, (2) only make trades 0 seconds (\textit{Fast}), 10 seconds (\textit{Slow}), and 20 seconds (\textit{VSlow}) after the information event, and (3) sell their inventory 60 seconds or 120 seconds after the information event. All profit variables are in $, aggregated per stock-day, and tested using robust standard errors clustered by stock and trading day. T-statistics are in parentheses. ***, **, and * denotes significance at the 1%, 5%, and 10% level respectively.

### Panel A: Future Shock

<table>
<thead>
<tr>
<th></th>
<th>Initiating Volume</th>
<th>Passive Volume</th>
<th>All</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>\textit{Real}</td>
<td>\textit{Fast}</td>
<td>\textit{Slow}</td>
</tr>
<tr>
<td>0 sec</td>
<td>556.15***</td>
<td>556.15***</td>
<td>-174.69***</td>
</tr>
<tr>
<td></td>
<td>(5.30)</td>
<td>(5.30)</td>
<td>(-3.27)</td>
</tr>
<tr>
<td>10 sec</td>
<td>632.76***</td>
<td>369.68***</td>
<td>261.19***</td>
</tr>
<tr>
<td></td>
<td>(5.90)</td>
<td>(5.86)</td>
<td>(5.71)</td>
</tr>
<tr>
<td>20 sec</td>
<td>630.94***</td>
<td>292.37***</td>
<td>138.46***</td>
</tr>
<tr>
<td></td>
<td>(6.14)</td>
<td>(6.12)</td>
<td>(4.86)</td>
</tr>
<tr>
<td>60 sec</td>
<td>654.82***</td>
<td>154.21***</td>
<td>75.99***</td>
</tr>
<tr>
<td></td>
<td>(6.06)</td>
<td>(5.25)</td>
<td>(5.05)</td>
</tr>
<tr>
<td>120 sec</td>
<td>676.22***</td>
<td>90.64***</td>
<td>50.13***</td>
</tr>
<tr>
<td></td>
<td>(4.68)</td>
<td>(4.22)</td>
<td>(3.10)</td>
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</table>
### Panel B: VIX Shock

<table>
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<th>Slow</th>
<th>VSlow</th>
<th>Real</th>
<th>Fast</th>
<th>Slow</th>
<th>VSlow</th>
<th>All</th>
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</thead>
<tbody>
<tr>
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<td>264.27***</td>
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<td>-104.05***</td>
<td>160.21***</td>
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<td>(5.77)</td>
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<td>(-3.31)</td>
<td>(3.67)</td>
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<td></td>
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<tr>
<td>10 sec</td>
<td>483.74***</td>
<td>262.97***</td>
<td>219.22***</td>
<td>-211.70***</td>
<td>-124.26***</td>
<td>-85.45**</td>
<td>272.04***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(t-value)</td>
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<td>(5.96)</td>
<td>(5.41)</td>
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<td>(-4.13)</td>
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<td>(3.58)</td>
<td></td>
<td></td>
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<tr>
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<td>194.61***</td>
<td>220.40***</td>
<td>191.78***</td>
<td>-316.90***</td>
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<td>289.88***</td>
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<td>(5.39)</td>
<td>(-3.90)</td>
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<td>(-4.18)</td>
<td>(-4.01)</td>
<td>(3.85)</td>
<td></td>
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<tr>
<td>60 sec</td>
<td>784.33***</td>
<td>120.43***</td>
<td>91.64***</td>
<td>94.18***</td>
<td>-512.75***</td>
<td>-57.83***</td>
<td>-73.51***</td>
<td>-75.27***</td>
<td>271.58***</td>
</tr>
<tr>
<td>(t-value)</td>
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<td>(6.11)</td>
<td>(4.22)</td>
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<td>(-3.19)</td>
<td>(-4.29)</td>
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</tr>
<tr>
<td>120 sec</td>
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<td>75.26***</td>
<td>67.68***</td>
<td>64.95***</td>
<td>-651.26***</td>
<td>-29.35***</td>
<td>-44.51***</td>
<td>-50.51***</td>
<td>311.26***</td>
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<td>(t-value)</td>
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<td>(3.97)</td>
<td>(4.24)</td>
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<td>(-3.01)</td>
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<td>(-3.96)</td>
<td>(2.85)</td>
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</table>

