(very preliminary and incomplete)

Middlemen in Limit-Order Markets[1]

Boyan Jovanovic and Albert J. Menkveld

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[1]Boyan Jovanovic, Department of Economics, New York University, 19 West 4th Street, New York, NY, USA, tel +1 212 998 8900, fax +1 212 995 4186, bj2@nyu.edu. Albert J. Menkveld, VU University Amsterdam, FEWEB, De Boelelaan 1105, 1081 HV, Amsterdam, Netherlands, tel +31 20 598 6130, fax +31 20 598 6020, albertjmenkveld@gmail.com. We thank Robert Engle, Thierry Foucault, Phil Haile, Joel Hasbrouck, Terrence Hendershott, Charles Jones, Lasse Pedersen, and Emiliano Pagnotta for comments. We are grateful to both Euronext and Chi-X for acting as data sponsor and to Bernard Hosman whose exploratory analysis has been invaluable. Jovanovic thanks the Kauffman Foundation for support and Menkveld gratefully acknowledges Robert Engle for sponsoring his NYU visit in 08/10 and VU University Amsterdam for a VU talent grant.

Middlemen in Limit Order Markets

Abstract

A limit-order market enables an early investor to trade with a late investor. But, public news in the interarrival period creates adverse-selection cost and hampers trade. A high frequency trader (HFT) might restore trade through its unique ability to quickly update its quote on news arrival. But, HFT entry might in itself worsen adverse selection if speed is used to adversely select investors' quotes. This paper studies HFT entry both theoretically and empirically. The entry of an HFT-friendly new market is used as an instrument. Middlemen arrival coincides with a 29% reduction in the bid-ask spread and a 13% drop in volume.

Technology revolutionized the way financial assets are traded. Electronic limit order markets enable agents to automate trading decisions. Computer algorithms are used to either minimize transaction cost when trading into position ('working' an order through time and across markets or to simply profit from buying and selling securities as a middleman. This latter type is the focus of our study and is often referred to as high frequency trader (HFT). We study the advent of middlemen both theoretically and empirically.

In principle, a limit order market removes the need for intermediation. Investors who are spaced out in time (due to a nontrivial opportunity cost of staying on in a market) establish trades through limit orders. For example, an early investor with low private value for her asset might post a limit sell ('ask quote') which is taken up by a late investor with high private value for the asset. But, if there is common value process the late investor might adversely select the early investor (as she is better informed). The early investor rationally posts a higher limit order to be compensated for this adverse selection cost. If common value innovations are large enough relative to private values the market hits a no-trade deadlock.

Middlemen can enhance welfare as their speed advantage helps to 'unlock' an adverse-selection induced trade deadlock. High frequency traders stand out by their superior information processing speed established through efficient algorithms that run on fast computers 'co-located' at a market's server. This creates an edge in terms of quickly updating limit orders on the arrival of public information. In the deadlock example, the early investor might sell to the middleman who keeps refreshing his limit sell until the late investor arrives.

Middlemen might reduce welfare if their speed creates an adverse selection risk for limit order that might not have otherwise existed. If the late investor is unaware of a common value innovation, trade is not hampered by adverse selection. If middlemen are introduced in this setting, they create an adverse selection risk for the early investor and might reduce trade.

The theory develops the arguments for and against middlemen formally. It adds to a vast literature on market intermediation. Classic models in financial economics assume information asymmetry where, rather than superiorly informed, middlemen are uninformed which was natural for markets where humans intermediate (see, e.g., Glosten and Milgrom (1985) and Kyle (1985)). Foucault, Roëll, and Sandas (2003) introduce costly monitoring ability for liquidity suppliers and analyze optimal intensity. More recent limit order models analyze how adverse selection risk affects the choice of an arriving agent to choose between a limit and a market order (see, e.g., Hollifield, Miller, Sandås, and Slive (2006) and Goettler, Parlour, and Rajan (2009)). They do not consider the entry of middlemen.

The empirical part analyzes the advent of middlemen by exploiting the introduction of an HFT-friendly trading venue as an instrument. Chi-X started trading Dutch index stocks on April 16, 2007. Unlike the incumbent market, Euronext, it did not charge limit order modifications, nor executions. Quite the contrary, limit orders that led to execution received a rebate. The first 77 trading days of 2007 and 2008 are compared to establish a 'treatment' effect. To control for time effects, Belgian index stocks serve as an 'untreated' control sample as they had not yet been introduced in Chi-X, yet were trading in Euronext under the same rules as Dutch stocks.

Post Chi-X, a middleman has entered for Dutch stocks who trades primarily passive (i.e., through limit orders). One new broker ID (not present in the pre-entry sample) trades very frequently—it is present in roughly every third trade in Chi-X and in every twelfth trade in Euronext. It is particularly active on days when most of a stock's price movement is explained by the index—the R^2 of a single-factor CAPM explains 45% of time variation in middleman participation. What makes this broker an HFT, though, is that its net position over the trading day is zero almost half of the sample days. A further finding is that 75-80% of its trades were passive. These observations provide empirical support for our theory which characterizes middlemen as cost-efficient intermediaries. They minimize adverse selection cost by quickly updating quotes on incoming 'hard' information, i.e., information that is easily processed by machines such as price quotes in the local index, same industry stocks, foreign exchange, etc.

A diff-in-diff analysis (post- minus pre-entry, treated minus untreated) shows that middlemen entry is accompanied by an increase in liquidity supply and a drop in volume. Post-entry realized volatility is 64% higher for (treated) Dutch stocks, which is the same order of magnitude as the 69% higher volatility for the (untreated) Belgian stocks. This is a reassuring result as it is unlikely that *low-frequency* volatility is affected by HFT entry. The bid-ask spread did not change for Dutch stocks, but did go up by a significant 35% for Belgian stocks. The diff-in-diff is therefore a 35% reduction in spread. The diff-in-diff analysis further shows that depth at the best quotes shrank by 13%, but this is second-order relative to the spread improvement as calibration shows that, net of depth change, the spread declined by 29%. The number of trades was unaffected by middlemen entry but volume declined by 13% (double-counts due to middleman intermediation are removed). The volume decline is either due to (i) investors shying away from the market or to (ii) 'old' intermediaries being replaced by HFTs. The results are therefore mixed in terms of how HFT entry affects welfare—the lower spread appears beneficial, the lower volume is worrisome.

The diff-in-diff results should be interpreted with care due to potential endogenous timing and selection bias. Chi-X might have decided to start the system on April 16, 2007, and select Dutch stocks because these stocks at that time showed particularly high activity and large spreads. If these were transitory effects, the subsequent volume decline and spread reduction are to be expected irrespective of HFT entry. We plan to study the size of transitory effects to verify whether (i) timing was indeed endogenous (spread and volume were temporarily high on April 16, 2007) and (ii) whether the size of these effects could explain the magnitude of the reported treatment effect.

The empirical findings add to a growing literature on automated trading. Foucault and Menkveld (2008) study smart routers that investors use to benefit from liquidity supply in multiple markets. Hendershott, Jones, and Menkveld (2010) use an instrumental variable to show that algorithmic trading (AT) causally improves liquidity and makes quotes more informative. Chaboud, Chiquoine, Hjalmarsson, and Vega (2009) relate AT to volatility and find little relation. Hendershott and Riordan (2009) find that both AT demanding liquidity and AT supplying liquidity makes prices more efficient.

More broadly, our findings contribute to the literature on middlemen in search markets. In Rubinstein and Wolinsky (1987) and Masters (2007) middlemen may improve allocations because they speed up the meeting process. Rents are divided via Nash bargaining. Hosios condition and optimality obtain when numbers are endogenous. In our model, however, market participation is exogenous. Our paper is closer to Li (1996) in which where middlemen have an advantage in terms of information in a lemons model. The contrast is (i) that the quality of the traded good is exogenous, and (ii) that the information is not about independent values but, rather, common values, which we believe to be at the heart of evaluating welfare effects of HFTs who specialized in speed to minimize being adversely selected on public information. A unique feature of limit order markets is that late investors cherry pick take-it-or-leave-it offers (i.e., limit orders) of early investors, leaving the latter with a winner's curse problem. Closer to home are models on search in decentralized markets, e.g., Duffie, Gârleanu, and Pedersen (2005), Lagos, Rocheteau, and Weill (2009), and Duffie, Malamud, and Manso (2009).

The remainder of the manuscript is structured as follows. Section 1 develops a static model. Section 2 extends the model to a recursive dynamic model. Section 3 discusses mechanism design issues. Section 4 contains the empirical analysis. Section 5 concludes.

1 One-period model

There is one indivisible security and two agents, a buyer and a seller. In a one-period model, assume that the private value of the asset to its owner is distributed uniformly according to $F(x) = x$ for $x \in [0, 1]$. We refer to the owner as the seller, **S**. There is also a buyer, **B**, whose private value is y, also distributed uniformly on the unit interval, and independently of x. The private values are known to each party, privately.

