The Economics of High-Frequency Trading: Taking Stock

Albert J. Menkveld[1,2]

[1]Finance, Vrije Universiteit Amsterdam, Amsterdam, Netherlands, 1081 HV
[2]Tinbergen Institute Amsterdam, Amsterdam, Netherlands, 1082 MS

Xxxx. Xxx. Xxx. Xxx. YYYY. AA:1–28

This article's doi:
10.1146/((please add article doi))

First page note to print below
DOI/copyright line.

Keywords

High-frequency trading, electronic markets, microstructure

Abstract

I review the recent high-frequency trader (HFT) literature to single out the economic channels by which HFTs affect market quality. I first group the various theoretical studies according to common denominators and discuss the economic costs and benefits they identify. I then, for each group, review the empirical literature that either speaks to the models' assumptions or their predictions. This enables me to come to a "data-weighted" judgement on the economic value of HFTs.

Contents

1. INTRODUCTION

Almost half a century ago Fisher Black shared a vision of a fully automated stock exchange (Black 1971a, 1971b p. 87):

> It seems likely, then, that [...] a stock exchange can be embodied in a network of computers, and the costs of trading can be sharply reduced, without introducing any additional instability in stock prices, and without being unfair either to small investors or to large investors.

We have come pretty close. Trading floors have been largely replaced by exchange servers. These new venues include centralized limit-order markets, but also crossing networks, dark pools, etc. The services that brokers, dealers, and specialists provided are now largely coded into computer algorithms operating at super-human speed. Securities trading in all asset classes has either migrated completely to electronic markets (e.g., US equities) or is in the process of migrating (Johnson 2010; Cardella, Hao, Kalcheva & Ma 2014).

One type of computerized trader attracted most attention: the high-frequency trader (HFT). A formal definition does not exist but most associate HFT with extremely fast computers running algorithms coded by traders who trade for their own account. Collectively, their participation rate in trades is typically a couple of deciles (SEC 2010). These traders typically do not work at the deep-pocket sell-side banks, but at privately held firms. They therefore need to keep their positions small and short-lived to keep the capital tied up in margin accounts in check. They trade a lot intradaily and avoid carrying a position overnight. These characterizations suggest that HFTs are best thought of as a new type of intermediary, either benefiting market quality or hurting it. This important question is fiercely debated in industry, among regulators, in the media, and in a rapidly growing academic literature that I will survey in this paper.

Before sinking deeply into the literature, I would like to share an observation that is often overlooked in the heated debate. HFTs and new venues helped us migrate quickly to electronic trading which, in turn, yielded lower transaction cost and more volume. Let me develop this argument in the next few paragraphs.

Electronic trading, new venues, and HFTs are intimately related. There is arguably a symbiotic relationship between new electronic venues and HFTs. These new venues need

Figure 1

Fisher Black's vision of a fully automated exchange appeared in the Financial Analyst Journal in 1971 (Black 1971a, 1971b).

HFTs to insert aggressively priced bid and ask quotes, and HFTs need the new venues to satisfy their requirements in terms of automation, speed, and low fees (more in Section 3.4).

The electronic market structure that resulted could be viewed as the product of automation. Replacing humans by machines yielded cheaper production in many industries,

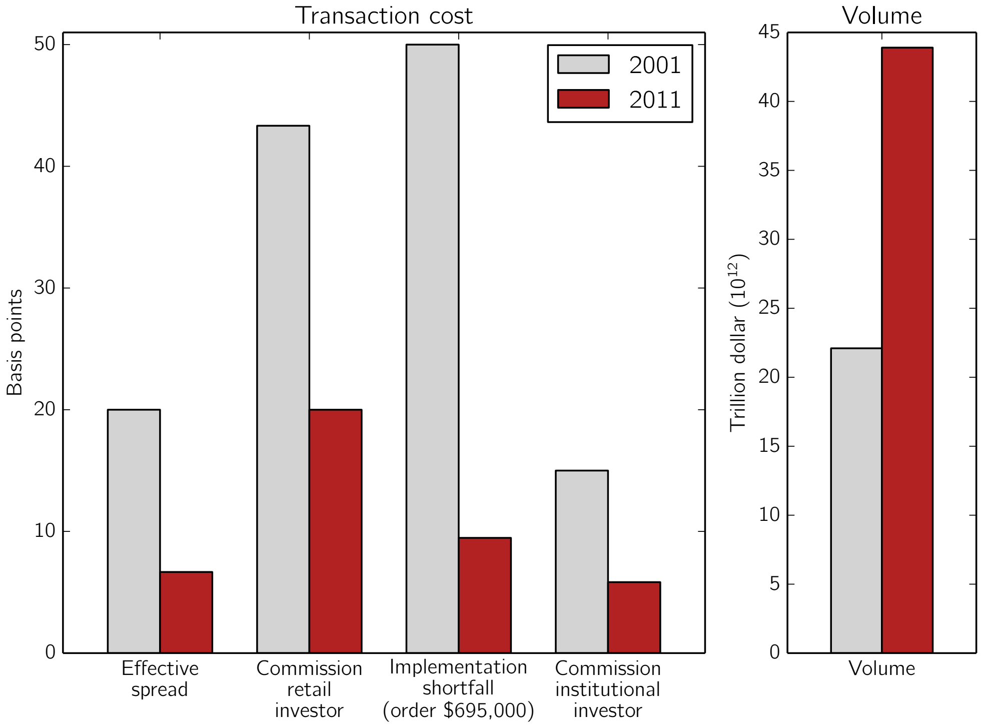


Figure 2

This figure plots estimates of implicit and explicit transaction cost for US equity in 2001 and 2011, arguably pre- and post-HFT-entry. The NYSE/NASDAQ effective spread and retail commission were taken from Angel, Harris & Spatt (2015), implementation shortfall from Frazzini (2012), and institutional investor commission from Cappon (2014). Average stock price was assumed to be $30 (Angel, Harris & Spatt 2015, p. 23) and the average retail order size was assumed to be $6000 (Lee & Radhakrishna 2000, p. 102). Volume is expressed in Feb 2016 dollars and was taken from data.worldbank.org.

so why not in the industry of securities trading? There is a lot more to say about "production" here, but it is useful to at least consider one measurable characteristic of securities markets: end-user transaction cost. Did it indeed decline and, if so, by how much?

Figure 2 depicts how transaction cost changed for US equities from 2001 to 2011. Arguably the most dramatic market structure changes for US equities all happened in this time span. For example, the New York Stock Exchange (NYSE) lost its dominant position in trading NYSE-listed shares, mostly to new electronic venues. It responded by changing its floor operation first into a hybrid market, but eventually into a fully electronic market. Also, high-frequency traders were largely absent in 2001 but participated in about half of the trades at the end of the decade (SEC 2010). The quote to trade ratio increased tenfold, from 2 in 2001 to 20 in 2011 (Angel, Harris & Spatt 2015).

The figure shows that end-user transaction cost declined substantially in this period, at least 50% in all categories. For example, the effective spread that investors paid on their market orders was 20 basis points (bps) in 2001 and 7 bps in 2011. This spread is a reasonable measure of the implicit trading cost for retail investors as their orders are small enough to trade through a single market order. The explicit cost of trading for them (i.e., the broker commission) was 43 bps in 2001 and only 20 bps in 2011. Institutional investors trade larger orders and minimize their price impact by splitting them into into many small child orders that are fed to the market sequentially. Their total transaction cost, referred to as implementation shortfall, was 50 bps in 2001 and only 9 bps in 2011. The explicit cost for them was 15 bps in 2001 and 6 bps in 2011.

Figure 2 further shows that US equity volume doubled from 2001 to 2011. This increase suggest that more securities were transferred from low- to high-marginal-utility investors. I carefully picked the word "suggests" as trades are typically intermediated and therefore volume numbers overstate true reallocation among end-users. If intermediation chains lengthened with the entry of HFTs, then reallocations might not have grown as much as volume did (more in Section 3.6).

The much lower transaction cost and strong volume growth do not, of course, prove that the current market structure is optimal. Perhaps electronic markets without HFTs could produce even better service at lower cost. This is what the public debate has centered on (although these markets might not have arrived without HFTs as argued above). Two popular books all but vilified high-frequency traders associating them with algo wars that leave "a path of destruction in their wake" (Patterson 2012, p. 63) or with "systemic market injustice" due to HFTs front-running orders (Lewis 2014, p. 70). Well-known financial economists contributed by publicly sharing their impressions of high-frequency trading: Paul Krugman and Joseph Stiglitz — both Nobel laureates — expressed concern (Krugman 2009; Stiglitz 2014), Burton Malkiel emphasized benefit (Malkiel 2009), and John Cochrane shared how it all puzzles him (Cochrane 2012).

Objective. The public debate on HFTs raged since 2009 thriving mostly on conjectures and fears. Opinions fail to converge. The only thing all seem to agree on is that the key distinguishing feature of HFTs is their relative speed advantage for trading a particular security. One reason for such an advantage is *information technology* that enables them to quickly generate signal from the massive amount of (public) information that reaches the market every (milli-)second. Examples are press releases by companies, governments, or central banks, analyst reports, or trade information including order-book updates not only for the security of interest but also for correlated securities. Another, more narrow, reason for HFT speed advantage is *quick access* to such information (by using, for example, microwave towers, Laughlin, Aguirre & Grundfest 2014).

In parallel to this public debate lots of scholars thought deeply about how HFTs could affect market quality. Theorists wrote down models to tease out what the social costs and benefits are of having extremely fast intermediaries in the market. Empiricists creatively exploited the scarce data available.