### Panel C: News Shock

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<th>Slow</th>
<th>VSlow</th>
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<th>Fast</th>
<th>Slow</th>
<th>VSlow</th>
<th>All</th>
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<tbody>
<tr>
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<td>10.43***</td>
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<td>-15.03***</td>
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<td>(3.02)</td>
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<td>(-3.14)</td>
<td>(-1.04)</td>
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<tr>
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<td>17.76</td>
<td>5.54</td>
<td>12.14*</td>
<td>27.79*</td>
<td>37.62**</td>
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<td></td>
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<tr>
<td>20 sec</td>
<td>34.82</td>
<td>0.45</td>
<td>6.59</td>
<td>27.79*</td>
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<td></td>
<td></td>
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<td>(0.40)</td>
<td>(1.81)</td>
<td>(1.87)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60 sec</td>
<td>55.29*</td>
<td>18.87**</td>
<td>-2.49</td>
<td>-10.57</td>
<td>38.71</td>
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</tr>
<tr>
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<td>(2.09)</td>
<td>(-0.11)</td>
<td>(-0.98)</td>
<td>(1.02)</td>
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</tr>
<tr>
<td>120 sec</td>
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<td>27.19***</td>
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</tr>
<tr>
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<td>(2.66)</td>
<td>(1.01)</td>
<td>(0.30)</td>
<td>(1.28)</td>
<td></td>
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</tbody>
</table>
Appendix A. List of Sample Stocks

Table A.1: Sample Descriptives

This table presents the 40 sample stocks and the absolute and relative HFT activity. Total denotes the average total number of trades per stock day, HFT trades the number of trades involving an HFT. Abs.Hinit and Abs.Hpass denote the absolute number of HFT initiated and passive trades respectively, while Rel.Hinit and Rel.Hpass is the relative percentage.

<table>
<thead>
<tr>
<th>Ticker</th>
<th>Total</th>
<th>HFT trades</th>
<th>Abs.Hinit</th>
<th>Abs.Hpass</th>
<th>Rel.Hinit</th>
<th>Rel.Hpass</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA</td>
<td>25,114</td>
<td>20,808</td>
<td>11,074</td>
<td>15,548</td>
<td>0.44</td>
<td>0.62</td>
</tr>
<tr>
<td>AAPL</td>
<td>80,133</td>
<td>61,555</td>
<td>39,180</td>
<td>40,798</td>
<td>0.49</td>
<td>0.51</td>
</tr>
<tr>
<td>ADBE</td>
<td>20,428</td>
<td>14,565</td>
<td>8,640</td>
<td>9,035</td>
<td>0.42</td>
<td>0.44</td>
</tr>
<tr>
<td>AGN</td>
<td>4,204</td>
<td>2,288</td>
<td>1,640</td>
<td>979</td>
<td>0.39</td>
<td>0.23</td>
</tr>
<tr>
<td>AMAT</td>
<td>31,595</td>
<td>25,738</td>
<td>13,403</td>
<td>19,403</td>
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<td>0.61</td>
</tr>
<tr>
<td>AMGN</td>
<td>23,413</td>
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<td>8,276</td>
<td>9,440</td>
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<td>0.40</td>
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<td>0.29</td>
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<td>14,430</td>
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<td>0.54</td>
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<tr>
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<td>7,204</td>
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<td>BIIB</td>
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<td>4,469</td>
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<td>CB</td>
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<td>2,301</td>
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<td>CELG</td>
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<td>3,893</td>
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<tr>
<td>CMCSA</td>
<td>36,859</td>
<td>30,790</td>
<td>16,649</td>
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<td>CSCO</td>
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<td>11,420</td>
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<td>0.60</td>
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<tr>
<td>DOW</td>
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<td>13,848</td>
<td>7,912</td>
<td>9,565</td>
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<td>0.55</td>
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<td>GE</td>
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<td>GILD</td>
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<td>14,571</td>
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<td>0.37</td>
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<td>GLW</td>
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<td>11,512</td>
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<td>9,599</td>
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<td>0.60</td>
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<td>8,559</td>
<td>5,448</td>
<td>5,293</td>
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<td>0.47</td>
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<td>HPQ</td>
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<td>11,155</td>
<td>16,225</td>
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<td>INTC</td>
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<td>39,351</td>
<td>0.43</td>
<td>0.64</td>
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<td>ISRG</td>
<td>4,863</td>
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<td>0.27</td>
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<td>KMB</td>
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<td>1,382</td>
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<td>KR</td>
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<td>4,662</td>
<td>3,625</td>
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<td>0.40</td>
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<td>0.41</td>
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<td>PFE</td>
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<td>PG</td>
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<td>17,711</td>
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<td>0.56</td>
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<tr>
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<td>3,871</td>
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<td>SWN</td>
<td>10,111</td>
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<td>5,748</td>
<td>3,577</td>
<td>0.57</td>
<td>0.35</td>
</tr>
<tr>
<td>All Stocks</td>
<td>22,915</td>
<td>17,705</td>
<td>10,348</td>
<td>11,983</td>
<td>0.46</td>
<td>0.46</td>
</tr>
</tbody>
</table>
Appendix B. VARX Results