Additionally there is a common value z, denoting a capital gain or loss on the security that each investor values in the same way. The asset yields utility $x + z$ to its owner, and would yield $y + z$ to the buyer. The variable z is the common value, best thought of as the change in the price of the security from one period to the next. It is the capital gain or loss that any investor experiences if he holds the security. It has distribution $G(z)$. Since stock prices tend to follow a random walk, we assume $E(z) = 0$.

First best allocations and welfare

The first best welfare is that the highest-valuation investor ends up with the security. Realized welfare would then be $z + \max(x, y)$. Since z has zero mean, expected welfare would then be

$$W_{\text{FIRST BEST}} = \int \int \max(x, y)\, dF(x)\, dF(y).$$

In the uniform $[0, 1]$ case where $F(x) = x$, the quick way to calculate this quantity is to note that the CDF of the maximum is x^2 with a density of $2x$. Then

$$W_{\text{FIRST BEST}} = 2 \int_0^1 x^2 dx = \frac{2}{3}.$$

Myerson and Satterthwaite (1983) showed that in a bilateral monopoly situation in which x and y are private information, we cannot attain first best with any mechanism with a zero budget balance.

1.1 Version 1: Only middleman has a private signal about z

By far the simpler version of the model to analyze is that in which neither **B** nor **S** has private information about z and in which middlemen who know z from the outset, bid for the security competitively. We shall start out without middlemen in the model, and analyze two alternative trading rules, the first being that in which **S** posts an ask that **B** must accept or reject, the second being that in which **B** posts a bid which **S** must accept or reject. The two cases correspond, formally, to which investor arrives first. In the next subsection we consider the case when one of the investors is better informed about z.[1]

Following that discussion, we shall introduce competitive middlemen. In this situation, middlemen *create* an adverse-selection problem that otherwise would not exist. The problem is partially resolved by letting the middlemen supply liquidity in the form of limit orders, or 'passive' orders. Nevertheless, trade is lower than it would be in the absence of middlemen.[2]

1.1.1 Case 1: S posts an asking price, B accepts or rejects

Since neither party knows z, both expect to receive $E(z) = 0$ from the common value. This leaves only the private values of the security to bargain over.[3] In other words, faced with the ask-price of p that is uncorrelated with z (it has to be because **S** has no signal about z), **B** accepts if and only if $y > p$. Then **S** solves the problem

$$\max_p [1 - F(p)] p + F(p) x,$$

which, since $F(x) = x$ boils down to the problem $\max_{p\in[0,1]} (1 - p) p + px$. This leads to the optimal pricing policy

$$p^a(x) = \frac{1 + x}{2} \tag{1}$$

which is plotted as the red line in Figure 1. The shaded area shows the pairs of points (x, y) that result in trade.

[1] Welfare turns out to be higher when the more informed investor posts the limit order, and this is the trading convention that we then would expect to see emerge.

[2] In the empirical section, we shall find that adverse selection existed before the entry of Chi-X, which is evidence against the stark assumption that in the absence of middlemen no adverse-selection problems would exist. This is shown in Table 2 and in the diff-in-diff analysis.

[3] The same would be true if both had a common signal s about z. In that case both expect to receive $E(z \mid s)$ from the common value, once again leaving only the private values of the securuty to bargain over.

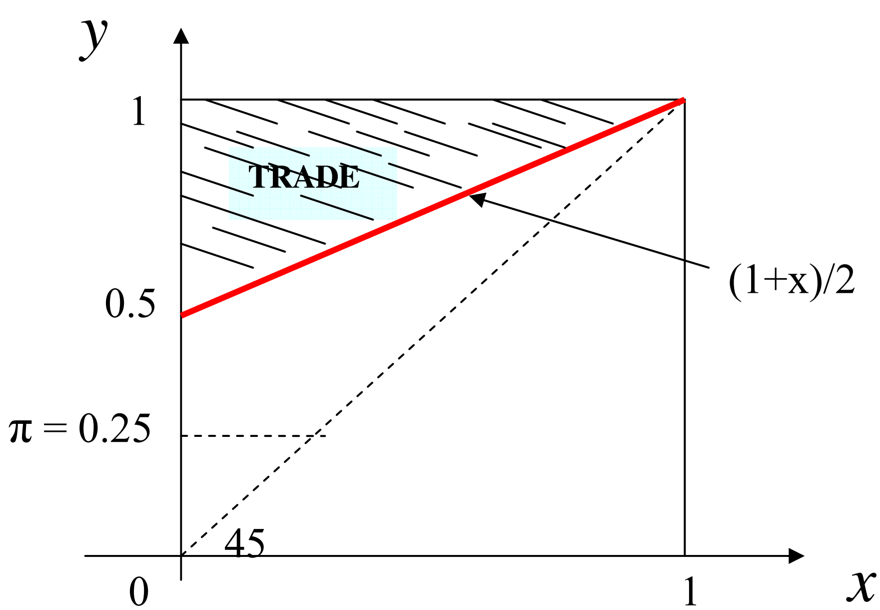

Figure 1: Equilibrium offer to sell when $\sigma = 0$

The probability of trade in Case 1.—In the case where F is uniform (as portrayed in the figure), the shaded area represents one quarter of the unit square. The number of trades is therefore 1/4. More formally, letting $p(x) = \arg\max_p \{p[1 - F(p)] + xF(p)\}$, the probability of trade is

$$\tau = \int [1 - F(p[x])] \, dF(x)$$

Since G does not affect $p(x)$, it also does not affect τ.

Welfare in Case 1.—If trade was prohibited, welfare would equal $E(x + z) = E(x) = 1/2$. But trade raises welfare above this level. Expected welfare conditional on x is then

$$\begin{aligned} E(\text{welfare} \mid x) &= x \Pr\left(y < \frac{1+x}{2}\right) + \frac{1 + \frac{1+x}{2}}{2} \Pr\left(y \geq \frac{1+x}{2}\right) = x\frac{1+x}{2} + \frac{1 + \frac{1+x}{2}}{2}\left(1 - \frac{1+x}{2}\right) \\ &= x\frac{1+x}{2} + \frac{1 + \frac{1+x}{2}}{2}\left(1 - \frac{1+x}{2}\right) = \frac{1}{2}\left(x(1+x) + 1 - \left(\frac{1+x}{2}\right)^2\right) \end{aligned}$$

and therefore

$$W = \int_0^1 E(\text{welfare} \mid x) \, dx = \frac{1}{2}\left(\frac{1}{2} + \frac{1}{3} + 1 - \frac{1}{4}\left.\frac{(1+x)^3}{3}\right|_0^1\right) = \frac{5}{8} = 0.625 \tag{2}$$

1.1.2 Case 2: B posts a bid, S accepts or rejects

If **B** buys the security, the buyer receives $u - p$, and zero otherwise. If he did not have to worry about competition from middlemen, **B** would solve

$$\max_p \{[F(p)](y - p)\},$$

with FOC

$$\begin{aligned} F &= (y - p) f \Longrightarrow \\ p^b(y) &= y - \frac{F(p)}{f(p)} \end{aligned}$$

which in the uniform case gives us

$$p^b(y) = \frac{y}{2}$$

which we illustrate in Figure 2.

The probability of trade in Case 2.—With $p(y) = \arg\max_p \{pF(p)\}$, the probability of trade is

$$\tau = \int F(p[y])\, dF(y)$$

Again, since G does not affect $p(y)$, it also does not affect τ. In the uniform case, the shaded are represents one quarter of the square. A comparison of the shaded areas in Figures 1 and 2 shows that they are the same. The probability of trade is again 1/4.

Welfare in Case 2.—It is easy to show that welfare is again 5/8, just as in (2) of CASE 1.[4]

[4] Conditional on y welfare, $E(\text{welfare} \mid y)$, is

$$y \Pr(x < y/2) + \frac{1}{2}\left(1 + \frac{y}{2}\right) \Pr(x \geq y/2) = \frac{1}{2} y^2 + \frac{1}{2}\left(1 + \frac{y}{2}\right)\left(1 - \frac{y}{2}\right) = \frac{1}{2}\left(y^2 + 1 - \frac{y^2}{4}\right) = \frac{1}{2} + \frac{1}{2}\frac{3}{4} y^2$$

and overall it is $\int_0^1 E(\text{welfare} \mid y)\, dy = \frac{5}{8}$, same as in (2)

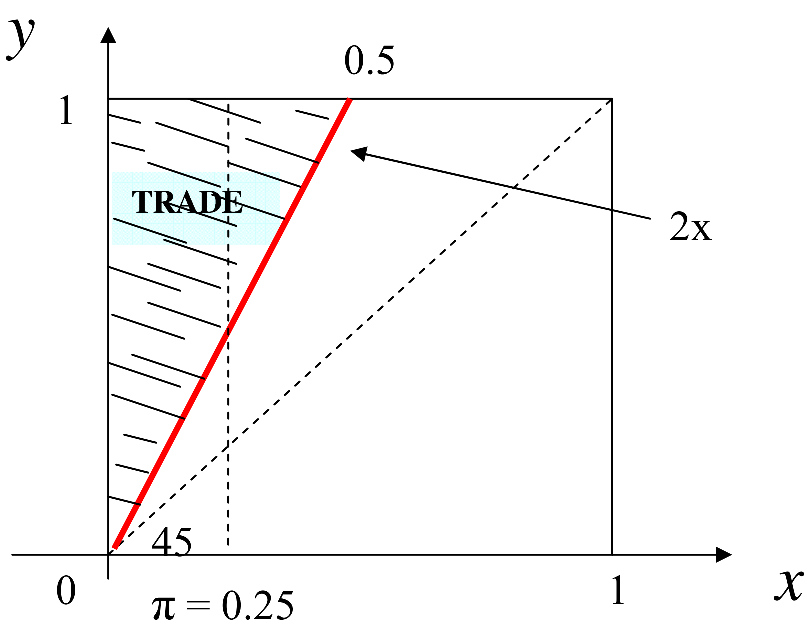

Figure 2: Equilibrium offer to buy when $\sigma = 0$

1.1.3 Case 3: Informed Middlemen post bids and asks

To be an HFT is to have the ability to react to news faster than investors can.[5] We now add to the game some middlemen who, unlike **B** and **S**, know z from the outset. Presumably the news about z is fresh, too fresh for the investors to have heard it. A middleman's utility from owning the asset is z. He has zero private value of holding it. Since x and y are positive, if the security ends up in the middleman's hands welfare is lower ex post in every state of the world.