The focus and scope of this survey is the HFT literature. I review the theoretical papers on HFT, weigh them by the amount of supportive evidence in empirical HFT papers, and come to a reasoned judgment on the net economic value of HFT. This structure distinguishes it from the many excellent HFT surveys that appeared thus far: Biais & Woolley (2011), Chordia, Goyal, Lehmann & Saar (2013), Easley, López de Prado & O'Hara (2013), Gomber, Arndt, Lutat & Uhle (2011), Goldstein, Kumar & Graves (2014), Jones (2013), Kirilenko & Lo (2013), Biais & Foucault (2014), SEC (2014), and O'Hara (2015).

The remainder is structured as follows. I start by discussing what could be learned about HFT by extrapolating from a classic model (Section 2). I then discuss the new models by grouping them into seven categories (Section 3). For each category I also review the empirical papers that speak to either the assumptions of these models or their predictions. The survey concludes with an evidence-weighted verdict on whether HFTs benefit security markets or not. In this sense, we “take stock” of the HFT literature.

2. SPEED AND TRADING: EXTRAPOLATIONS FROM A CLASSIC MODEL

Before reviewing any new model proposed for HFTs, it is useful to ask what classic models can tell us about adding faster agents. Perhaps the model that speaks most to high-frequency trading is one that emphasizes how information asymmetry affects trading. A classic reference is Glosten & Milgrom (1985) who model how a specialist issues price quotes to buy or sell a security, bid and ask quotes respectively. He is risk-neutral and acts under competitive pressure. If information were symmetric across the specialist and the investors he trades with, then the zero profit condition implies that he sets his bid and ask price equal to the expected payoff of the security. The bid-ask spread thus becomes zero as he is not adversely selected on his quotes.

Asymmetric information with some investors being better informed, drives a wedge between the bid and ask quote. These informed investors may be thought of as corporate insiders or as (p. 77) “individuals who are particularly skillful in processing public information.” I will revisit this latter interpretation in the context of high-frequency traders, in particular when discussing run games in Section 3.3.

This parsimonious model yields two important economic insights. First, the informed earn a positive profit effectively paid for by the uninformed. Second, the larger the information asymmetry is between the informed and the uninformed, the larger the transfers are between them. The cost for the uninformed might at some point exceed their private gains from trade in which case information asymmetry leads to market breakdown.

How would speed affect trading in this model? If one were to replace the specialist by a high-frequency trader, then this speed upgrade will help the market maker maintain his price quotes. He is now able to quickly parse the public flow of information for value-relevant signals, and update his quote fast when needed. This reduces information asymmetry at least vis-à-vis informed investors who get their information advantage off of public news. Loosely extrapolating from the Glosten-Milgrom model along these lines suggests:

1. A tighter bid-ask spread due to
2. Less adverse-selection cost,
3. More quote updates in between trades,
4. More price discovery through these quote updates as opposed to trades,
5. A higher trade probability as the tighter spread creates more trades either at the intensive margin (existing investors trade more) or at the extensive margin (new investors enter); the tighter spread enables investors to lock in private gains from trade that would otherwise have been too small to make up for paying the (half) spread.

These observations correspond to some of the empirical facts documented for HFTs, mostly reviewed in Section 3.1. This section features models that embed the speed/informational friction of HFTs in the most common electronic market structure: limit-order books. The models echo some of these predictions developed by loose extrapolation, but derive them more rigorously in often much richer models. For example, HFTs might endogenously become either markers or takers of price quotes.

I discussed only one classic model to help shape intuition. For excellent reviews of classic theory I refer to O'Hara (1995), Biais, Glosten & Spatt (2005), Parlour & Seppi (2008), de Jong & Rindi (2009), Foucault, Pagano & Röell (2013), and Vayanos & Wang (2013).

3. SPEED AND TRADING: INSIGHTS FROM NEW MODELS

The discussion of recent theoretical work on HFT is grouped into seven subsections. Each of them first reviews the economic insights that the new theory provides, then discusses relevant empirical work on the issue, and concludes with a brief summary. All discussions will be extremely brief. For example, I do not mention the data used in the empirical papers I review unless it is non-standard (i.e., non-equity) data. Proceeding this way guarantees a steady flow of insights and empirical facts.

The following terminology is used throughout:

Acronym	Description
HFT	High-frequency trader
HFM	High-frequency market maker: an HFT who trades passively by submitting bid and ask quotes for others to take
HFB	High-frequency bandit: an HFT who trades aggressively by taking out stale quotes quickly after seeing (public) information
OT	Other trader: anyone who is not an HFT

Table 1 characterizes all theoretical papers I reviewed in terms of their structure and results.

3.1. Speed dispersion in limit-order markets

Most electronic exchanges operate as a limit-order market. A limit order is essentially a price quote to either buy or sell a pre-specified amount of securities. The exchange processes incoming orders in continuous time. It tries to match any new order against a stock of unexecuted orders. If there is such match then the incoming order is referred to as a market order. If in fact many matches are possible, then a market sell order will be matched with the highest priced limit buy, referred to as the best bid, and a transaction is concluded at that price. A market buy will trade with the lowest limit sell, referred to as the best ask. If there is no match, the new order will be added to the stock of unexecuted orders, the limit-order book. The distance between the best bid and the best ask is referred to as the bid-ask spread. I refer to Parlour & Seppi (2008) for an in-depth review of limit-order markets.

3.1.1. Theory.

HFTs as better informed agents good. Aït-Sahalia & Saglam (2014) analyze a more informed HFM in a continuous-time dynamic inventory model. They find that if the HFM is better able to predict the sign of future market orders, then the liquidity he provides improves. He adds more depth to his bid and ask quote (he cannot change the spread as the authors assume it is to be fixed). Goettler, Parlour & Rajan (2009) also find liquidity improvement when market makers become more informed about fundamental value. In their model, agents arrive randomly and, conditional on the state of the limit-order book, they decide to either send a limit or a market order. They find that low private value

Table 1 Structure/results of reviewed papers.

Paper	Model structure						Model results				
	HFM endogenous?	HFB endogenous?	OT trading endogenous?	Information endogenous?	Market fragmentation?	Dynamic model?	Analytic results?	Effect on liquidity?	Effect on volatility?	Effect on welfare?	Policy evaluation?[a)]
Aït-Sahalia & Saglam (2014)	✓					✓	✓	✓	✓		✓
Baldauf & Mollner (2015)	✓	✓	✓	✓	✓		✓	✓	✓		✓
Baruch & Glosten (2016)	✓						✓	✓			
Bernales (2014)	✓	✓	✓			✓		✓	✓	✓	✓
Biais et al. (2015b)		✓	✓	✓	✓		✓	✓		✓	✓
Bongaerts & Van Achter (2015)	✓			✓		✓	✓	✓	✓	✓	✓
Bongaerts et al. (2015)	✓	✓				✓	✓	✓		✓	
Boulatov et al. (2016)	✓		✓			✓	✓	✓			
Brunnermeier & Pedersen (2005)	✓					✓	✓	✓	✓	✓	
Budish et al. (2015)	✓	✓					✓	✓		✓	✓
Cartea & Penalva (2012)	✓		✓				✓	✓	✓	✓	
Cespa & Vives (2015)	✓		✓			✓	✓	✓	✓	✓	
Du & Zhu (2014)	✓		✓	✓		✓	✓	✓	✓	✓	
Foucault et al. (2016)		✓				✓	✓	✓			
Foucault et al. (2015)	✓	✓	✓		✓		✓	✓			
Glode & Opp (2016)	✓						✓	✓		✓	
Goettler et al. (2009)	✓	✓	✓	✓		✓		✓	✓	✓	
Han et al. (2014)	✓						✓	✓			
Hoffmann (2014)	✓	✓	✓			✓	✓		✓	✓	✓
Jarrow & Protter (2012)		✓				✓	✓		✓	✓	
Jovanovic & Menkveld (2015b)	✓						✓	✓	✓	✓	
Jovanovic & Menkveld (2015a)	✓	✓	✓				✓	✓		✓	
Li (2014)		✓	✓	✓		✓	✓	✓	✓	✓	✓
Li (2015)		✓		✓		✓	✓	✓	✓	✓	
Menkveld & Yueshen (2014)	✓		✓	✓	✓		✓	✓	✓	✓	
Menkveld & Zoican (2016)	✓	✓					✓	✓		✓	
Pagnotta & Philippon (2015)	✓	✓	✓		✓	✓	✓	✓		✓	✓
Roşu (2016)		✓		✓		✓	✓	✓	✓		
Weller (2013)	✓					✓	✓	✓		✓	
Yang & Zhu (2015)		✓	✓	✓		✓	✓	✓	✓		

[a)] Policy-relevant means that the manuscript explicitly discusses regulatory proposals.

agents endogenously become market makers. If these agents become more informed liquidity improves.

HFTs as faster acting agents bad. Bernales (2014) extends the Goettler et al. (2009) model by randomly assigning agents to be either fast or slow. He finds that creating such speed dispersion leads to less gains from trade being realized. Slow traders are effectively forced out of using limit orders due to increased adverse-selection risk. Hoffmann (2014) analyzes a model where HFTs quickly cancel their outstanding limit orders after news. This endogenously makes OTs post limit orders at less aggressive prices reducing the trade rate and welfare. Du & Zhu (2014) vary speed in their model by adding more trading rounds per time unit. Only HFTs have the ability to keep up and be present in all rounds. They thus effectively force themselves in between trades of OTs who do not have such ability. OTs experience higher trading cost as a result.