Table B.1: Impact of Future Shocks on Net Trading

This table presents coefficients of HFT and NHFT net trading after arrival of an exogenous hard information event, proxied by abnormally high and low returns of the S&P 500 future. The VARX model is implemented with respective trading variables as the dependent variables. The independent variables are lagged and contemporaneous HFT and NHFT order flow and returns. All variables are aggregated into ten second intervals and standardized using mean and standard deviation for each firm and each trading day. Panel A reports aggregated impact on initiating net trading for HFT \((HFT_{init})\) and NHFT \((NHFT_{init})\) to abnormally high and low future shocks as well as their respective difference \((Diff)\). Panel B reports aggregated impact on passive net trading for HFT \((HFT_{pass})\) and NHFT \((NHFT_{pass})\). \(SR\) denotes the contemporaneous impact in the short run, \(LR\) denotes the aggregated impact for the following 12 ten second intervals, i.e. 2 minutes after the information shock, \(LR - SR\) denotes the long-run impact minus the short-run impact. Variables are aggregated per stock-day and tested using double clustered standard errors on stock and trading day (c.f. Thompson, 2011). T-statistics are in parentheses. ***, **, and * denotes significance at the 1%, 5%, and 10% level respectively.

### Panel A: Positive Future Shocks

<table>
<thead>
<tr>
<th></th>
<th>Initiating Order Flow</th>
<th>Passive Order Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(HFT_{init})</td>
<td>(NHFT_{init})</td>
</tr>
<tr>
<td>SR</td>
<td>0.268***</td>
<td>0.195***</td>
</tr>
<tr>
<td>((t\text{-value}))</td>
<td>(8.71)</td>
<td>(11.73)</td>
</tr>
<tr>
<td>LR</td>
<td>-0.046</td>
<td>0.377***</td>
</tr>
<tr>
<td>((t\text{-value}))</td>
<td>(-0.95)</td>
<td>(5.21)</td>
</tr>
<tr>
<td>LR-SR</td>
<td>-0.314***</td>
<td>0.182***</td>
</tr>
<tr>
<td>((t\text{-value}))</td>
<td>(-7.09)</td>
<td>(2.69)</td>
</tr>
</tbody>
</table>

### Panel B: Negative Future Shocks

<table>
<thead>
<tr>
<th></th>
<th>Initiating Order Flow</th>
<th>Passive Order Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(HFT_{init})</td>
<td>(NHFT_{init})</td>
</tr>
<tr>
<td>SR</td>
<td>-0.258***</td>
<td>-0.193***</td>
</tr>
<tr>
<td>((t\text{-value}))</td>
<td>(-8.54)</td>
<td>(-13.25)</td>
</tr>
<tr>
<td>LR</td>
<td>-0.022</td>
<td>-0.340***</td>
</tr>
<tr>
<td>((t\text{-value}))</td>
<td>(-0.51)</td>
<td>(-6.24)</td>
</tr>
<tr>
<td>LR-SR</td>
<td>0.236***</td>
<td>-0.147***</td>
</tr>
<tr>
<td>((t\text{-value}))</td>
<td>(5.93)</td>
<td>(-2.83)</td>
</tr>
</tbody>
</table>
Table B.2: Impact of Volatility Shocks on Net Trading
This table presents coefficients of HFT and NHFT net trading after arrival of an exogenous hard information event, proxied by abnormally high and low VIX returns. The VARX model is implemented with respective trading variables as the dependent variables. The independent variables are lagged and contemporaneous HFT and NHFT order flow and returns. All variables are aggregated into ten second intervals and standardized using mean and standard deviation for each stock and each trading day. Panel A reports aggregated impact on initiating net trading for HFT (\(HFT_{init}\)) and NHFT (\(NHFT_{init}\)) to abnormally high and low VIX shocks as well as their respective difference (\(Diff\)). Panel B reports aggregated impact on passive net trading for HFT (\(HFT_{pass}\)) and NHFT (\(NHFT_{pass}\)). \(SR\) denotes the contemporaneous impact in the short run, \(LR\) denotes the aggregated impact for the following 12 ten second intervals, i.e. 2 minutes after the information shock, \(LR - SR\) denotes the long-run impact minus the short-run impact. Variables are aggregated per stock-day and tested using double clustered standard errors on stock and trading day (c.f. Thompson, 2011). T-statistics are in parentheses. ***, **, and * denotes significance at the 1%, 5%, and 10% level respectively.