On the other hand, the presence of middlemen in this environment creates a winner's curse problem for any uninformed investor (in this case **B** and **S**) wishing to post a limit order. Being faster, middlemen would accept an offer to sell when z is large and reject it when z is small, and would top an offer to buy that B would reasonably make. We shall now assume that such private information dissuades investors from posting offers and opens the door to middlemen to post bids and asks.

The middlemen are competitive. Middlemen their bids p_b at a value at which they break even in the sense that their expected profit from attempting to sell the security equals p_b. To calculate p_b we work backwards

[5]Our empirics show that the middleman's price quotes react faster, and especially so to "hard" information. We also find middlemen to be more active in more volatile stocks, which is where they can presumably reap the benefits of their superior capability of tracking hard information.

from the value of selling the security. Should a middleman, **M**, procure the security from **S**, he can turn around and try to sell it to **B** right away. At this point **M** is the monopolist and **B** still the monopsonist. I.e., if **M**'s bid succeeds, the bilateral monopoly situation shifts from being between **S** and **B** to one between **M** and **B**. But there is a further change: The asymmetric information about z has now disappeared: **B** will by then have seen the post, p_b, and from it he has been able to infer z, because p_b will in equilibrium be a monotone-increasing function of z.

At this point, the situation is much the same as it was in Case 1 under which **B** and **S** both had the same expected value of z, namely $E(z) = 0$. This time, both **M** and **B** have the same value of z, namely the realized value of z which **M** knew from the start and which **B** has been able to infer. Therefore, **M**'s asking price will be

$$p_a = z + u \tag{3}$$

where

$$u = \arg\max u\,[1 - F(u)] \tag{4}$$

and **M**'s willingness to bid for **S**'s security is

$$p_b = z + \pi \tag{5}$$

where

$$\pi = \max_u u\,[1 - F(u)]\,. \tag{6}$$

Therefore p_b is indeed monotone in z as claimed.

Since **S** also knows how p_b relates to z, he realizes that if he keeps the security he will get a payoff of $x + z$, whereas if he sells, (5) tells us that he will get $z + \pi$. Therefore **S** sells iff $x < \pi$.

The probability of trade in Case 3.—In Figure 3, the red square contains the (x, y) pairs of the traders that take part in the M-mediated transfer of securities. The number of trades exceeds this number, however, because of how the data are collected. Since a sale **S**→**M** followed by a sale **M**→**B** counts as two separate trades in the data, the total number of trades that Case 3 predicts is

$$\tau = F(\pi) + F(\pi)\,[1 - F(u)] = \frac{1}{4} + \frac{1}{4}\frac{1}{2} = \frac{3}{8} = 0.375. \tag{7}$$

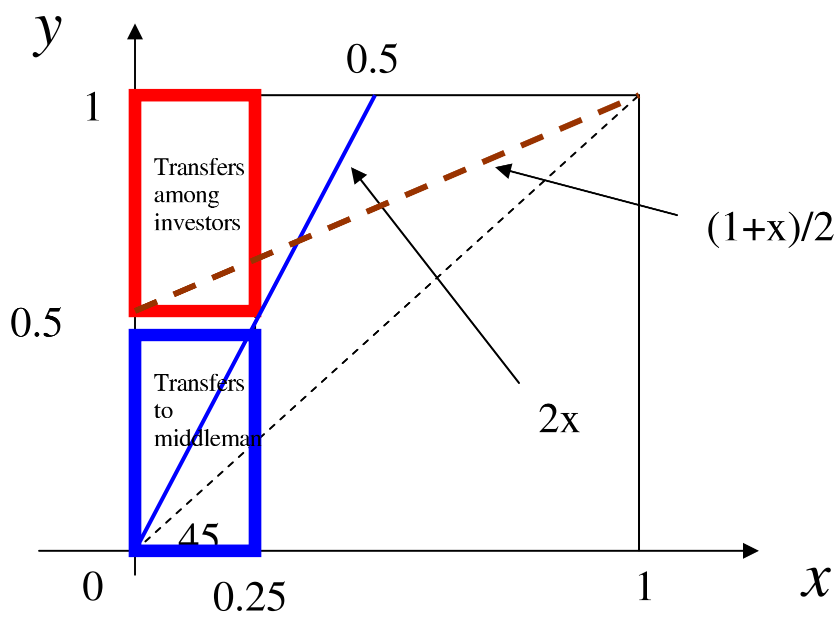

Figure 3: Transfers in Case 3

Figure 3 also plots the asking price $p(x) = (1+x)/2$ for Case 1, and for Case 2 the bid $p(y)$ the inverse of which is $2x$. We then find that the agents involved in trades that eventually move the security from one investor to another in Case 3 are a strict subset of those that trade in Case 2, but not a strict subset (though still a smaller one) of those that trade in Case 1. These are in the upper (red) rectangle. The lower (blue) rectangle involves an equal number of transfer where the final owner is the middleman.

Welfare in Case 3.—The average x of the transferred securities is $1/8$ whereas their average y is $3/4$. Of the $1/4$ shares sold, half are kept by M and draw no private value. Thus total number of effective transfers is $1/8$, and so the welfare gain is $\frac{1}{8}\frac{3}{4} - \frac{1}{4}\frac{1}{8} = \frac{1}{16}$, so that total welfare is $\frac{9}{16} = 0.563$.

1.1.4 Feasible strategies

Middlemen are the only agents that in the model can post more than one price or, rather, revise their actions in light of information received during the period. They can post a bid and if it is accepted, they can turn around and post an ask. Investors are assumed to be unable to act as fast as to accomplish this. In particular, investor **S** can infer z from p_b, he cannot then reject the bid, and post an asking price that reflects z. If **S** could do this, he could drive middlemen out of business. The reasoning is similar to that for why in the absence of noise traders the informed traders would not want to pay the information cost in Grossman and Stiglitz (1980) because equilibrium is then fully revealing.

Let us review the logic in Case 1 and Figure 1. Since $\pi = 1/4$, **M**'s bid of $p_b = z + 1/4$ would be too low to meet any of **S**'s asks which, when **S** knows z, would equal $z + (1 + x)/2$. Alternatively, in Case 2 and Figure 2, let **M** try to enter the game in which **B** bids $p(y) = y/2$. Could he post a bid of p_b and hope to re-sell the security at a profit? If he succeeds in buying the security at the price p_b, this would mean that $y < 2p_b$. Then $p_a = \arg\max_p p[F(2p_b) - F(p)]$. Since p_b will not exceed 1/2 in the uniform case, the maximand is $p([2p_b - p])$. The FOC is $2p_b - 2p_a = 0$ which implies that $p_a = p_b$. But **M** cannot possibly break even this way because the probability of sale at p_a is less than unity. Therefore regardless of who posts the limit order (**B** or **S**), **M** cannot profitably acquire the security with a positive probability.

1.1.5 Summary of Version 1

Let us summarize implications in a table. The bid-ask spread for the situation without middlemen can be defined as the average of $p^a(x)$ for Case 1 minus the average of the $p^b(y)$ in Case 2. That is,[6]

$$\text{Spread} = \int p^a(x)\,dF(x) - \int p^b(y)\,dF(y) = \frac{3}{4} - \frac{1}{4} = \frac{1}{2}$$

We consider this to be the "realized spread" caused purely by monopoly power. This would arise even without any adverse selection.

Summary of Version 1

REGIME	# TRADES	WELFARE	SPREAD
First best	0.50	0.666	- -
No middlemen	0.25	0.625	0.5
Middlemen	0.38	0.563	0.25

The important feature of the summary is that the properties of the distribution of z have no bearing on the numbers in the table.

[6] A smaller number would probably be appropriate if an investor of a given type x was to post both an ask and a bid.

(i) In row 1 of the Table, the first-best depends on transferring shares to the larger of x and y. The allocations do not depend on z.