HFTs as faster informed and faster agents either good or bad. Bongaerts & Van Achter (2015) focus on HFM price competition in a limit-order market and find that increased speed (in terms of contact rate) leads to faster undercutting and therefore benefits liquidity. If HFMs further have an informational advantage then liquidity is reduced due to increased adverse selection risk for OT market makers. Jovanovic & Menkveld (2015b) find that the entry of well informed and fast HFTs raises welfare when OTs use them to reduce information asymmetry between them. An early OT seller might post an ask quote (through a limit sell order) but suffers adverse-selection cost when trading with a late OT buyer who might have seen (common-value) news that arrived in between their arrivals. HFTs effectively offer the seller a cost-free route to the buyer when the seller sells to HFTs who can post and update an ask quote aimed at the late buyer. HFTs have the information and speed to do such updating. They show that more gains from trade are realized this way. If however HFTs see news that even the buyer was not aware of, then they can reduce gains from trade as they effectively add adverse-selection cost to the trading game. An important implication that follows from their analysis is that one needs to exercise extreme caution when interpreting lower bid-ask spreads as better market quality. In the model, a reduced spread due to HFT entry might be dominated by OTs not being able to earn the spread by posting a limit order themselves (due to the threat of adverse selection by HFTs).

3.1.2. Evidence.

HFTs are extremely fast. Menkveld (2016) analyzes nanosecond data and finds that 20% of trades cluster within a millisecond. The analysis suggests HFT response times are in the order of microseconds (one microsecond is 10^{-6} second).

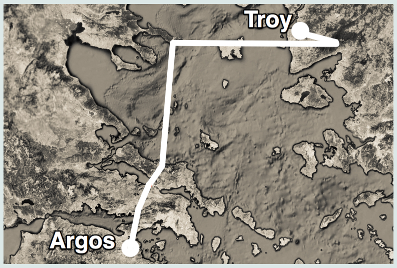
High-frequency market making. The early empirical papers examined algorithmic traders (ATs) a group that includes high-frequency traders but more generally all traders who use computers to automatically make trade decisions. An example of a non-HFT algorithmic trader is one who aims to minimize the price impact of a large order that has to be executed. Such order is typically executed through a series of smaller child orders that are sent to the market sequentially.

Hendershott, Jones & Menkveld (2011) exploit an exogenous NYSE event to establish that AT causally reduces the bid-ask spread. They find that price quote experience lower

OPTICAL DATA TRANSMISSION, THEN AND NOW

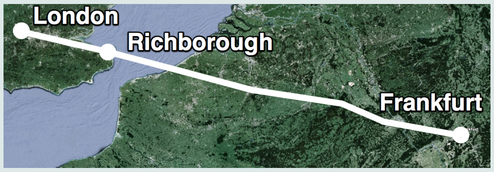
Light has been used for fast communication ever since classical age.

Then: Troy-Argos 1185 BC



Agamemnon used prearranged beacon fires to announce the fall of Troy to his wife Clytemnestra in Argos. Speed turned against him as it gave her and her lover time to prepare for his assassination. Note that the small detour at Troy adds latency to the one-bit communication line — light needed to travel up the nearest mountain before it could travel across the sea (Laughlin 2014).

Now: Frankfurt-London 2016 AD



Vigilant Global, an HFT, reportedly plans to build a tower taller than the Eiffel tower in a town in south-east England: Richborough. In a local town hall meeting a company spokesman informed worried residents but was rather vague about what the tower would be used for. (Laumonier 2016).

adverse-selection cost which explains the lower spread. They further document that more AT results in more price discovery through quotes as opposed to trades. Malinova, Park & Riordan (2013) also find that AT reduces spread exploiting a Canadian regulatory fee change.

Hendershott & Riordan (2013) show that ATs are quick to post limit orders when spreads are wide, but take limit orders when spreads are narrow. Latza, Marsh & Payne (2014) zoom in on "fast" market orders. They define them as market orders that are quick to arrive after a limit order was added to the book (they arrived within 50 milliseconds of such event and traded with these limit orders). The authors find these fast market orders to be uninformed, potentially indicating HFMs offloading inventory.

Empirical studies on data samples with HFTs identification generally echo the findings of AT studies. In particular, HFTs are more likely to add limit orders to the book when the spread is wide, and thus supply liquidity (Carrion 2013; Jarnecic & Snape 2014; Hagströmer, Nordén & Zhang 2014). Similarly, Yao & Ye (2015) find that HFT liquidity supply is larger for stocks for which the spread is constrained to be large due to tick size.

More HFT competition seems to further decrease the spread, and lead to quicker recovery of the spread after it widened (e.g., after a market order arrival). Hasbrouck (2015) finds positive skewness for ask quote changes and negative skewness for bid quote changes. He interprets it as Edgeworth cycles, essentially HFTs undercutting each other leading to gradual price improvement until a large market order hits and removes the best price quote(s), thus making the best quote move by potentially multiple ticks. Brogaard & Garriott (2015) have HFT identification and find that HFT entry is followed by a reduction in the bid-ask spread. The result is strongest when an HFT is the first to enter.

HFTs further supply liquidity by trading against (transitory) price pressures. Boehmer, Li & Saar (2015) find that HFTs follow similar strategies and the extent of their competition (or correlated activity) is negatively related to short-term volatility. They interpret this finding as consistent with competition between HFTs in market-making. Brogaard, Hendershott & Riordan (2014b) use the state space model of (Hendershott & Menkveld 2014) to identify the permanent and transitory component in price changes. They find that HFTs trade against transitory shocks. Brogaard, Carrion, Moyaert, Riordan, Shkilko & Sokolov (2015a) analyze extreme price movements and find them to be caused by non-HFT order imbalance. HFTs trade against them and thus stabilize prices. Benos, Brugler, Hjalmarsson & Zikes (2015) also find a strong commonality in HFT order flow and their trading (p. 1) "does not generally contribute to undue price pressure and price dislocations."

Perhaps colocation events provide the best laboratory to study how HFTs affect limit-order markets. A reasonable conjecture is that HFTs benefit most from colocation, the service an exchange provides (at a fee) to locate close to the exchange server. One could therefore interpret the results of a colocation event study as evidence of "more treatment with HFTs." Boehmer, Fong & Wu (2014) find that colocation reduces the bid-ask spread and improves the quality of price discovery. Gai, Yao & Ye (2013) also find that order book liquidity improves, but through more depth rather than an improved spread. Brogaard, Hagströmer, Nordén & Riordan (2015b) study a colocation event where traders are given various options. They find that the fastest colocation service is primarily used for HFT market making. This suggests that HFTs endogenously become market makers, as predicted by theory.

Type of information. The evidence discussed thus far showed that HFTs are quick to snap up the bargains provided by spread-improving limit orders, but are they also more informed? If so, what type of information do they have access to? To whet the appetite Figure 3 illustrates how an HFM's limit orders (right-hand side) are relatively short-lived and generally in sync with the best bid and ask quote when compared to all other limit orders (left-hand side). This pattern suggests quoting by a fast and informed trader.

HFTs seem to actively manage their limit orders and these quote updates reflect information. Hasbrouck & Saar (2013) provide the most detailed account of active limit-order managements. They find that about 60% of quote cancellations are followed by resubmissions within 100 milliseconds (of which 49% at one or zero milliseconds). The median stock experienced 26,862 limit order submissions (daily average), 24,015 limit order cancellations, and 2,482 market orders. Brogaard, Hendershott & Riordan (2015c) document that the majority of price discovery occurs through quote updates as opposed to trades. HFTs produce

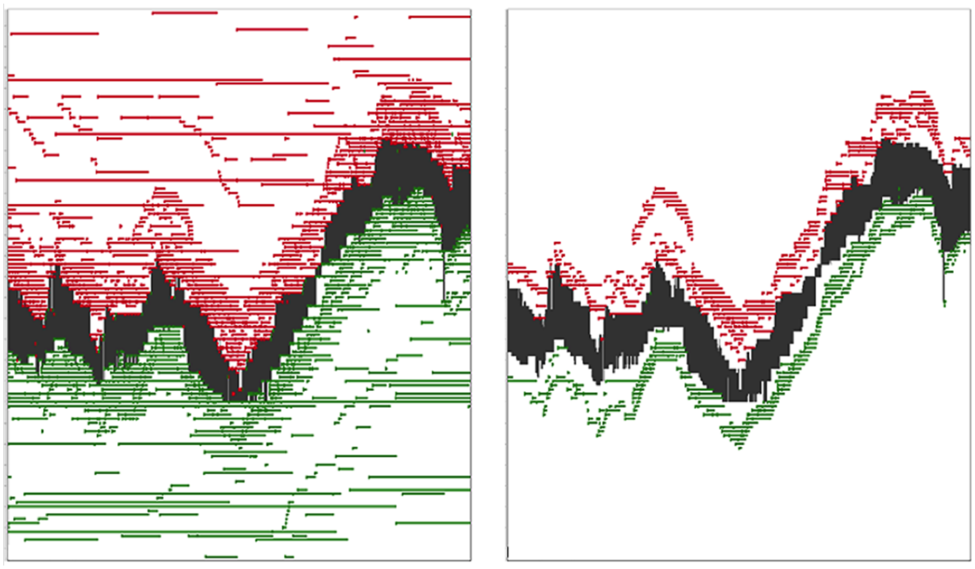


Figure 3

This figure illustrates order book dynamics for one security traded at Euronext Amsterdam. The graph on the left illustrates dynamics of the entire book where time is on the horizontal axis and price is on the vertical axis. A red/green bar depicts the life of a limit sell/buy order (ask/bid quote). The black area depicts the bid-ask spread. The graph on the right repeats this graph, but only shows the limit orders of one HFT. Source: AFM (2016, Fig. 1).

most of this information in quote updates, 60-80% of it.