<table>
<thead>
<tr>
<th>Panel A: Positive VIX Shocks</th>
<th></th>
<th></th>
<th></th>
<th>Panel B: Negative VIX Shocks</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(HFT_{init})</td>
<td>(NHFT_{init})</td>
<td>(Diff)</td>
<td></td>
<td>(HFT_{pass})</td>
<td>(NHFT_{pass})</td>
<td>(Diff)</td>
</tr>
<tr>
<td>SR</td>
<td>0.026***</td>
<td>-0.019***</td>
<td>0.045***</td>
<td>-0.035***</td>
<td>0.016***</td>
<td>-0.051***</td>
<td>-0.051***</td>
</tr>
<tr>
<td>((t-value))</td>
<td>(3.52)</td>
<td>(-4.99)</td>
<td>(7.54)</td>
<td>(-4.33)</td>
<td>(3.62)</td>
<td>(-6.87)</td>
<td>(-6.87)</td>
</tr>
<tr>
<td>LR</td>
<td>0.081***</td>
<td>-0.128***</td>
<td>0.209***</td>
<td>-0.089***</td>
<td>0.151***</td>
<td>-0.240***</td>
<td>-0.240***</td>
</tr>
<tr>
<td>((t-value))</td>
<td>(3.59)</td>
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<td>(7.47)</td>
<td>(-3.74)</td>
<td>(6.42)</td>
<td>(-7.90)</td>
<td>(-7.90)</td>
</tr>
<tr>
<td>LR-SR</td>
<td>0.055**</td>
<td>-0.109***</td>
<td>0.164***</td>
<td>-0.055**</td>
<td>0.134***</td>
<td>-0.189***</td>
<td>-0.189***</td>
</tr>
<tr>
<td>((t-value))</td>
<td>(2.52)</td>
<td>(-5.18)</td>
<td>(6.11)</td>
<td>(-2.55)</td>
<td>(6.33)</td>
<td>(-6.83)</td>
<td>(-6.83)</td>
</tr>
</tbody>
</table>
Table B.3: Impact of News Shocks on Net Trading
This table presents aggregated coefficients of HFT and NHFT net trading after the arrival of an exogenous soft information event, proxied by positive and negative news events. The VARX model is implemented with respective trading variables as the dependent variables. The independent variables are lagged and contemporaneous HFT and NHFT order flow and returns. All variables are aggregated into ten second intervals and standardized using mean and standard deviation for each firm and each trading day. Panel A reports aggregated impact on initiating net trading for HFT ($HFT_{init}$) and NHFT ($NHFT_{init}$) after news arrivals as well as their respective difference ($Diff$). Panel B reports aggregated impact on passive net trading for HFT ($HFT_{pass}$) and NHFT ($NHFT_{pass}$). $SR$ denotes the contemporaneous impact in the short run, $LR$ denotes the aggregated impact for the following 12 ten second intervals, i.e. 2 minutes after news arrival, $LR - SR$ denotes the long-run impact minus the short-run impact. Variables are aggregated per stock-day and tested using double clustered standard errors on stock and trading day (c.f. Thompson, 2011). T-statistics are in parentheses. ***, ***, and * denotes significance at the 1%, 5%, and 10% level respectively.