(ii) In row 2, the investors cannot forecast z, and simply behave as if z were equal to its expected value of zero. This will cease to be true when we introduce private information about z.

(iii) In row 3, the actions of the middlemen reveal z to the traders.

In the next section, we shall find that when we introduce some private information on z, the welfare rankings of the second and third rows will change

1.2 Version 2: Buyer too has a private signal about z

Version 2 differs from Version 1 mainly in that now an adverse-selection problem exists without middlemen. This is supposed to capture the reality that whoever posts a limit order and cannot continuously monitor it, risks having it accepted in an unfavorable state. The investor posting a bid could be a buyer or a seller. To keep things simple we shall deal only with the case in which the uninformed agent is the seller.

The severity of the problem depends on the importance of z relative to that of x and y. We shall show that in the absence of informed middlemen this reduces trade and welfare regardless of whether the informed party (i.e., the seller) or the uninformed party (i.e., the buyer) makes the offer. The welfare conclusions can be anticipated as summarized in Figure 4. On the horizontal axis σ, is the standard deviation of z.

We conjecture that the effects are monotone in σ, as depicted. This is based on eq. (17) which shows an upper bound for trade, a bound that converges to zero. As trade converges to zero, welfare converges to its no-trade level.

Relation to the no-trade results.—The result is closely related to the no-trade theorem (Milgrom and Stokey (1982)) which states that as long as differences in beliefs arise from differences in signals that come about as a result of an agreed-upon distribution, one cannot have trade without assuming differences in traders' utility functions. We can write those preferences as $x + \sigma z$ for the buyer and $y + \sigma z$ for the seller, but since everyone is risk neutral, we can divide payoffs by σ without affecting incentives or equilibrium. Then the

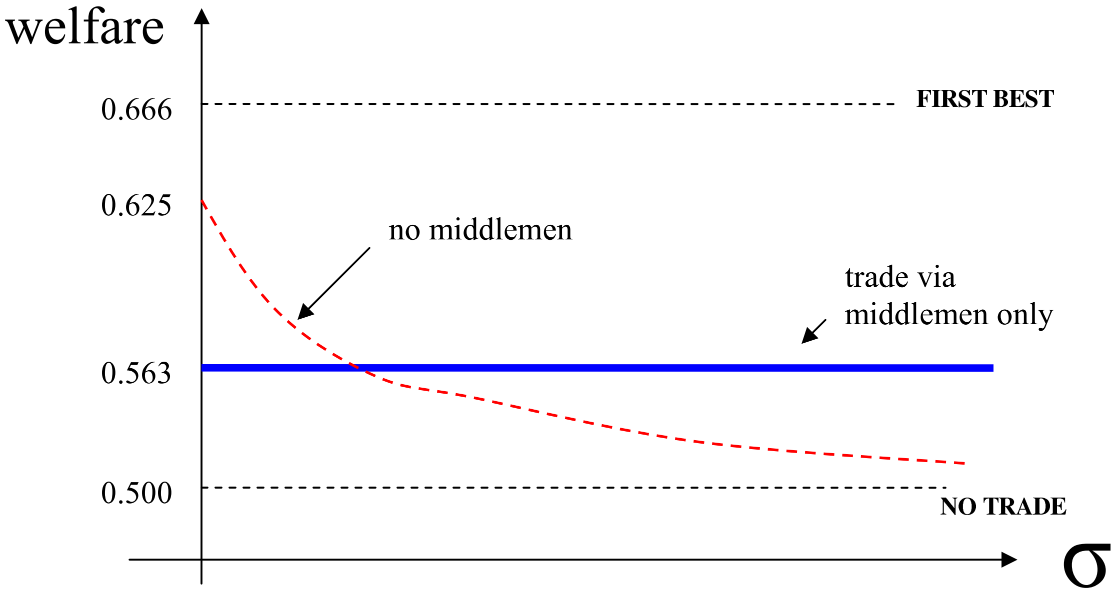

Figure 4: Welfare and middlemen involvement

preferences are $z+x/\sigma$ and $z+y/\sigma$ respectively. As σ gets large, the preferences become identical and equal to z and trade disappears.

1.2.1 Case 1A: Seller posts limit order

As in Case 1 above, **S** meets **B** who, as before, values the security at $y+z$, where y is drawn independently from F. The difference is that now **B** knows z.

The owner makes the non-owner a take-it-or leave it offer of p, and the (possibly new) owner remains in the market, and the non owner leaves for ever.

The prospective buyer knows more than the seller about the common value z. In support of this assumption, our data show that the effect of a trade is to change the long-run value of the security, i.e., it has a long-run impact on the price – see Table 1 and the detailed discussion of it.

B accepts an offer at P iff $y+z>p$. Then **S** solves

$$\max_p \int_{-\infty}^{\infty} \left[p\left[1-G\left(p-y\right)\right] + \int_{-\infty}^{p-y} \left(x+z\right) g\left(z\right) dz \right] dF\left(y\right).$$

Differentiating and cancelling the term $pg(p-y)$ which appears twice, we get the FOC

$$1-\int_{-\infty}^{\infty} G(p-y)\,dF(y)=\int_{-\infty}^{\infty}(x-y)\,g(p-y)\,dF(y)\,. \tag{8}$$

Normally distributed x, y and z.—We suppose that x and $y \sim N(1,1)$, and that $z \sim N\left(0,\sigma^2\right)$. We wish to vary the parameter σ which, when it gets larger relative to the unit variance of x and y, worsens the adverse-selection problem. Since y and z are independent, their sum $s \equiv (y+z)$ is normal, with variance $1+\sigma^2$. Let

$$\phi(u)=\frac{1}{\sqrt{2\pi}}e^{-u^2/2} \quad \text{and} \quad \Phi(u)=\int_{-\infty}^{u}\phi(s)\,ds$$

be the standard normal density and CDF. We shall hold the variances of x and y at unity. Then

$$F(y)=\Phi(y-1)\,, \qquad f(x)=\phi(x-1)\,, \quad G(z)=\Phi\left(\frac{z}{\sigma}\right), \text{ and } g(z)=\frac{1}{\sigma}\phi\left(\frac{z}{\sigma}\right) \tag{9}$$

We then can write

$$v(x)\equiv\max_p\int_{-\infty}^{\infty}\{\left[1-\Phi\left(\frac{p-y}{\sigma}\right)\right]\cdot p+\int_{-\infty}^{p-y}\frac{x+z}{\sigma}\phi\left(\frac{z}{\sigma}\right)dz\}\phi(y-1)\,dy. \tag{10}$$

The FOC w.r.t. p is

$$0=\int_{-\infty}^{\infty}\left[1-\Phi\left(\frac{p-y}{\sigma}\right)+\left(\frac{x-y}{\sigma}\right)\phi\left(\frac{p-y}{\sigma}\right)\right]\phi(y-1)\,dy. \tag{11}$$

Now let $p(x)$ be the optimal price and

$$\tau(x)=\int_{-\infty}^{\infty}\left[1-\Phi\left(\frac{p-y}{\sigma}\right)\right]\phi(y-1)\,dy \tag{12}$$

be the probability that the offer of a type-x seller is accepted.

Lemma 1 *Under the normality assumptions in (9), the probability that the buyer accepts the offer of seller x can be expressed as*

$$\tau(x)=\left(\frac{1}{1+\sigma^2}p(x)+\alpha^2-x\right)\frac{\alpha}{\sqrt{2\pi}\sigma}\exp\left(\frac{p^2-1}{2\sigma^2}\left(\frac{p+\sigma^2}{1+\sigma^2}\right)\right), \tag{13}$$

where α is defined as

$$\alpha = \overline{m} + [1 - F(k)](k + \Delta) = \overline{m} + \frac{[1 - F(k)]^2}{f(k)} = \frac{\beta}{1-\beta}\frac{[1 - F(k)]^2}{f(k)}. \tag{14}$$

We now use the Lemma to prove our result that the adverse-selection problem destroys trade in the absence of middlemen.

Proposition 2 *Under the normality assumptions in (9),*

$$\lim_{\sigma\to\infty} \tau(x) = 0 \quad \textit{for all } x \in R \tag{15}$$

Proof. As $\sigma \to \infty$ if, for each x, $p/\sigma \to +\infty$, then (15) follows because then by (12) $\tau(x) \to 0$ because $\Phi\left(\frac{p-y}{\sigma}\right) \to 1$ for each y. Conversely, if p/σ is bounded, then so is C and therefore $B \to 0$ [where C is defined in (56)]. And in this case , the term $\frac{1}{1+\sigma^2}p$ in (57) is also bounded, and therefore $B \to 0 \Longrightarrow \tau(x) \to 0$. ■

Lower bound on p.—Since $\tau \geq 0$ and since B is strictly positive, (57) implies that

$$\frac{p(x)}{1+\sigma^2} \geq x - \alpha^2 \tag{16}$$

Upper bound on τ.—In (12),

$$\tau(x) = \Pr(y + z \geq p(x)) = \Pr(y - 1 + z \geq p(x) - 1) = 1 - \Phi\left(\frac{p(x) - 1}{1+\sigma}\right) = \Phi\left(\frac{1 - p(x)}{1+\sigma}\right)$$

where the last equality follows because for any $u \in R$, $\Phi(-u) = 1 - \Phi(u)$. Now from (16),

$$p(x) \geq \left(1+\sigma^2\right)\left(x - \alpha^2\right) = \left(1+\sigma^2\right)x - \left(1+\sigma^2\right)\alpha^2 = \left(1+\sigma^2\right)x - \sigma^2$$

and therefore

$$\tau(x) \leq \Phi\left(\frac{1 - \sigma^2(x-1) - x}{1+\sigma}\right) = \Phi\left(-\frac{\left(1+\sigma^2\right)(x-1)}{1+\sigma}\right) \tag{17}$$

which, for x to the right of the mean, gives us an estimate of the rate at which $\tau(x)$ converges to zero. This rate forms the basis for the dashed red line the welfare gains to trade in Figure 4 in the absence of middlemen. As trade converges to zero, welfare converges to its no-trade level.