HFTs are quick to process public information. Hu, Pan & Wang (2014) show how powerful their textual algorithms are when parsing macro announcements. They find that when the news is released to HFTs two seconds before the official announcement, most of the index-futures price discovery happens within 0.2 seconds after HFTs had their early peek. HFT will also parse order flow to predict price changes. Harris & Saad (2014) show that future returns can indeed be predicted based on the (publicly available) message traffic between traders and the exchange. The size of message traffic quickly makes this a "big data" challenge. HFTs will further try to obtain such data quickly, typically by subscribing to proprietary data feeds made available by the exchange. Ding, Hanna & Hendershott (2014) show that these feeds lead the public data feed by milliseconds. Finally, Jovanovic & Menkveld (2015a) find that a large HFM uses index futures information to update his quotes.

HFMs are informed, but cannot completely avoid being adversely selected on their quotes. Menkveld (2013) and Brogaard, Hendershott & Riordan (2014b) find that also HFMs are adversely selected on their quotes. Fishe, Haynes & Onur (2015) study trading around local price trends. They find that those who best predict either the start or the end of such trend are typically not the fastest traders.

Net effect of HFT entry in limit-order markets. The evidence suggests HFTs are both fast and informed. Theoretical studies predicted results to be mixed in this case. Jovanovic

& Menkveld (2015a) calibrate their model based on an event that led to HFT entry. They find a moderately positive welfare effect.

3.1.3. Summary. HFTs reduce market quality if they are faster to act than others. They increase market quality if they are better informed. If both, then the prediction is non-trivial. The evidence is that they are both extremely fast to act and better informed. Colocation event studies and a model calibration suggest that the net effect for market quality is moderately positive.

3.2. Speed used to prey on large orders

3.2.1. Theory.

HFTs preying on large uninformed orders. Brunnermeier & Pedersen (2005) show that strategic traders could prey on (inelastic) demand from a distressed uninformed trader. This trader sees liquidity suddenly diminish when the predatory traders trade in the same direction. This paper is the only non-HFT paper added to the review simply because HFTs are often referred to as predatory traders. They dominate the market in the short-run and rationally exploit their speed.

HFTs preying on large informed orders. HFTs will prey on informed orders once they learn about them, thus delaying price discovery and potentially reducing long-term efficiency. Li (2014) finds that if HFTs anticipate incoming orders then liquidity is reduced, more so when these HFTs have heterogeneous speeds. Yang & Zhu (2015) find that if HFTs become particularly good at detecting informed orders, then their "back-running" will make the informed trader switch to a mixed strategy. Both papers emphasize that the informed trader's endogenous response of trading less aggressively delays price discovery. The trader might forego collecting information altogether in which case this information might never be revealed in prices, thus hurting long-term efficiency.

Boulatov, Bernhardt & Larionov (2016) study Nash equilibria when multiple traders seek to minimize transaction cost when trading continuously in a fixed time period. Each trader takes the price impact function as exogenous. This function makes the net order flow have both a transitory and a permanent price impact (in the sense of Almgren & Chriss (2000)). They find that traders who have a small position to trade, either lean against the orders of large-position traders or prey on them. Both types of behavior can occur in equilibrium. The large-position traders' optimal response to preying is to delay trading.

3.2.2. Evidence. The findings in various empirical studies suggest that HFTs are able to predict order flow. Hirschey (2016) provides perhaps the most direct evidence. He reports that this second's HFT aggressive flow predicts OT aggressive flow in the next 30 seconds. He interprets this finding as anticipatory trading by HFTs. In further analysis he discards various alternative interpretations: HFTs reacting faster to news, positive-feedback trading by OTs, or HFTs being misclassified as OTs. Breckenfelder (2013) finds that HFT entry makes stocks less liquid measured at a daily frequency. The new HFT might have ways to detect informed order that differ from incumbent HFTs, thus worsening trade condition for OTs. Raman, Robe & Yadav (2014) find that electronic market makers withdraw at times of directional flow.

Some studies focus on institutional investors executing large orders through multiple (child) trades. They find that transaction costs are higher when HFTs run on their orders. Brogaard, Hendershott, Hunt & Ysusi (2014a) use exchange speed upgrades to identify a causal effect. They find that HFT activity increases around such events, but institutional investor cost remains unchanged. They are careful to note that statistical power is low as HFTs are only a bit more active and transaction costs of institutional investors are volatile. Korajczyk & Murphy (2016) and van Kervel & Menkveld (2015) analyze HFT trading in the lifetime of institutional orders. They both document HFTs initially lean against large institutional orders (e.g., they buy when the investor sells), but they eventually switch and trade along with the long-lasting ones. Korajczyk & Murphy (2016) focus on HFT market making and inventory management. van Kervel & Menkveld (2015) further analyze the same-direction trading. They find that it is stronger than simply closing the initial position built up when trading against the institutional order. HFTs not only close the position but seem to enter a position in the direction of the order. They show that such behavior is profitable for HFTs and that, coincidentally, transaction costs are higher for institutional investors when HFTs engage in such trading. They further show that the institutional orders for which this happens are informed and interpret the evidence as being consistent with back-running.

Finally, less price discovery ahead of announcements might be early evidence of delayed price discovery due to predatory trading. Weller (2016) finds that algorithmic trading proxies correlate positively with price jumps on earnings announcements. This finding suggests that AT presence discourages costly information acquisition ahead of an announcement.

3.2.3. Summary. If HFTs have an ability to detect large orders of OTs then they could prey on them. This raises OT transaction cost and leads to slower price discovery. The evidence suggests HFTs are able to predict OT orders, and back-run on long-lasting informed orders of institutional investors. The latter experience higher transaction costs when this happens.

3.3. Speed in a run game after (public) news

3.3.1. Theory. HFTs all trading on the same public signal creates costly run games in continuous-time markets. That public-news trading comes with a negative externality was well known for human-intermediated markets (Foucault, Röell & Sandås 2003). Budish, Cramton & Shim (2015) explore it for HFTs trading in continuous-time markets and show that a wasteful arms race becomes inevitable. When the news breaks both the HFM and the HFBs run to the market. If the HFM arrives first he will update his outstanding quote. If the HFB arrives first he will trade with the stale quote and thus impose adverse-selection on the HFM. The latter anticipates such cost and raises the spread accordingly effectively making OTs pay for this cost. The run game further incentivizes HFTs to engage in a wasteful arms race (e.g., HFTs building towers as discussed in the text box on p. 10). The authors argue that the root cause of this dead-weight cost is that venues match orders in *continuous time*. They show that changing to (high-frequency) discrete time batch auction reduces the benefit of speed investment by an order of magnitude. This largely avoids the costly arms race.

Run games in the context of multiple markets. Costly speed races seem particularly relevant in multi-market settings where an event in one market (e.g., the arrival of a market sell order) serves as the public signal. Foucault, Kozhan & Tham (2015) show that such run game creates toxic arbitrage and thus widens the bid-ask spread. They essentially add speed as a choice variable to earlier work on arbitrage and differential speed (Kumar & Seppi 1994). Biais, Foucault & Moinas (2015b) argue that becoming an HFB (fast trader) is privately beneficial as it enables one to find the best price in a fragmented setting, yet it is socially costly as it creates adverse-selection cost for low-frequency market makers. Baldauf & Mollner (2015) show that increasing exchange speed stimulates cross-market HFB activity and thus reduces the incentive of an analyst to collect information. The moment one of the analyst orders hits a market, HFBs learn about it and quickly trade on this signal in other markets. Random communication latency (delay) makes it impossible for all of the analyst orders to arrive at all of the markets at exactly the same time. This reduced ability for an analyst to trade on his information harms long-term efficiency (similar in spirit to Li (2014) and Yang & Zhu (2015) discussed in Section 3.2.1).

Run games with speed heterogeneity across HFTs. HFTs operating at different speeds has a nontrivial effect on the bid-ask spread. Han, Khapko & Kyle (2014) show that informed fast market makers impose a winner's curse on slow ones. A crucial parameter is the probability that fast HFMs shows up in the market (an event that is independent of news). If fast HFMs appear with higher probability then the always present slow HFMs have to raise the spread they charge. But, at the same time, these wider spreads are more likely to be undercut by fast HFMs who arrive with higher probability. The authors show that the net effect could go either way. Foucault, Hombert & Roşu (2016) propose a dynamic model where securities with more informative news attract more HFBs, yet the average effective spread is lower. The reason is that trading with HFBs after news imposes adverse-selection cost on market makers thus raising the spread, but the more informative news *itself* lowers the spread. The latter effect dominates in equilibrium.

The effect of exchange speed on run games. A faster exchange could either lower the bid-ask spread, or increase it. Menkveld & Zoican (2016) find that making exchanges faster raises the probability of an HFM-HFB run game after news. A slower exchange helps an HFM to avoid such duels as, the moment news hits, the exchange might still be processing an OT order that is on its way to the matching engine. If this is the case then the outstanding HFM quote will meet the OT order and thus evade the costly HFT duel. The upside of a faster exchange is that it allows an HFM to refresh his quotes more often and thus reduce adverse-selection cost should it come to a duel. The authors find that increasing exchange speed lowers the bid-ask spread if the news-to-liquidity-trader ratio is high, but increases it when this ratio is low. Li (2015) analyzes exchange speed by changing the frequency of batch auctions. He generalizes the standard Kyle (1985) model by replacing the monopolistic informed trader by an oligopoly of them. He finds that batching orders less frequently does not necessarily improve market quality. The profitability of informed traders drops and some might have to exit for informed trading to remain profitable (net of a fixed cost). The ones who remain experience less competition, extract more rents, and this increases the transaction cost of others.

Persistent pricing errors. Jarrow & Protter (2012) show that if HFTs collectively trade on public signals then this does not necessarily yield "value discovery." They show that it might lead to persistent pricing errors in such a way that the no-arbitrage condition is not violated.