### Panel A: Positive News Shocks

<table>
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<tr>
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<th>Initiating Order Flow</th>
<th>Passive Order Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$HFT_{init}$</td>
<td>$NHFT_{init}$</td>
</tr>
<tr>
<td>SR ($t$-value)</td>
<td>0.077**</td>
<td>0.105**</td>
</tr>
<tr>
<td>LR ($t$-value)</td>
<td>0.133</td>
<td>0.705***</td>
</tr>
<tr>
<td>LR-SR ($t$-value)</td>
<td>0.056</td>
<td>0.600***</td>
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</table>

### Panel B: Negative News Shocks

<table>
<thead>
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<th>Initiating Order Flow</th>
<th>Passive Order Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$HFT_{init}$</td>
<td>$NHFT_{init}$</td>
</tr>
<tr>
<td>SR ($t$-value)</td>
<td>0.014</td>
<td>-0.055*</td>
</tr>
<tr>
<td>LR ($t$-value)</td>
<td>0.009</td>
<td>-0.084</td>
</tr>
<tr>
<td>LR-SR ($t$-value)</td>
<td>-0.004</td>
<td>-0.029</td>
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</tbody>
</table>

B-4
Table B.4: Impact of Information Shocks on Net Trading - Robustness over time

This table presents aggregated coefficients of HFT and NHFT net trading after an information shock for different periods of the sample. We distinguish between the pre-crisis period (Jan-Aug 2008; Panel A1, B1, C1), the crisis period (Sep 2008-June 2009; Panel A2, B2, C2), and the post-crisis period (July 2009-Dec 2009; Panel A3, B3, C3). The VARX model is implemented with the respective trading variables as the dependent variables. The independent variables are lagged and contemporaneous HFT and NHFT order flow and returns. All variables are aggregated into ten second intervals and standardized using mean and standard deviation for each stock and each trading day. Panel A reports aggregated impact on initiating and passive net trading for HFT ($HFT_{\text{init}}$, $HFT_{\text{pass}}$) and NHFT ($NHFT_{\text{init}}, NHFT_{\text{pass}}$) as well as their respective difference ($\text{Diff}$). Panel B reports result for VIX shocks and Panel C for news events. Panel D presents differences between reaction to future shocks and news events. $SR$ denotes the contemporaneous impact in the short run, $LR$ denotes the aggregated impact for the following 12 ten second intervals, i.e. 2 minutes after the information shock, $LR - SR$ denotes the long-run impact minus the short-run impact. Variables are aggregated per stock-day and tested using double clustered standard errors on stock and trading day (cf. Thompson, 2011). T-statistics are in parentheses. ***, **, and * denotes significance at the 1%, 5%, and 10% level respectively.
Table B.4: Impact of Future Shocks on Net Trading - continued

### Panel A1: Future Shocks 2008 Pre-Crisis

<table>
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<tr>
<th></th>
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<tbody>
<tr>
<td></td>
<td>( \text{HFT}_{\text{init}} )</td>
<td>( \text{NHFT}_{\text{init}} )</td>
<td>( \text{Diff} )</td>
<td>( \text{HFT}_{\text{pass}} )</td>
<td>( \text{NHFT}_{\text{pass}} )</td>
<td>( \text{Diff} )</td>
</tr>
<tr>
<td>( \text{SR} )</td>
<td>0.087**</td>
<td>0.134***</td>
<td>-0.047</td>
<td>-0.007</td>
<td>-0.168***</td>
<td>0.160***</td>
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<tr>
<td>( \text{t-value} )</td>
<td>(2.17)</td>
<td>(6.10)</td>
<td>(-1.35)</td>
<td>(-0.30)</td>
<td>(-5.05)</td>
<td>(5.88)</td>
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<tr>
<td>( \text{LR} )</td>
<td>-0.184**</td>
<td>0.199**</td>
<td>-0.383***</td>
<td>-0.124**</td>
<td>-0.016</td>
<td>-0.109</td>
</tr>
<tr>
<td>( \text{t-value} )</td>
<td>(-2.58)</td>
<td>(2.49)</td>
<td>(-4.47)</td>
<td>(-2.31)</td>
<td>(-0.18)</td>
<td>(-1.19)</td>
</tr>
<tr>
<td>( \text{LR-SR} )</td>
<td>-0.271***</td>
<td>0.065</td>
<td>-0.336***</td>
<td>-0.117***</td>
<td>0.152**</td>
<td>-0.269***</td>
</tr>
<tr>
<td>( \text{t-value} )</td>
<td>(-4.13)</td>
<td>(0.94)</td>
<td>(-3.98)</td>
<td>(-2.68)</td>
<td>(1.97)</td>
<td>(-3.29)</td>
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</table>