1.2.2 Case 2A: Buyer posts limit order

In this case the offer is made by the informed agent, and it therefore partially reveals the state z to the seller. The seller's expectations thus depend on the buyer's equilibrium strategy. The buyer of course recognizes that fact, and this leads to a fixed-point problem for the equilibrium bidding strategy

We imagine, then, that in the absence of middlemen the buyer can post a limit order at the start of the period. It will turn out that the buyer's bid, will be a monotone function of $u \equiv y + z$, thereby allowing the seller to infer u while deciding on whether or not to accept the bid. He will, in other words, condition his beliefs on u. The distribution of z conditional on u is Normal, with mean

$$E(z \mid u) = \frac{\sigma^2}{1+\sigma^2}(u-1). \tag{18}$$

Let p denote the buyer's bid. In equilibrium, the bid will be a function

$$p = \mathbf{h}(u)$$

that will turn out to be strictly monotone and, hence, invertible. Upon seeing the offer at p, the seller will form the expectation of z that we shall denote by

$$\begin{aligned} Z(p) &\equiv E\left(z \mid u = \mathbf{h}^{-1}[p]\right) \\ &= \frac{\sigma^2}{1+\sigma^2}\left(\mathbf{h}^{-1}[p] - 1\right) \end{aligned} \tag{19}$$

(using (18)) and he will accept this offer iff $x + Z(p) < p$, i.e., iff

$$x < p - Z(p). \tag{20}$$

The buyer's decision problem.—The buyer understands that his offer influences the seller's beliefs about z, via (20). If he buys the security, the buyer receives $u - p$, and zero otherwise. The buyer's problem then is

$$\max_p \{F(p - Z(p))(u - p)\}$$

The FOC is

$$F(p - Z(p)) = (u - p) f(p - Z(p))(1 - Z'(p)) \tag{21}$$

where, upon using (19), we find that

$$Z'(p) = \frac{\sigma^2}{1 + \sigma^2} \frac{d\mathbf{h}^{-1}}{dp} \tag{22}$$

Equilibrium.—Nash equilibrium requires that the buyer's expectations about the strategy that the seller uses should be self-fulfilling. This requires, in turn, that

$$\frac{\partial \mathbf{h}^{-1}}{\partial p} = \frac{1}{dp/du}$$

or simply that

$$\mathbf{h}'(u) = h'(u) \tag{23}$$

where $dp/du = h'(u)$ is the optimal response of the seller to a change in u. This response obtained as a comparative static result in (21) taking $Z(p)$ as determined – via (19) – by the seller's expectations $\mathbf{h}$. In other words, we seek a fixed point for h.

The previous section showed that as σ gets large, the asking price of the uninformed goes to plus infinity for each u. Now we shall show that under the same conditions, the bid of the informed buyer converges to minus infinity for each u, so that there is again no trade

Proposition 3 *Under the normality assumptions in (9), for each $u \in R$,*

$$\lim_{\sigma \to \infty} p(u) = -\infty$$

The proof goes as follows. Let $r(s) = F(s)/f(s)$, and

(a) substitute for Z from (19) into (21) and

(b) substitute for $Z'(p)$ from (22) noting that $\frac{d\mathbf{h}^{-1}}{dp} = 1/h'(u) = 1/p'(u)$

so that the latter reads

$$r\left(p - \frac{\sigma^2}{1+\sigma^2}(u-1)\right) - (u-p)\left(1 - \frac{\sigma^2}{1+\sigma^2}\frac{1}{p'(u)}\right) = 0 \tag{24}$$

Now (24) must hold for all u. The solution $p = h(u)$ is, unfortunately, not linear.[7] Equilibrium then satisfies the first-order differential equation

$$\frac{1}{u-p}r\left(p - \frac{\sigma^2}{1+\sigma^2}(u-1)\right) = 1 - \frac{\sigma^2}{1+\sigma^2}\frac{1}{p'(u)} \tag{25}$$

i.e.,

$$\frac{du}{dp} = \frac{1+\sigma^2}{\sigma^2}\left[1 - \frac{1}{u-p}r\left(p - \frac{\sigma^2}{1+\sigma^2}(u-1)\right)\right] \tag{26}$$

Now it is simpler to study the behavior of the variable

$$s = u - p > 0, \tag{27}$$

where the inequality follows because it is optimal for the seller to bid strictly less than his value. Then (26) implies

$$\frac{ds}{dp} = \frac{1}{\sigma^2} - \frac{1}{s}r\left(\frac{\sigma^2}{1+\sigma^2}(1-s) + \frac{p}{\sigma^2}\right) \tag{28}$$

Analysis of the ODE (28).—We now proceed informally and analyze a sequence of first-order differential equations indexed by the parameter σ.

LEMMA: Let the ODE

$$\frac{ds}{dp} = \psi_\sigma(s,p)$$

admit a solution $s_\sigma(p)$. For any compact set $A \subset R^2$ let

$$\lim_{\sigma\to\infty}\sup_{s\in A}|\psi_\sigma(s,p) - \psi_\infty(s,p)| = 0 \tag{29}$$

and let the family (ψ_σ) be uniformly Lipshitz continuous on A . Then if the solution $s_\infty(p)$ exists, then the

[7] Suppose that it were linear so that $p = a+bu \implies p'(u) = b$ Then since r is nonlinear, we would have to have $b = \sigma^2/\left(1+\sigma^2\right) = p'(u)$ which would imply that $r = 0$, and this is impossible except in the limit as $p \to -\infty$.

sequence of solutions $(s_\sigma(p))$ converges pointwise to $s_\infty(p)$ on A.

[The *proof* of the lemma is not included]

If we confine attention to the region where s is bounded away from zero then condition (29) is satisfied and the convergence

$$\frac{ds}{dp} \to -\frac{1}{s} r(1-s) < 0 \tag{30}$$

is uniform. Therefore we shall study the properties of the limiting ODE given by the RHS of (30) and then apply the lemma to infer something about the sequence of solutions as σ gets large.

Let Φ and ϕ denote the standard normal CDF and density. F is the normal distribution with mean and variance one, and f the corresponding density, and $r = F/f$. Then

$$r(1-s) = \frac{\Phi(-s)}{\phi(-s)} = \frac{1-\Phi(s)}{\phi(s)} > \frac{s}{1+s^2}$$

where the last inequality follows from a well-known inequality concerning Mill's ratio (Baricz (2008), eq. 1.1). Combining this inequality with (30)

$$\lim_{\sigma\to\infty} \frac{ds}{dp} < -\frac{1}{1+s^2}$$

Therefore

$$\begin{aligned} s > 0 &\Longrightarrow \frac{du}{dp} < 0 \Longleftrightarrow \frac{dp}{du} < 0 \\ s \in (-1, 0] &\Longrightarrow \frac{du}{dp} < 1 \end{aligned}$$

Now fix u at u_0 and suppose $\lim_{\sigma\to\infty} p(u_0)$ existed. Let

$$s_0 = u_0 - \lim_{\sigma\to\infty} p(u_0)$$

faster than u, which means that there exists a value $u_1 \geq u_0 + s_0$, such that $p(u_1) > u_1$, which would contradict (27).[8]

[8]Of course once s approaches zero, the uniform convergence assumptions in (29) fail, and the argument needs to be stated more carefully.

Although the informed agent can extract the rents, he cannot commit to an function that relates the bid to z. The lack of commitment can be seen as an inability to use a contract the terms of which are indexed to z. If the buyer could commit to an indexed contract, he would do so. Such contracts are not much traded so there must be a force outside our model that prevents that from happening.

For that reason, welfare in the absence of middlemen declines overall as σ rises from zero to infinity, and that is why the dashed red line in Figure 4 must slope down roughly as shown in the figure. On the other hand we have not proved that the decline is monotonic.

1.2.3 Case 3A: Middlemen in the game

Middlemen operate precisely as in Case 3, and the equilibrium is precisely that described in that case. That is to say, equations (3) - (6) hold here as well and the allocations are precisely the same. The reason is that competition at the bidding stage reveals z to **B** anyway, and therefore no asymmetry remains at the stage where the ask-price p_a is determined.