3.3.2. Evidence. High-frequency traders actively engage both in market-making and in sniping stale quotes. Hagströmer & Nordén (2013) document strong persistence in types with about half a dozen HFM types and two dozen HFB types. Benos & Sagade (2016) find the same and further report that both types seem to be informed. Brogaard, Hendershott & Riordan (2014b) carefully distinguish transitory and permanent price changes and find that HFT market orders trade in the direction of permanent price changes, and HFM limit orders opposite to them. Brogaard, Hendershott & Riordan (2016) use the 2008 short sales as an instrument to identify that HFTs adversely select limit orders and thus affect liquidity negatively. The evidence in these papers is consistent with the hypothesized HFB-HFM duels.

Other studies provide perhaps more direct evidence of HFB-HFM run games. They show that a stronger HFB presence correlates with a higher spread, and only the fastest market makers still earn a positive (gross) profit. Brogaard & Garriott (2015), for example, find that the exit of aggressive HFTs leads to an improved spread. van Kervel (2015) documents that an increase in fast traders imposes additional cost on market makers who quote in multiple venues. Biais, DeClerck & Moinas (2015a) find that only the fastest traders earn a small positive (gross) profit on their limit order executions; the adverse-selection cost they incurred was just short of the (half) spread they earned. Menkveld (2016) finds the same for a dataset with HFT identification: HFTs earned money on their limit-order executions, OTs lost money on limit-order executions (net of the rebate that market makers received in case their order executed; by the way, there was no such rebate in the Biais et al. sample). Chaboud, Hjalmarsson & Vega (2015) study the introduction of a 250 milliseconds minimum-quote-life (MQL) and find that it reduced the adverse-selection cost for OTs, but did not change the bid-ask spread. These two observations are not necessarily inconsistent as Han, Khapko & Kyle (2014) emphasize that the lower spreads OTs are able to post might be offset by fewer HFMs willing to undercut them (as they cannot quickly remove their quotes after seeing news). These two might cancel so that the *average* spread remains unchanged.

The multi-market models get some empirical support from two foreign exchange studies. They both find that HFBs are highly active in a multi-market setting. Chaboud, Chiquoine, Hjalmarsson & Vega (2014) analyze triangular arbitrage and document that arbitrage opportunities decline after machines (HFBs) entered the market. Foucault, Kozhan & Tham (2015) find that the days with more run games (toxic arbitrage) are also the days with higher spreads.

Finally, the evidence on how an exchange speed upgrade affects the bid-ask spread suggests a weakly negative correlation. Riordan & Storkenmaier (2012) find a lower spread after a speed upgrade, but only for small stocks. Gai, Yao & Ye (2013) find no relationship between the two.

3.3.3. Summary. Public signals trigger HFT run games. HFMs run to update their outstanding quotes; HFBs run to take out the stale quotes. These run games make trading more costly for OTs, in particular since HFTs need to recoup the costs of an arms race. Exchange speed affects these run games in nontrivial ways. The evidence is largely consistent with run games. It is mixed for how exchange speed affects the bid-ask spread, as predicted by theory.

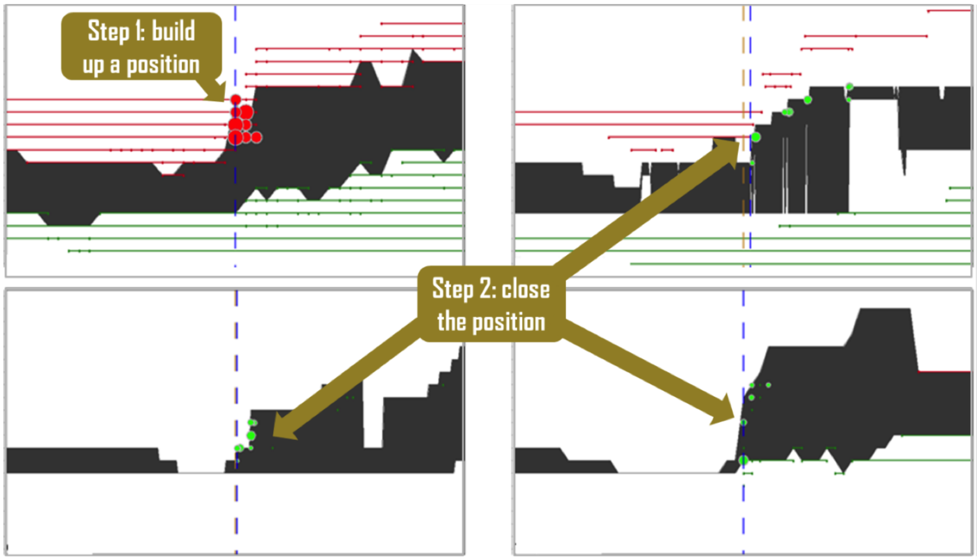


Figure 4

This figure illustrates how one HFT traded in a large Dutch cap in four limit-order books. The red/green bars depict the life of his limit sell/buy orders (ask/bid quotes). The red/green dots represent his sell/buy transactions. Larger dots correspond to larger sized transactions. The black area depicts the bid-ask spread. The top right graph shows how some traders take the HFT's ask quotes. The other graphs show how the HFT quickly closes his position by taking the ask quotes of others in the three other limit-order books. Source: AFM (2016, Fig. 8).

3.4. Speed to connect fragmented markets

Menkveld (2014) argues that the two most salient trends in securities markets since the turn of the century — order flow fragmentation and HFT entry — are intimately related, and both driven by technology and regulation. First off, it is hard for new exchanges to enter in human-intermediated markets. Opening up another trading floor and charging a lower fee is unlikely to attract order flow. The reason is that search costs (checking for a better price quote at the other floor) are high and the liquidity externality therefore is extremely high in these markets; traders go where other traders are. The incumbent exchange benefits as the competitive threat is low.

Technology and regulation changed this status quo, most dramatically in the first decade of the century. Trading floors were replaced by exchange servers matching electronic buy and sell messages. New regulation, Reg-NMS in the US and MiFID in Europe, allowed for entry of new trading venues. Entry became viable as search costs declined by an order of magnitude when humans-on-phones are replaced by computers-on-networks. It became trivial to poll other new venues for better price quotes.

High-frequency traders specialized in cross-market arbitrage and effectively matched buyers and sellers across venues. Figure 4 illustrates this by showing how one HFT traded a large-cap stock across four limit-order books. It shows that the moment his ask quotes are being taken in market A, he runs to markets B, C, and D to take the ask quotes of others and thus rid himself of the position. He connected buyers in A with sellers in B, C, and D. It makes economic sense that one group specializes in this type of activity as only they then pay the nontrivial cost of maintaining high-speed connectivity to all markets.

Venues competing for order flow benefited end users in several ways. First, it created a downward pressure on trading fees. Second, it strengthened competition among limit-order submitters leading to higher overall depth (Foucault & Menkveld 2008). Third, it fostered innovation and created heterogeneity in venues. Such heterogeneity could either improve liquidity in the presence of homogeneous investors (Parlour & Seppi 2003) or it could create value simply by serving investors with different needs.

Two recent theoretical studies both identify economic costs of speed and fragmentation. They therefore provide some counterweight to the rather rosy perspective sketched thus far.

3.4.1. Theory. Pagnotta & Philippon (2015) find that exchange competition lowers fees and raises investor participation, but entry could be excessive. Exchanges position themselves strategically on speed with some paying for a faster system to serve investors with highly volatile private values. The fastest type over-invests in speed from a social perspective as it privately benefits by differentiating a lot from others and this lowers fee competition (by effectively creating a captive client base). The slowest type under-invests for the same reason.

Menkveld & Yueshen (2014) find that fragmented markets benefit from HFT presence, except when reselling opportunities suddenly turn out to be low (e.g., due to reduced inter-market connectivity). HFTs might have just taken on inventory by buying from a large seller when they privately learn that reselling opportunities are low. They will quickly trade the hot potato among themselves on a rapidly declining (endogenous) price. The large seller interprets this volume increase as possibly indicating that lots of other end-users are present and rationally decides to accelerate his selling. The authors argue their stylized rational-expectations model could explain the Flash Crash.

3.4.2. Evidence. Menkveld (2013) finds that exchange entry reduced the bid-ask spread, but only after a large HFT switched on its quoting robots. The HFT is shown to be equally active in both exchanges, the entrant and the incumbent. Malinova & Park (2016) document how these "modern" market makers operate across markets.

The Flash Crash evidence is largely consistent with suddenly reduced reselling opportunities that left HFTs trading a hot potato in E-Mini. Kirilenko, Kyle, Samadi & Tuzun (2014, Fig. 8) shows that the steepest price drop coincides with a steep increase in HFT participation in trades. Menkveld & Yueshen (2015) find that cross-market arbitrage broke down one minute before the crash. This in turn might have been the result of data feeds suddenly slowing down as discussed in Aldrich, Grundfest & Laughlin (2016). Some OTs responded by submitting inter-market sweep orders. The stocks that fell most during the Flash Crash experienced most inter-market sweep orders (McInish, Upson & Wood 2013). This, in turn, could explain why the most fragmented ETFs suffered the deepest price declines (Madhavan 2012). Strongly fragmented securities rely most on cross-market arbitrage and become vulnerable once such arbitrage disappears. I refer to SEC (2010) for a detailed descriptive summary of the Flash Crash.

3.4.3. Summary. High-frequency traders and new venues needed each other to thrive; HFTs needed lower fees and the new venues needed attractive prices quotes. Investors benefit from lower fees and more innovation. Recent theory suggests venue competition could be further improved and (rare) Flash Crash events exist in equilibrium. The evidence is largely in line with these predictions.