### Panel A2: Future Shocks 2008 Crisis

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<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>( \text{HFT}_{\text{init}} )</td>
<td>( \text{NHFT}_{\text{init}} )</td>
<td>( \text{Diff} )</td>
<td>( \text{HFT}_{\text{pass}} )</td>
<td>( \text{NHFT}_{\text{pass}} )</td>
<td>( \text{Diff} )</td>
</tr>
<tr>
<td>( \text{SR} )</td>
<td>0.326***</td>
<td>0.218***</td>
<td>0.108***</td>
<td>-0.173***</td>
<td>-0.327***</td>
<td>0.154***</td>
</tr>
<tr>
<td>( \text{t-value} )</td>
<td>(11.49)</td>
<td>(17.40)</td>
<td>(3.62)</td>
<td>(-10.86)</td>
<td>(-17.66)</td>
<td>(10.01)</td>
</tr>
<tr>
<td>( \text{LR} )</td>
<td>0.034</td>
<td>0.510***</td>
<td>-0.476***</td>
<td>-0.410***</td>
<td>-0.257***</td>
<td>-0.153***</td>
</tr>
<tr>
<td>( \text{t-value} )</td>
<td>(0.80)</td>
<td>(14.19)</td>
<td>(-12.40)</td>
<td>(-13.48)</td>
<td>(-5.56)</td>
<td>(-3.75)</td>
</tr>
<tr>
<td>( \text{LR-SR} )</td>
<td>-0.292***</td>
<td>0.292***</td>
<td>-0.584***</td>
<td>-0.236***</td>
<td>0.071*</td>
<td>-0.307***</td>
</tr>
<tr>
<td>( \text{t-value} )</td>
<td>(-8.60)</td>
<td>(8.56)</td>
<td>(-13.34)</td>
<td>(-10.41)</td>
<td>(1.86)</td>
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</table>

### Panel A3: Future Shocks 2009 Post-Crisis

<table>
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<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>( \text{HFT}_{\text{init}} )</td>
<td>( \text{NHFT}_{\text{init}} )</td>
<td>( \text{Diff} )</td>
<td>( \text{HFT}_{\text{pass}} )</td>
<td>( \text{NHFT}_{\text{pass}} )</td>
<td>( \text{Diff} )</td>
</tr>
<tr>
<td>( \text{SR} )</td>
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<td>0.122***</td>
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<td>-0.313***</td>
<td>0.207***</td>
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<td>(4.83)</td>
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Table B.4: Impact of VIX Shocks on Net Trading - continued

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<td><strong>NHFT\textsubscript{init}</strong></td>
<td><strong>Diff</strong></td>
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<td><strong>Init+Pass</strong></td>
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<tr>
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<td><strong>NHFT\textsubscript{init}</strong></td>
<td><strong>Diff</strong></td>
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Table B.4: Impact of News Shocks on Net Trading - continued

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<td>passive order flow</td>
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<tr>
<td></td>
<td>HFT&lt;sub&gt;init&lt;/sub&gt; NHFT&lt;sub&gt;init&lt;/sub&gt; Diff</td>
<td>HFT&lt;sub&gt;pass&lt;/sub&gt; NHFT&lt;sub&gt;pass&lt;/sub&gt; Diff</td>
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<tr>
<td>SR</td>
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<td>(0.48) (0.88) (-0.36)</td>
<td>(-0.31) (-0.61) (0.25)</td>
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<tr>
<td>LR</td>
<td>0.217 0.309 -0.092</td>
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<td>(-0.48) (-0.75) (0.46)</td>
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<td>LR-SR</td>
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<td>-0.084 0.209 0.125</td>
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<td>(t-value)</td>
<td>(0.57) (0.91) (-0.23)</td>
<td>(-0.43) (-0.67) (0.45)</td>
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Note: All values are adjusted for news shocks. Significance levels: **p < 0.01, *p < 0.05.
Table B.5: Impact of Information Shocks on Net Trading - Reverse Ordering