For that reason, welfare in the presence of middlemen does not depend on the properties of the distribution G, and that is why the solid blue line in Figure 4 is flat.

2 Dynamics

We now show that the results extend to an infinite number of periods. We begin with a situation where there are just two investors in the game at any one time, labelled again **S** (the beginning-of-period owner of the asset) and **B**, the potential buyer.

Sequencing of events in a period

1. **S** observes x, **B** observes y and z separately

2. **S** makes an offer (an “ask”), or **B** makes a bid

3. Offer is accepted or rejected

4. The (possibly new) owner stays in the market, the other leaves for good

5. Owner collects $x + z$ (or $y + z$), and draws a new x' (or y')

Everyone is risk neutral and lives for ever and discounts the future with factor β.

The i.i.d. assumption.—Because of the near random walk of prices, the assumption of an i.i.d. common value seems innocuous. We shall also assume, however, that the variable x, the private value that is independent over investors and i.i.d. with distribution $F(x)$.

The i.i.d. assumption is convenient. In reality, x and y are likely to be autocorrelated. In our model, they are uncorrelated between periods but do not change (i.e., are perfectly autocorrelated) within the period, and we allow the security to be transferred within the period, in time for another investor to enjoy his currently high private value. Therefore we think of β partially as an inverse index of how autocorrelated the private values are per unit of time.

2.0.4 Case 1B

We now look at the regime where in each period posted offers are ask prices posted by **S**. Since the owner does not see z when making the offer and since z is i.i.d., the state is x. Let $v(x)$ again be the lifetime PV of holding the asset today and drawing x utility if it is not sold, or collecting P if the offer is accepted. Denote the continuation value by

$$\bar{v} \equiv \beta \int v(x)\, dF(x).$$

The buyer accepts an offer at P if has drawn a value y satisfying

$$y + z + \bar{v} \geq P. \tag{31}$$

The probability that (31) holds, conditional on (z, P) is

$$1 - F(P - z - \bar{v}). \tag{32}$$

Then

$$v(x) = \max_P \int [P[1 - F(P - z - \bar{v})] + F(P - z - \bar{v})(x + z + \bar{v})]\, dG(z). \tag{33}$$

Equilibrium.—It is two functions $v(x)$ and $P(x)$ satisfying and (33).

Analysis.—We can re-write (33) as

$$\begin{aligned}
v(x) &= \max_P \int [\Pr(z \geq P - \bar{v} - y) P + \Pr(z < P - \bar{v} - y)\{Ex + z + \bar{v} \mid y,\ z < P - \bar{v} - y\}]\, dF(y) \\
&= \max_p \int \{[1 - G(p-y)] \cdot (p + \bar{v}) + G(p-y) E[x + z + \bar{v} \mid y,\ z < p - y]\} dF(y) \\
&= \max_p \int \{[1 - G(p-y)] \cdot (p + \bar{v}) + \int_{-\infty}^{p-y} (x + z + \bar{v})\, g(z)\, dz\} dF(y) \\
&= \bar{v} + \max_p \int \{[1 - G(p-y)] \cdot p + \int_{-\infty}^{p-y} (x + z)\, g(z)\, dz\} dF(y).
\end{aligned}$$

where, in the second line, $p \equiv P - \bar{v}$ is the markup over $\bar{v}$. Differentiating and cancelling the term $pg(p-y)$, we get the same FOC analyzed in the static Case 1A, namely (8), and the results on the disappearance of trade in (15) follow.

2.0.5 Case 2B: Buyer posts limit order

The informed agent makes the offer in this case, and it therefore partially reveals the state z to the seller. Let P denote the buyer's bid, and let

$$p = P - \bar{v}$$

once again denote the markup over $\bar{v}$, just as in Case 1B As in Case 2A, the equilibrium bid will be a monotone, invertible function $p = \mathbf{h}(u)$. Upon seeing the offer at p, the seller will form the expectation of z that we shall denote by $Z(p)$ as in (19), which uses the assumption of normality and, hence (18)). and he will accept this offer iff

$$x + Z(p) + \bar{v} < P,$$

i.e., iff (20) holds. The rest of the analysis in Case 2A then goes through.

2.0.6 Case 3B: Middlemen

We now introduce middlemen into the above environment.

Timing.—Middlemen are faster[9] and can post a limit order first and then try to re-sell the security in the

[9] Although we do not have the middleman's quotes, Chi-X is more hospitable in the sense of allowing free unlimited cancellations

same period. A low-x investor-owner can wait for the next period in the hope that the new draw x' will be higher. Indeed, since the draws are i.i.d., he has as high chance of getting a good draw tomorrow as the chance of the arriving investor having the good draw of y today. But x' is discounted and y is not, and this is where the middleman can add value.

If he fails to sell a security he has bought, the middleman collects z and enters the next period as the security's owner, in which case his only action is to post an order to sell. Faced with an order to buy, the seller must either accept it or hold on to the security for the remainder of the period. As before, the seller cannot react to a middleman's offer within the period and post a limit order instead reflecting the information in that order, so that any limit order the seller posts cannot incorporate the knowledge of z.

Analyzing this requires some non-trivial modifications because **M** will acquire the security from **S** and not succeed in selling it to **B**. In that case, **M** enters the next period as the security's owner. Case 3 analyzed only the case in which the initial owner was **S**. Now we need to also cover the case in which the initial owner is **M**. Accounting for this turns out to lower the welfare benefits from middlemen roughly by a factor of five over those reported in Figure 4, from 12 percent to 2.5 percent. Nevertheless, when σ is large, these benefits are still positive.

If **M** is surrounded by other competitive middlemen who have no idea who owns the security, he then will face bids, p_b given in (5), with a slightly modified version of u and π originally given in (4) and (6) which we shall now derive. The modifications must recognize that **S, B,** and **M** all have continuation values.

The middleman's selling decision.—If he has managed to acquire the security at an earlier date, or even at the start of the period in question, then he will offer it for sale to the arriving investor[10] at the price that we shall denote by P. Let $m(z)$ be the value of owning the security in state z. Let

$$\bar{m} = \beta \int m(z)\, dG(z) \tag{34}$$

be the expected present value of carrying the asset into the next period. There is no asymmetric information

and faster, as the speed comparison Table3 and Table 4 both show. See the discussion of those tables. These tables reveal a speed difference between Chi-X and Euronext, and this is indirect evidence of our modeling assumption concerning the speed of the middleman.

[10] We assume **M** sells to **B**, and not to other middlemen because middlemen are all the same. Since **M** always asks for more than his own continuation value, no other middlemen would accept the offer and their presence in the game does not affect the resulting ask price.

about z at this stage. Faced with the ask price P, the buyer accepts the middleman's offer iff

$$y + z + \overline{v} > P$$

If he owns a security, the middleman tries to sell it, and his value $m(z)$ solves the decision problem

$$\begin{aligned} m(z) &= \max_{\hat{P}} \{[1 - F(P - z - \overline{v})] P + F(P - z - \overline{v})(z + \overline{m})\} \\ &= z + \overline{m} + \max_{P} \{[1 - F(P - z - \overline{v})](P - z - \overline{m})\} \\ &= z + \overline{m} + \max_{p} \{[1 - F(p - z)](p - z + \Delta)\} \end{aligned} \tag{35}$$

where $p = P - \overline{v}$, and where

$$\Delta = \overline{v} - \overline{m} \tag{36}$$

is the difference in the two parties' continuation values of ownership where, as before, $\overline{v} = \beta \int v(x)\, dF(x)$. The FOC is

$$k = -\Delta + \frac{1 - F(k)}{f(k)}, \tag{37}$$

where

$$k = p - z$$

is a constant. In (35) we see that

$$m(z) = z + \alpha, \tag{38}$$

where α is a constant is defined as in (14). Combining (35) and (34),

$$\begin{aligned} \overline{m} &= \beta \overline{m} + \frac{[1 - F(k)]^2}{f(k)} \\ &= \frac{\beta}{1 - \beta} \frac{[1 - F(k)]^2}{f(k)} \end{aligned}$$

Bid-ask spread.—The middlemen's bid is

$$m(z) = z + \alpha \tag{39}$$

while the ask is $P = p + \bar{v} = z + k + \bar{v}$. Therefore the ask minus the bid, or the bid-ask spread **S** is

$$\begin{aligned}\mathbf{S} &= k + \bar{v} - \alpha = -\Delta + \frac{1 - F(k)}{f(k)} + \bar{v} - \bar{m} - \frac{[1 - F(k)]^2}{f(k)} \\ &= \frac{F(k)[1 - F(k)]}{f(k)},\end{aligned}$$

where k solves (37).