3.5. Speed as a source of (endogenous) quote flickering

3.5.1. Theory. Quote flickering — the rapid change of price quotes — could be the result of healthy HFT competition. Price of others are easily learned in electronic limit-order markets and one's one price quote is easily changed. Baruch & Glosten (2016) show that fleeting orders could arise in such setting due to HFMs playing a mixed strategy over prices. They find that a pure-strategy equilibrium is "difficult to obtain." They further show that HFTs could earn rents when there are only finitely many of them. These rents disappear when taking the number of HFTs to infinity.

Jovanovic & Menkveld (2015a) find that a pure-strategy equilibrium does not exist when HFMs pay a (tiny) cost to submit a price quote. They show that in this case there is a unique mixed-strategy equilibrium. HFMs first toss a (biased) coin to decide on whether or not to issue a price quote. If yes, they then randomly pick a price quote from a non-degenerate distribution. Contrary to Baruch & Glosten (2016), they find that any HFT added beyond the first two raises the cost for OTs. The reason is that more HFTs competing adds to the total dead-weight costs of submitting price quotes. This is ultimately the result of HFTs not internalizing the negative cost they impose on others when deciding to submit a price quote.

3.5.2. Evidence. High-frequency flickering of quotes is episodic in nature. Hasbrouck (2015) argues that regular quotes changes are more likely the result of HFTs undercutting each other after market orders remove price quotes from the book (see earlier discussion of his paper on p. 11). High-frequency flickering is more likely to explain why Egginton, Van Ness & Van Ness (2016) find episodic bursts of quoting activity not triggered by market orders. They report that 74% of US securities experience such spikes at least once a year. Cartea, Payne, Penalva & Tapia (2016) study a 2007-2015 sample and find that the number of quotes that was canceled within 100 milliseconds peaked in 2014 at, on average, 61.8 per minute in 2014.

Price quotes seem to have become noisier over time. Hasbrouck (2015, Table X) analyzes variance ratios. He shows that 256 times the variance of 50-millisecond quote returns is 2.90 larger than the variance of 256*50-millisecond (12.8 seconds) quote returns in 2001. This ratio suggests that there is substantial noise in prices; it far exceeds one which is the value for a random walk benchmark. He further shows that ratio increased over time to 3.16 in 2011, an increase of 9%. If extreme peaks are clipped, then this ratio almost doubles from 1.55 in 2001 to 2.91 in 2011. This shows that the nature of quote changes changed over time; in 2011 they exhibit relatively more oscillations of lower amplitude. This might be due to more flickering and fewer Edgeworth cycles over time. Yueshen (2015) uses a reduced-form structural model to estimate the time trend in excess price dispersion. He estimates the size of noise in relative terms, expressed as a fraction of information flow. He finds for second by second quote returns in 2001 that the noise is about twice the size of the information in order flow (his Figure 8). In 2011 it more than doubled with noise being about five times larger.

3.5.3. Summary. Quote flickering seems endemic to HFMs competing on price. They resort to random quoting (mixed strategies) to avoid being undercut. The evidence suggests that quote flickering is episodic in nature. It seems to have grown over time in particular in the period of quick migration to electronic venues and rapid HFT growth: 2001-2011.

3.6. Speed to create productive intermediation chains

3.6.1. Theory. HFTs increase the transaction cost for others if they only add a layer of intermediation. Cartea & Penalva (2012) formalize this conjecture by analyzing HFTs that interpose themselves between "liquidity traders" and "professional traders." These HFTs exploit their monopoly to extract part of the trade surplus and thus raise the cost of trading for OTs.

Three papers argue that a longer intermediation chain could actually benefit liquidity. First, Weller (2013) shows that a chain that results from not all HFMs being equally fast increases liquidity supply. The reason is that the speed heterogeneity creates a productive ordering of events. The fastest HFMs pick out the most attractive (i.e., less informed) market orders by quickly cancelling ahead of unattractive orders. The latter thus land on slower HFMs causing them to experience higher (adverse-selection) cost. This additional cost might however be more than offset by these last movers having a lower inventory to begin with (for the simple reason that they are last movers). This implies their marginal cost is lower for taking one more security into their inventory. The author cautions that endogenizing speed might kill such potentially productive sequencing.

Second, Glode & Opp (2016) argue that intermediation chains could benefit liquidity as the chain enables intermediaries to sequentially parcel out the burden of information asymmetry across all of them. It would be too costly for any individual intermediary to intermediate alone as he would have to charge a price higher than the gains from trade, thus shutting down the market.

Third, Roşu (2016) relates hot potato trading to an "intermediation chain effect" in a model with symmetrically and privately informed HFBs. He argues that if some HFBs are faster than others, then they trade more aggressively than in a benchmark case where all HFBs have the same speed. This enables the market maker to learn more quickly and charge a lower spread on average (measured as the price impact of a market order). The author cautions that the model only focuses on HFBs, not HFMs as the market makers are assumed to be slow.

3.6.2. Evidence. Weller (2013) presents direct evidence on intermediation chains in commodity futures trading. High-frequency market makers provide rapid execution to investors and effectively consume inventory risk-bearing services from slower market makers. He finds that 65-75% of all trades are intermediated. The median chain is two members long and the longest chains consist of six members (90% percentile).

Speed not only sets HFTs apart from the rest, it also sorts HFTs into fast and fastest. Baron, Brogaard, Hagströmer & Kirilenko (2015) find that speed is a meaningful attribute of an HFT. Some HFMs are persistently faster than others and the same goes for HFBs. They further find that the fastest types earn higher profits. The exchange fosters such speed heterogeneity by offering a menu of colocation services where the faster ones are more expensive. Brogaard, Hagströmer, Nordén & Riordan (2015b) study trading before and after the exchange offered a richer menu of colocation services. If exchanges strive for maximum trade among investors, then such encouragement of speed heterogeneity is evidence that they believe intermediation chains are good for trade. The authors find that HFTs sorted themselves across the various options (not all bought the fastest service). They further show that the bid-ask spread declined and depth improved after the event, consistent with intermediation chains benefiting liquidity.

3.6.3. Summary. Intermediation chains can be useful in completing trade between end-users, either by forcing intermediaries to line up in a productive sequence, or by having intermediaries effectively share the burden of an information asymmetry, or by faster ones trading more aggressively thereby revealing information early thus reducing information asymmetry later. The evidence shows that intermediation chains exist with some intermediaries being persistently faster than others. More speed heterogeneity among HFTs is shown to reduce spread and raise depth.

3.7. Speed to satisfy investors' appetite for faster trade completion

3.7.1. Theory. If investors appreciate faster trade completion then an HFT arms race could be desirable from a social perspective. Bongaerts, Kong & Van Achter (2015) formalize this argument in a standard Merton (1969) model. They first observe that, in a continuous-time setting, price changes generate continuous-time rebalancing needs for a constant relative risk aversion (CRRA) investor. They prove that for such investor the value of rebalancing increases less than proportionally with speed in the limit. If technology cost increases more than proportionally with speed then an arms race is indeed wasteful in the limit. More generally, they note that the net result critically depends on investor preference (i.e., the shape of his utility function).

Investors might appreciate extremely fast trading but should expect episodic flash crashes to come with it. Cespa & Vives (2015) find that if some investors' hedging needs are extremely short-lived to the point that only some intermediaries are in sync, then market freezes could occur in periods when not all intermediaries are present. The reason is that the absence of some intermediaries enlarges order imbalance potentially to the point of market breakdown .

3.7.2. Evidence. The evidence is thin on this issue. Empiricists have not converged on the shape of investor utility functions thus complicating judgment on how utility scales with trading speed. Moallemi & Sağlam (2013) approaches the problem from a completely different angle to get an estimate of how beneficial lower latency is for investors. They calibrate the solution of an optimal-control problem in a partial equilibrium setting. Lower latency essentially allows an investor to reduce adverse-selection cost on his price quotes. Their calibration suggests that reducing latency from a human reaction time of 500 milliseconds to a machine reaction time of 5 milliseconds reduces such adverse-selection cost from 20% of the bid-ask spread to 5%. Finally, the occasional-flash-crash prediction of Cespa & Vives (2015) seems to be borne out by Easley, López de Prado & O'Hara (2012, 2011) who find that (initiator-signed) order imbalance was extremely high just ahead of the Flash Crash.

3.7.3. Summary. Faster trade completion might benefit investors as it keeps them closer to the frictionless target portfolio. If however markets tick faster than intermediaries can keep up with, it might come with occasional market freezes (flash crashes). The evidence on these issues is thin.