This table presents aggregated coefficients of HFT and NHFT net trading after an information shock under the assumption that NHFT trade before HFT. The VARX model is implemented with the respective trading variables as the dependent variables. The independent variables are lagged and contemporaneous HFT and NHFT order flow and returns. All variables are aggregated into ten second intervals and standardized using mean and standard deviation for each stock and each trading day. Panel A reports aggregated impact on initiating and passive net trading for HFT ($HFT_{init}$, $HFT_{pass}$) and NHFT ($NHFT_{init}$, $NHFT_{pass}$) as well as their respective difference ($Diff$). Panel B reports result for VIX shocks and Panel C for news events. SR denotes the contemporaneous impact in the short run, LR denotes the aggregated impact for the following 12 ten second intervals, i.e. 2 minutes after the information shock, $LR-SR$ denotes the long-run impact minus the short-run impact. Variables are aggregated per stock-day and tested using double clustered standard errors on stock and trading day. T-statistics are in parentheses. ***, **, and * denotes significance at the 1%, 5%, and 10% level respectively.

### Panel 1: Impact of Future Shocks on Net Trading

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<td>HFT$_{pass}$: 0.102***</td>
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<td>$(t$-value)</td>
<td>(9.06)</td>
<td>(-6.75)</td>
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<tr>
<td>$NHFT_{init}$</td>
<td>LR: -0.009</td>
<td>LR$_{pass}$: -0.263***</td>
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<tr>
<td>$(t$-value)</td>
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<td>(-7.51)</td>
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<tr>
<td>$Diff$</td>
<td>SR: 0.061**</td>
<td>LR$_{pass}$: -0.189***</td>
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<td>(2.51)</td>
<td>(-3.29)</td>
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<tr>
<td></td>
<td>HR: -0.102***</td>
<td>$LR-SR$: -0.243***</td>
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<td>(-6.75)</td>
<td>(-1.37)</td>
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<td>(t-value): (10.89)</td>
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### Panel 2: Impact of VIX Shocks on Net Trading

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<td>HFT$_{pass}$: 0.017***</td>
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<td>(4.51)</td>
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<td>$NHFT_{init}$</td>
<td>LR: 0.079***</td>
<td>LR$_{pass}$: -0.020</td>
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<td>$(t$-value)</td>
<td>(9.75)</td>
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<td>$Diff$</td>
<td>SR: 0.049***</td>
<td>LR$_{pass}$: 0.238***</td>
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<td>(9.75)</td>
<td>(10.24)</td>
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<td>HR: -0.010**</td>
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### Panel 3: Impact of News Shocks on Net Trading

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<td>(-3.92)</td>
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<tr>
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<td>(-4.02)</td>
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<td>HR: -0.049*</td>
<td>$LR-SR$: -0.071</td>
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B-9
Appendix C. Trading Profits

Table C.1: HFT Profits after Information Shocks - Robustness over time
This table presents HFT revenue after information events. Panel A shows profits after future shocks, Panel B after VIX shocks, and Panel C after news shocks. We distinguish between the pre-crisis period (Jan-Aug 2008; Panel A1, B1, C1), the crisis period (Sep 2008-June 2009; Panel A2, B2, C2), and the post-crisis period (July 2009-Dec 2009; Panel A3, B3, C3). \( \text{Real} \) denotes the total realized trading revenue of initiating and passive HFT. \( \text{Fast}, \text{Slow}, \) and \( \text{VSlow} \) are fictitious revenues under the assumption that HFT: (1) start at occurrence of an information shock with 0 inventory, (2) only make trades 0 seconds (\( \text{Fast} \)), 10 seconds (\( \text{Slow} \)), and 20 seconds (\( \text{VSlow} \)) after the information event, and (3) sell their inventory 60 seconds or 120 seconds after the information shock. All profit variables are in $, aggregated per stock-day, and tested using double clustered standard errors on stock and trading day. T-statistics are in parentheses. ***, **, and * denotes significance at the 1%, 5%, and 10% level respectively.
Table C.1: Impact of Future Shocks on Trading Revenues - continued

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### Panel B1: VIX Shock - 2008 Pre-Crisis

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### Panel B2: VIX Shock - 2008 Crisis

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### Panel B3: VIX Shock - 2009 Post-Crisis

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### Panel C2: News Shock - 2008 Crisis

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### Panel C3: News Shock - 2009 Post-Crisis

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