For instance if F is uniform on $[0, 1]$, $k = (1 - \Delta)/2$ so that

$$\bar{m} = \frac{1}{2}\frac{\beta}{1-\beta}(1 + \bar{v} - \bar{m})^2$$

The investor-owner's value.—If the asset is in the investor's hands when the period starts, then middlemen (there are at least two) compete by posting orders to buy. Bertrand competition among the middlemen drives the bids to equal $m(z)$. The owner thereby infers z from the price. He sells iff

$$x + z + \bar{v} < m(z) \Leftrightarrow x < \alpha - \bar{v}$$

and thereby obtains the reward of $m(z)$. If he does not sell, his reward is $x + z + \bar{v}$. Therefore

$$\begin{aligned}v(x) &= \int \max(m(z), x + z + \bar{v})\, dG(z) \\ &= \int [z + \max(\alpha, x + \bar{v})]\, dG(z) \\ &= \max(\alpha, x + \bar{v}) \qquad (40)\end{aligned}$$

Therefore on average the value is

$$\frac{1}{\beta}\bar{v} = \alpha F(a - \bar{v}) + [1 - F(\alpha - \bar{v})](\bar{v} + E(x \mid x \geq \alpha - \bar{v}))$$

Ownership transitions.—To figure out welfare we shall need the stationary fraction of time that the security is in the hands of investors as opposed to in the hands of middlemen. Let I_t denote the ownership status, i.e., let

$$I_t = \begin{cases} 1 & \text{if the date-}t\text{ owner is initially an investor} \\ 0 & \text{if the date-}t\text{ owner is initially a middleman} \end{cases}$$

It follows a first-order Markov process. The transition from 1 to 0 occurs if the middleman's buy offer is accepted but his sell offer is then rejected. The probability that a seller accepts a middleman's buy offer is $F(\alpha - \overline{v})$, and the probability that the buyer then rejects the middleman's sell offer is $F(k)$. Thus the $1 \to 0$ transition has probability $F(\alpha - \overline{v}) F(k)$. The matrix of transition probabilities can therefore be written as

$$\begin{array}{ccc} & & I_{t+1} \\ & & \begin{array}{cc} 0 & 1 \end{array} \\ I_t & \begin{array}{c} 0 \\ 1 \end{array} & \begin{bmatrix} F(k) & 1 - F(k) \\ F(k) F(\alpha - \overline{v}) & 1 - F(k) F(\alpha - \overline{v}) \end{bmatrix} \end{array} \tag{41}$$

Therefore the stationary probability, call it λ, of being in state $I = 1$ satisfies

$$\lambda = \lambda \left(1 - F(k) F(\alpha - \overline{v})\right) + (1 - \lambda)\left[1 - F(k)\right],$$

i.e., $0 = -\lambda F(k) F(\alpha - \overline{v}) + [1 - F(k)] - \lambda [1 - F(k)]$, so that the fraction of time the investor has the security is

$$\lambda = \frac{1 - F(k)}{1 - F(k)[1 - F(\alpha - \overline{v})]}, \tag{42}$$

and the fraction of time a middleman has it is

$$1 - \lambda = \frac{F(k) F(\alpha - \overline{v})}{1 - F(k)[1 - F(\alpha - \overline{v})]}. \tag{43}$$

Welfare

Welfare is a weighted average of the welfare levels of the middleman and the investor owner. The weights are the stationary probabilities that the asset will be in the hands of the one or the other type. The common value is enjoyed by whomever owns the security and therefore we can omit it from the welfare calculations.

Now x is i.i.d., and so it is uncorrelated with the ownership state. Therefore welfare is

$$W = \lambda \int \max\left(\alpha, x + \overline{v}\right) dF\left(x\right) + \left(1 - \lambda\right) U$$

where

$$\begin{aligned} U &= \left(1 + \beta F\left(k\right) + \beta^2 F\left(k\right)^2 + ...\right) \int_k \left(x + \overline{v}\right) dF\left(x\right) \\ &= \frac{1}{1 - \beta F\left(k\right)} \int_k \left(y + \overline{v}\right) dF\left(y\right) \end{aligned}$$

therefore

$$W = \lambda \int_{-\infty}^{\infty} \max\left(\alpha, x + \overline{v}\right) dF\left(x\right) + \frac{1 - \lambda}{1 - \beta F\left(k\right)} \int_k^{\infty} \left(x + \overline{v}\right) dF\left(x\right)$$

Evidently, W does not depend on the properties of the distribution G. Anticipating a bit, this is why the dashed line in Figure 4 is flat, i.e., independent of σ which is the variance of the distribution $G\left(z\right)$.

The remainder of this subsection will recognize the ownership transitions in (41) and the stationary probabilities (42) and (43) for the ownership fractions in steady state. The utility of agents in each state will, however, be evaluated under the assumption that $\beta = 0$. In what follows, the middleman will be on the passive side of each trade, which our data support – see Table 2 in which this was true for 80% of all trades our middleman was in.

Middleman's selling decision.—Since $\beta = 0$, on the RHS of (35) we set $\Delta = \overline{v} = \overline{m} = 0$ and collect an expected payoff of

$$m\left(z\right) = z + \max_p \left\{\left(p - z\right)\left[1 - F\left(p - z\right)\right]\right\} = z + \pi$$

with π as defined in (6) of case 3. the optimal decision – a limit order to sell a unit – is just as it was in Case 3 and eq. (3), i.e., $p_a = z + u$. When $F\left(y\right) = y$, the FOC is $2\left(p - z\right) = 1$,

$$p_a = z + \frac{1}{2} \tag{44}$$

and $\pi = 1/4$. This then becomes the expected value of acquiring the security for all the middlemen at the start of the period.

Middleman's buying decision.—Since $\pi = 1/4$, (5) implies

$$p_b = z + \frac{1}{4}. \tag{45}$$

Welfare.—This part is different in the multi-period context.

(**A**) If the period starts with the middleman owning the security, then welfare is

$$\text{welfare} = \begin{cases} y & \text{if there is a sale} \\ 0 & \text{if not} \end{cases}$$

and expected welfare is

$$W_{\textbf{MID OWNS}} = \int_{1/2}^{1} y dy = \frac{3}{8} \tag{46}$$

Since the RHS of (46) is less than the RHS (47), welfare is less if we condition on a middleman starting out as the owner.

(**B**) If the period starts out with the investor owning the security, then

$$\text{welfare} = \begin{cases} 3/8 & \text{if there is a sale} \\ (1 + 1/4)/2 & \text{if not} \end{cases}$$

A sale occurs with probability 1/4 and therefore expected welfare is

$$W_{\textbf{INV OWNS}} = \frac{1}{4}\left(\frac{3}{8}\right) + \left(\frac{3}{4}\right)\frac{1}{2}\left(\frac{5}{4}\right) = \frac{9}{16}. \tag{47}$$

Now in (42) and (43), $F(k) = 1/2$ and $F(\alpha - \overline{v}) = 1/4$ and so the fraction of the time that the investor holds the security is

$$\lambda = \frac{1/2}{1 - \frac{1}{2}\frac{3}{4}} = \frac{4}{5},$$

and the fraction of time a middleman has it is $1/5$. Therefore average welfare in the long run is

$$W^* = \left(\frac{4}{5}\right) W_{\textbf{INV OWNS}} + \left(\frac{1}{5}\right) W_{\textbf{MID OWNS}} = \frac{21}{40}$$

which means that

$$W^* - W_{\textbf{NO TRADE}} = \frac{1}{40}$$

This is about two and half times smaller than the difference of 0.563-0.5=0.063 that is implied by the static-model results reported in Figure 4.

First-best welfare.—Allocating the asset to the highest-value investor at all times yields $W_{\text{FIRST BEST}} = \int_0^1 \max(x, y)\, dydx = \frac{2}{3}$. Therefore relative to what first-best gains would be, the gains that middlemen bring about in the multiple-period case are

$$\frac{W^* - W_{\text{NO TRADE}}}{W_{\text{FIRST BEST}} - W_{\text{NO TRADE}}} = \frac{1/40}{2/3 - 1/2} = \frac{6}{40} = 15\%. \tag{48}$$

3 Mechanism-design issues

In our model, middlemen add value by removing the winner's curse problem facing an ordinary investor posting a limit order such as the offer that **S** posts in cases 1A and 1B. Nevertheless, middlemen deliver only 15%-33% of the possible welfare gains depending on whether we consider the static model or the dynamic model. Myerson and Satterthwaite (1983) showed that first-best welfare is unattainable under any mechanism. The theory of auctions with resale (e.g., Haile (2003)) deals, in related contexts, with some of the issues raised below. Our discussion here is brief and quite informal.

Endogenizing the participation of middlemen.—A fuller discussion of optimal mechanisms probably requires thinking about how the numbers of investors and middlemen are determined. That would require including a cost an investor would need to bear for keeping track of z more or less continuously. This is beyond the ordinary investor for it requires the development of programs and the acquisition of expensive hardware. Algorithmic traders have made the needed investment and can therefore post limit orders that they can quickly cancel and readjust when news about z arrives. We then could figure out whether the number of middlemen is optimal or whether a smaller or larger number is needed.