4. SUMMARY POINTS AND FUTURE ISSUES

SUMMARY POINTS

1. **Transaction costs decreased substantially.** In the decade of migration to electronic trading and HFT arrival, transaction cost decreased by over 50% for both retail and institutional investors.
2. **HFT market-making reduces transaction cost.** If HFTs enter limit-order markets with only a speed advantage, they hurt trading. If they enter with an informational advantage they benefit trading by endogenously becoming market makers. If both, then the outcome depends on the strength of both forces. The evidence is that HFTs are extremely fast and well informed. As predicted, they are important price quote submitters (i.e., market makers). A calibration finds HFT entry to have a modest positive welfare effect.
3. **HFT preying on large orders increases transaction cost.** If HFTs have an ability to predict institutional order flow, then they might extract rents by preying on these orders. The evidence suggests that HFTs are mostly market makers for large institutional orders, and only prey on them when they are extremely large and execute through a long series of child trades.
4. **An HFT run game on public signals increases transaction cost.** In continuous-time markets HFTs, both the ones with quotes outstanding and those without, race to the market on a public signal. The market makers run to update their stale quotes; the bandits run to take them out. This run game comes with an arms race that raises transaction cost. Exchange redesign could reduce this cost.
5. **HFTs facilitate venue competition.** Cross-market arbitrage by HFTs effectively connects buyers and sellers across venues. HFTs thus make venue competition possible with more innovation and lower trading fees as a result.
6. **Quote flickering as a by-product of healthy HFT competition.** Quotes flicker when HFTs play mixed strategies in equilibrium. They resubmit randomized price quotes in order to avoid being undercut. The evidence is indicative at best. Quote uncertainty has increased over time and is episodic in nature.
7. **HFTs might operate in productive intermediation chains.** An HFT intermediation chain could reduce information asymmetry and thus benefit trade. The evidence suggests such chains are prevalent.
8. **HFTs serve an investor need for continuous rebalancing.** Faster trading adds opportunities to rebalance for investors. The additional marginal utility this yields is unlikely to offset the marginal cost of an HFT arms race.
9. **Bottom line: I believe economic benefits outweighs costs.** Electronic markets and HFTs arrived and coincidentally transaction costs declined for investors. This suggests the identified economic benefits of HFTs (market making, venue competition, more trading opportunities) outweigh their economic costs (large-order predation and run games). Market quality might be further improved by exchange redesign to stimulate the economic benefits of HFT and reduce their costs (e.g.,

through frequent batch auctions). Fisher Black's automated stock exchange arrived, reduced costs, but might not be in its best possible shape yet.

FUTURE ISSUES

1. An issue that continues to concern regulators and the public at large is HFTs manipulating markets to their advantage. For example, can momentum ignition strategies exist (SEC 2010, p. 56, spoofing) in equilibrium? If so, under what conditions? And, how might trading protocols be redesigned to reduce such practice? The same can be asked for other manipulative strategies such as smoking or spoofing (Biais & Woolley 2011)?
2. Is there systemic risk embedded in electronic trading? Do automated strategies crowd out human judgment in a way that prices might become less informationally efficient (in the sense of less revelation of soft information such as the quality of a new management team or the value of a patent)? In what circumstances does this occur?
3. Might machine-intermediated markets be better simply because they reduce the cost of behavioral biases present in human-intermediated markets? For example, Coates, Gurnell & Rustichini (2008) find that some human traders are biologically predisposed to take lots of risk propelled by high testosterone levels.

DISCLOSURE STATEMENT

The author is not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

I benefited from many conversations on this topic over the years with experts in academia and industry, and would like to mention in particular Thierry Foucault, Terrence Hendershott, Bernard Hosman, Charles Jones, Mark Spanbroek, and my students at VU: Wenqian Huang, Sunny Li, Bart Yueshen, and Marius Zoican. I am grateful to Eric Budish, Thierry Foucault, Björn Hagströmer, Terrence Hendershott, and the editorial committee members Yacine Aït-Sahalia, Andrew Lo, and Robert Merton for invaluable comments on an earlier draft of this review. I gratefully acknowledge NWO for a VIDI grant.

LITERATURE CITED

AFM. 2016. A case analysis of critiques on high-frequency trading. Report of the Netherlands Authority for the Financial Markets

Aït-Sahalia Y, Saglam M. 2014. High frequency traders: Taking advantage of speed. Manuscript, Princeton University

Aldrich EM, Grundfest JA, Laughlin G. 2016. The Flash Crash: A new deconstruction. Manuscript, University of California, Santa Cruz

Almgren R, Chriss N. 2000. Optimal execution of portfolio transactions. *Journal of Risk* 3:5–39

Angel JJ, Harris LE, Spatt CS. 2015. Equity trading in the 21st century: An update. *Quarterly Journal of Finance* 5

Baldauf M, Mollner J. 2015. High-frequency trading and market performance. Manuscript, Stanford University

Baron M, Brogaard J, Hagströmer B, Kirilenko A. 2015. Risk and return in high-frequency trading. Manuscript, University of Washington

Baruch S, Glosten LR. 2016. Strategic foundation for the tail expectation in limit order book markets. Manuscript, Columbia University

Benos E, Brugler J, Hjalmarsson E, Zikes F. 2015. Interactions among high-frequency traders. Manuscript, Bank of England (Working Paper No. 523)

Benos E, Sagade S. 2016. Price discovery and the cross-section of high-frequency trading. *Journal of Financial Markets (forthcoming)*

Bernales A. 2014. Algorithmic and high frequency trading in dynamic limit order markets. Manuscript, Universidad de Chile

Biais B, DeClerck F, Moinas S. 2015a. Who supplies liquidity, how and when? Manuscript, Toulouse University

Biais B, Foucault T. 2014. HFT and market quality. *Bankers, Markets & Investors* 128:5–19

Biais B, Foucault T, Moinas S. 2015b. Equilibrium fast trading. *Journal of Financial Economics* 73:3–36

Biais B, Glosten L, Spatt C. 2005. A survey of microfoundations, empirical results, and policy implications. *Journal of Financial Markets* 8:217–264

Biais B, Woolley P. 2011. High frequency trading. Manuscript, Toulouse University

Black FS. 1971a. Towards a fully automated exchange, part I. *Financial Analyst Journal* 27:29–34

Black FS. 1971b. Towards a fully automated exchange, part II. *Financial Analyst Journal* 27:24–87

Boehmer E, Fong K, Wu J. 2014. International evidence on algorithmic trading. Manuscript, EDHEC Business School

Boehmer E, Li D, Saar G. 2015. Correlated high-frequency trading. Manuscript, Cornell University

Bongaerts D, Kong L, Van Achter M. 2015. Trading speed competition: Can the arms race go too far? Manuscript, Rotterdam School of Management

Bongaerts D, Van Achter M. 2015. High-frequency trading and market stability. Manuscript, Rotterdam School of Management

Boulatov A, Bernhardt D, Larionov I. 2016. Predatory and defensive trading in a dynamic model of optimal execution by multiple traders. Manuscript, Higher School of Economics (Moscow)

Breckenfelder J. 2013. Competition between high-frequency traders, and market quality. Manuscript, European Central Bank

Brogaard J, Carrion A, Moyaert T, Riordan R, Shkilko A, Sokolov K. 2015a. High-frequency trading and extreme price movements. Manuscript, University of Washington

Brogaard J, Garriott C. 2015. High-frequency trading competition. Manuscript, University of Washington

Brogaard J, Hagströmer B, Nordén L, Riordan R. 2015b. Trading fast and slow: Colocation and liquidity. *Review of Financial Studies* 28:3407–3443

Brogaard J, Hendershott T, Hunt S, Ysusi C. 2014a. High-frequency trading and the execution costs of institutional investors. *The Financial Review* 49:345–369

Brogaard J, Hendershott T, Riordan R. 2014b. High frequency trading and price discovery. *Review of Financial Studies* 27:2267–2306

Brogaard J, Hendershott T, Riordan R. 2015c. Price discovery without trading: Evidence from limit orders. Manuscript, UC Berkeley

Brogaard J, Hendershott T, Riordan R. 2016. High frequency trading and the 2008 short sale ban. *Journal of Financial Economics (forthcoming)*

Brunnermeier MK, Pedersen LH. 2005. Predatory trading. *Journal of Finance* 60:1825–1863

Budish E, Cramton P, Shim J. 2015. The high-frequency trading arms race: Frequent batch auctions as a market design response. *Quarterly Journal of Economics* 130:1547–1621

Cappon A. 2014. The brokerage world is changing, who will survive? http://www.forbes.com/sites/advisor/2014/04/16/the-brokerage-world-is-changing-who-will-survive

Cardella L, Hao J, Kalcheva I, Ma YY. 2014. Computerization of the equity, foreign exchange, derivatives, and fixed-income markets. *The Financial Review* 49:231–243

Carrion A. 2013. Very fast money: High-frequency trading on the NASDAQ. Manuscript, Lehigh University

Cartea A, Payne R, Penalva J, Tapia M. 2016. Ultra-fast activity and market quality. Manuscript, Universidad Carlos III de Madrid

Cartea A, Penalva J. 2012. Where is the value in high frequency trading? *Quarterly Journal of Finance* 2:1–46

Cespa G, Vives X. 2015. The welfare impact of high frequency trading. Manuscript, City University London

Chaboud A, Chiquoine B, Hjalmarsson E, Vega C. 2014. Rise of the machines: Algorithmic trading in the foreign exchange market. *Journal of Finance* 69:2045–2084

Chaboud A, Hjalmarsson E, Vega C. 2015. The need for speed: Minimum quote life rules and algorithmic trading. Manuscript, Federal Reserve Board

Chordia T, Goyal A, Lehmann BN, Saar G. 2013. High-frequency trading. *Journal of Financial Markets* 16:637–645

Coates JM, Gurnell M, Rustichini A. 2008. Second-to-fourth digit ratio predicts success among high-frequency financial traders. *Proceedings of the National Academy of Sciences of the United States of America* 106:623–628

Cochrane J. 2012. Weird stuff in high frequency markets. http://johnhcochrane.blogspot.nl/2012/02/weird-stuff-in-high-frequency-markets.html

de Jong F, Rindi B. 2009. The microstructure of financial markets. Cambridge: Cambridge University Press

Ding S, Hanna J, Hendershott T. 2014. How slow is the NBBO? A comparison with direct exchange feeds. *The Financial Review* 49:313–332

Du S, Zhu H. 2014. Welfare and optimal trading frequency in dynamic double auctions. Manuscript, MIT

Easley D, López de Prado MM, O'Hara M. 2011. The microstructure of the 'Flash Crash': Flow toxicity, liquidity crashes, and the probability of informed trading. *Journal of Portfolio Management* 37:118–128

Easley D, López de Prado MM, O'Hara M. 2012. Flow toxicity and liquidity in a high frequency world. *Review of Financial Studies* 25:1457–1493

Easley D, López de Prado MM, O'Hara M. 2013. High-frequency trading. London: Risk Books

Egginton J, Van Ness BF, Van Ness RA. 2016. Quote stuffing. *Financial Management (forthcoming)*

Fishe R, Haynes R, Onur E. 2015. Anticipatory traders and trading speed. Manuscript, CFTC

Foucault T, Hombert J, Roşu I. 2016. News trading and speed. *Journal of Finance* 71:335–382

Foucault T, Kozhan R, Tham WW. 2015. Toxic arbitrage. Manuscript, HEC Paris

Foucault T, Menkveld AJ. 2008. Competition for order flow and smart order routing systems. *Journal of Finance* 63:119–158

Foucault T, Pagano M, Röell A. 2013. Market liquidity: Theory, evidence, and policy. Oxford: Oxford University Press

Foucault T, Röell A, Sandås P. 2003. Market making with costly monitoring: An analysis of the SOES controversy. *Review of Financial Studies* 16:345–384

Frazzini A. 2012. Trading costs of asset pricing anomalies. Manuscript, Chicago Booth Paper No. 14–05

Gai J, Yao C, Ye M. 2013. The externalities of high-frequency trading. Manuscript, University of Illinois at Urbana-Champaign

Glode V, Opp C. 2016. Asymmetric information and intermediation chains. *American Economic Review (forthcoming)*

Glosten L, Milgrom P. 1985. Bid, ask, and transaction prices in a specialist market with heterogeneously informed agents. *Journal of Financial Economics* 14:71–100

Goettler R, Parlour C, Rajan U. 2009. Informed traders in limit order markets. *Journal of Financial Economics* 93:67–87

Goldstein MA, Kumar P, Graves FC. 2014. Computerized and high-frequency trading. *The Financial Review* 49:177–202

Gomber P, Arndt B, Lutat M, Uhle T. 2011. High-frequency trading. Manuscript, Goethe Universität

Hagströmer B, Nordén L. 2013. The diversity of high frequency traders. *Journal of Financial Markets* 16:741–770

Hagströmer B, Nordén L, Zhang D. 2014. How aggressive are high-frequency traders? *The Financial Review* 49:395–419

Han J, Khapko M, Kyle AS. 2014. Liquidity with high-frequency market making. Manuscript, Stockholm School of Economics

Harris JH, Saad M. 2014. The sound of silence. *The Financial Review* 49:203–230

Hasbrouck J. 2015. High frequency quoting: Short-term volatility in bids and offers. Manuscript, NYU

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

Hendershott T, Jones CM, Menkveld AJ. 2011. Does algorithmic trading improve liquidity? *Journal of Finance* 66:1–33

Hendershott T, Menkveld AJ. 2014. Price pressures. *Journal of Financial Economics* (forthcoming)

Hendershott T, Riordan R. 2013. Algorithmic trading and information. *Journal of Financial and Quantitative Analysis* 48:1001–1024

Hirschey NH. 2016. Do high-frequency traders anticipate buying and selling pressure? manuscript, London Business School

Hoffmann P. 2014. A dynamic limit order market with fast and slow traders. *Journal of Financial Economics* 113:156–169

Hu GX, Pan J, Wang J. 2014. Early peek advantage? Manuscript, MIT

Jarnecic E, Snape M. 2014. The provision of liquidity by high-frequency participants. *The Financial Review* 49:371–394

Jarrow R, Protter P. 2012. A dysfunctional role of high frequency trading in electronic markets. *International Journal of Theoretical and Applied Finance* 15:219–249

Johnson B. 2010. Algorithmic trading & DMA. London: 4Myeloma Press

Jones CM. 2013. What do we know about high-frequency trading? Manuscript, Columbia University

Jovanovic B, Menkveld AJ. 2015a. Dispersion and skewness of bid prices. Manuscript, Vrije Universiteit Amsterdam

Jovanovic B, Menkveld AJ. 2015b. Middlemen in limit-order markets. Manuscript, Vrije Universiteit Amsterdam

Kirilenko A, Kyle A, Samadi M, Tuzun T. 2014. The Flash Crash: The impact of high frequency trading on an electronic market. Manuscript, University of Maryland

Kirilenko AA, Lo AW. 2013. Moore's law versus Murphy's law: Algorithmic trading and its discontents. *Journal of Economic Perspectives* 27:51–72

Korajczyk RA, Murphy D. 2016. High frequency market making to large institutional trades. Manuscript, Northwestern University

Krugman P. 2009. Rewarding bad actors. *New York Times* Aug. 2

Kumar P, Seppi D. 1994. Information and index arbitrage. *Journal of Business* 69:481–509

Kyle A. 1985. Continuous auctions and insider trading. *Econometrica* 53:1315–1335

Latza T, Marsh I, Payne R. 2014. Fast aggressive trading. Manuscript, Cass Business School

Laughlin G. 2014. Optical data transmissions. Http://oklo.org/2014/11/28/optical-data-transmission/

Laughlin G, Aguirre A, Grundfest J. 2014. Information transmission between financial markets in Chicago and New York. *The Financial Review* 49:283–312

Laumonier A. 2016. HFT in the banana land. http://sniperinmahwah.wordpress.com

Lee CM, Radhakrishna B. 2000. Inferring investor behavior: Evidence from TORQ data. *Journal of Financial Markets* 3:83–111

Lewis M. 2014. Flash boys. New York: W.W. Norton & Company

Li S. 2015. Long lived flow of private information, high frequency competition, and market efficiency. Manuscript, SEC

Li W. 2014. High frequency trading with speed hierarchies. Manuscript, Johns Hopkins University

Madhavan AN. 2012. Exchange-traded funds, market structure, and the Flash Crash. *Financial Analyst Journal* 68:20–35

Malinova K, Park A. 2016. "Modern" market makers. Manuscript, University of Toronto

Malinova K, Park A, Riordan R. 2013. Do retail traders suffer from high-frequency traders? Manuscript, University of Toronto

Malkiel B. 2009. Opinion: High-frequency trading is a natural part of market evolution. *Financial Times* Dec. 14

McInish TH, Upson J, Wood RA. 2013. The Flash Crash: Trading aggressiveness, liquidity supply, and the impact of intermarket sweep orders. *Financial Review* 49:481–509

Menkveld AJ. 2013. High frequency trading and the new market makers. *Journal of Financial Markets* 16:712–740

Menkveld AJ. 2014. High frequency traders and market structure. *The Financial Review* 49:333–344

Menkveld AJ. 2016. High-frequency trading viewed through an electronic microscope. Manuscript, Vrije Universiteit Amsterdam

Menkveld AJ, Yueshen BZ. 2014. Middlemen interaction and its effect on market quality. Manuscript, Vrije Universiteit Amsterdam

Menkveld AJ, Yueshen BZ. 2015. The Flash Crash: A cautionary tale about highly fragmented markets. Manuscript, Vrije Universiteit Amsterdam

Menkveld AJ, Zoican MA. 2016. Need for speed? Low latency trading and adverse selection. Manuscript, Vrije Universiteit Amsterdam

Merton RC. 1969. Lifetime portfolio selection under uncertainty: The continuous-time case. *Review of Economics and Statistics* 51:247–257

Moallemi C, Sağlam M. 2013. The cost of latency in high-frequency trading. *Operations Research* 61:1070–1086

O'Hara M. 1995. Market microstructure theory. Malden, MA: Blackwell Publishers

O'Hara M. 2015. High frequency market microstructure. *Journal of Financial Economics* 116:257–270

Pagnotta E, Philippon T. 2015. Competing on speed. Manuscript, NYU

Parlour C, Seppi D. 2003. Liquidity-based competition for order flow. *Review of Financial Studies* 16:301–343

Parlour CA, Seppi DJ. 2008. Limit order markets: A survey, In *Handbook of Financial Intermediation and Banking*, eds. A Boot, A Thakor. Amsterdam, Netherlands: Elsevier Publishing

Patterson S. 2012. Dark pools: The rise of the machine traders and the rigging of the U.S. stock market. New York: Crown

Raman V, Robe M, Yadav PK. 2014. Electronic market makers, trader anonymity and market fragility. Manuscript, CFTC

Riordan R, Storkenmaier A. 2012. Latency, liquidity and price discovery. *Journal of Financial Markets* 15:416–437

Roşu I. 2016. Fast and slow informed trading. Manuscript, HEC Paris

SEC. 2010. Concept release on equity market structure. Release No. 34–61358. File No. S7–02-10

SEC. 2014. Equity market structure literature review. Part II: High frequency trading. Literature review

Stiglitz JE. 2014. Tapping the brakes: Are less active markets safer and better for the economy? Manuscript, Columbia University

van Kervel V. 2015. Competition for order flow with fast and slow traders. *Review of Financial Studies* 28:2097–2127

van Kervel V, Menkveld AJ. 2015. High-frequency trading around large institutional orders. Manuscript, Vrije Universiteit Amsterdam

Vayanos D, Wang J. 2013. Market liquidity: Theory and empirical evidence, In *Handbook of the Economics of Finance*, eds. G Constantinides, M Harris, R Stulz. Amsterdam: Elsevier Press

Weller B. 2013. Intermediation chains. Manuscript, University of Chicago (job market paper)

Weller B. 2016. Efficient prices at any cost: Does algorithmic trading deter information acquisition? Manuscript, Northwestern Kellogg

Yang L, Zhu H. 2015. Back-running: Seeking and hiding fundamental information in order flows. Manuscript, MIT

Yao C, Ye M. 2015. Why trading speed matters: A tale of queue rationing under price controls. Manuscript, University of Illinois

Yueshen BZ. 2015. Market making uncertainty. Manuscript, INSEAD