Why not z-contingent contracts?—One way to improve allocations is to have state-contingent pricing. In our model trading in which prices were indexed on z would overcome the adverse selection problem that traders face and eliminate the positive role of middlemen. Therefore our model perhaps overestimates the welfare benefits from middlemen because in their absence, alternative arrangements would emerge. In international portfolio theory, covered interest parity is one result of the availability of insurance of exchange-rate risk. The analog here would be to have prices be z-contingent (see Black (1995)). In practice, however, this is unlikely to completely remove HFTs competitive edge for at least two reasons. First, whereas the index is a natural candidate to 'peg' an order to, there are many sources of public information that might be relevant for a stock's fundamental value. Identifying all of them and establishing their correlation is an art. Second, correlations might be time-varying and quote updating therefore required modeling skill (see, e.g., the DCC model proposed by Engle (2002)). Nevertheless, our logic implies that if middlemen were taxed or if their activities were curtailed in some other way, we would presumably see a rise in the trading of derivatives on the 'hard' components of z, whatever those may be.

More competition among the informed agents?—Another way to achieve optimality is to introduce competition among the informed agents. If several investors, all knowing x and z, were in the market continuously, we would expect a near-optimal outcome. But at the frequency of microseconds and even of seconds, the investor market is quite thin – on Euronext and Chi-X combined we observe a trade only once every 6 seconds. One would need to interrupt trading for even longer if one wanted to to ensure enough investors would be present to achieve a near-competitive outcome in which the security ends up with whomever values it the most. Moreover, few investors would even then have up-to-date information about z and an efficient outcome would be unlikely. In other words, even at lower trading frequencies, middlemen are likely to be a valuable source of liquidity.

Inventories by several middlemen.—We have stressed the alternative mechanism of middlemen providing the liquidity. We have done so under some restrictive assumptions. The mechanism we have modeled in section 3 has competition at the bidding stage – At the bid in (45), the middleman earns zero rents. Could competition also be introduced at the ask stage? The ask-price in (44) maximizes the owner's rent. If more than just one middleman were to own a unit of the asset then the ask price would presumably be lower. This would introduce several effects that affect welfare in more than one direction.

(*i*) Competition among middlemen not just at the bidding stage but also at the ask stage, would lower p_a below 1/2 in states in which it was common knowledge among middlemen that they both were in possession of a unit to sell. This would be good for welfare;

(*ii*) The effect of (*i*) is to lower the value to a middleman of buying the asset, and it would lower p_b below

1/4 and this would reduce trade and welfare;

(*iii*) If the middlemen were collectively to hold a larger inventory, this would lower welfare because it would raise the fraction of the time that a security was held by a middleman drawing a zero private value from it.

Policies.—Aside from taxes on HFTs, on cancelled offers, other restrictions have been used. For instance, the NYSE follows the practice of selling people the right to be the sole possessors of information for a while – e.g., information about the whole book and not just about the best quotes; the product is called "Open Book."

4 Empirical results

4.1 Background

The European Union aimed to create a level playing field in investment services when it introduced the *Markets in Financial Instruments Directive* (MIFID) on November 1, 2007. For markets, MIFID created competition between national exchanges and it allowed new markets to enter.

Instinet pre-empted MIFID when it launched the trading platform Chi-X (Chi-X) on April 16, 2007, for Dutch and German index stocks.[11] At the end of 2007, it allowed a consortium of the world largest brokers to participate in equity through minority stakes.[12] Before Chi-X Instinet had successfully introduced the product as 'Island' in the U.S. which distinguished itself from others through fast-execution and subsidization of passive orders (see fee discussion below). Eventually Instinet sold the U.S. license to NASDAQ but kept the international license which led to Chi-X.

In the first 77 trading days of 2008, our sample period, Chi-X traded British, Dutch, French, German, and Swiss local index stocks. It had captured 4.7% of all trades and was particularly strong in Dutch stocks with a share of 13.6%. Volume-wise, Chi-X overall market share was 3.1% and its Dutch share was 8.4%. Chi-X started off particularly strong for the stocks studied in this manuscript.

[11] "Chi-X Successfully Begins Full Equity Trading, Clearing and Settlement," Chi-X press release, April 16, 2007.

[12] These brokers were: BNP Paribas, Citadel, Citi, Credit Suisse, Fortis, Getco Europe, Ltd, Goldman Sachs, Lehman Brothers, Merrill Lynch, Morgan Stanley, Optiver, Société Générale and UBS (op. cit. footnote 14).

Prior to Chi-X entry, Euronext was by far the main venue for trade in Dutch stocks. Its trading platform ran in much the same way as the Chi-X platform and competition focused on fees and speed (see discussion below). Dutch stocks also traded as ADRs in the U.S. and in the Xetra system run by the German Stock Exchange. They did not yet trade in NASDAQ OMX, Turquoise, or BATS-Europe which entered later on a business model similar to Chi-X: subsidies on passive orders and a fast system.

The broker identified as a middleman in this study was a substantial participant in Chi-X. In our sample period, it participated in 10.8 million of the 99.2 million Chi-X trades. It was particularly active in Dutch stocks with participation in 1.7 million out of 8.6 million Chi-X trades.

Fee structure. In our sample period, Chi-X did not charge for limit order submissions and cancellations. Quite the opposite, it paid 0.2 basis points if the order becomes the passive side of a trade. If however the order is 'marketable' and executes against a standing limit order upon arrival it gets charged 0.3 basis points. For example, in the stock of limit sell orders in the book, the one with the lowest price becomes the prevailing 'ask' quote. If a limit buy order arrives with a price (weakly) higher than this ask price, it immediately executes against this limit sell and a transaction is recorded. For simplicity, in this example it is assumed that orders are of the same size. For a detailed description of the generic limit-order market mechanism we refer to Biais, Hillion, and Spatt (1995).

Euronext on the other hand charges a fixed fee of €1.20 per trade which for an average size trade of ~€25,000 (see Table 1) is effectively 0.48 basis points. Highly active brokers benefit from volume discounts that can bring the fixed fee down to €0.99 per trade (~0.40 basis points). In addition, Euronext charges an 'ad valorem' fee of 0.05 basis points. The act of submitting an order or cancelling it is not charged (i.e., only executions get charged without an aggressive/passive distinction). But, if on a daily basis the cancellation-to-trade ratio exceeds 5, all orders above the threshold get charged a €0.10 fee (~0.04 basis points).

In terms of post-trade costs, Chi-X clears and settles through EMCF which claims to be over 50% cheaper than other European clearing houses including the ones used by Euronext.[13]

System speed. In a April 7, 2008 press release Chi-X celebrates its first anniversary. It claims to run one of the fastest platforms in the industry with a system response time (often referred to as 'latency') of two

[13] See, "EMCF cuts clearing fees", The Trade News, 4/24/08.

milliseconds. This is “up to 10 times faster than the fastest European primary exchange.”[14]

Overall, Chi-X appears to be particularly friendly venue for the middleman type that is central to the theory. Its fees are lowest across the board and particularly low for a strategy that relies on passive orders that get cancelled and resubmitted upon the arrival of public news. Its speed advantage allows one to do so quick enough in order not to be picked off.

4.2 Data, Approach, and Summary statistics

Data. The main sample consists of trade and quote data on Dutch index stocks for both Chi-X and Euronext from January 1 through April 23, 2008. The quote data consist of best bid and ask price and the associated depth. The trade data contain transaction price, size, and an anonymized broker ID for both sides of the transaction. The broker ID anonymization is done for each market separately and broker IDs can therefore not be matched across markets—say the first market uses 1,2,3,... and the second one uses a,b,c,.... The time stamp is to the second in Euronext and to the millisecond in Chi-X. In the analysis, Chi-X data is aggregated to the second in order to create a fair comparison across markets.

In a final analysis we aim to identify the net effect of middlemen introduction through a difference-in-difference analysis (see Section 4.6). The instrument is essentially the introduction of Chi-X and the advent of the identified middleman to the market. A first step in identifying such effect is to collect and analyze the exact same data for Euronext in the first 77 trading days in 2007 when there was no Chi-X, nor was the middleman broker ID active in the Euronext data (comparing the same period in 2007 and 2008 avoids the impact of calendar effects).[15] This is the ‘treated’ sample. To control for all that changed comparing 2007 with 2008, Belgian index stocks are analyzed as the ‘untreated’ sample as Chi-X had not yet been introduced (as a matter of fact, Chi-X introduced Belgian stocks on April 24, 2008 which motivates the choice of our main sample period). Other than the absence of Chi-X, Belgian stocks traded in the same way as Dutch stocks as Euronext operated its trading system across its four markets (Belgium, France, the Netherlands, and Portugal). In terms of the actual data, the Belgian sample only differs from the Dutch sample in that it lacks broker IDs on transactions.

[14]“Chi-X Europe Celebrates First Anniversary,” Chi-X press release, April 7, 2008.

[15]This makes the pre-entry period run through April 20, 2007. This appears at odds with the Chi-X effective date of April 16, 2007, but in the data no trade materialized in the Chi-X system until after April 20, 2007.

The list of all stocks that are analyzed in this study is included as an appendix. It contains security name, isin code, and weight in the local index.

Finally, a dataset with quotes from the highly active index futures market is used to track changes in both the Dutch AEX index AEX and the Belgian BEL20 index.

Approach. The analysis was done in two steps (i) to make it feasible (the entire dataset contains roughly 100 million event records) and (ii) to do proper statistical inference. The first step calculates all variables of interest for each stock-day. For example, it calculates the time-weighted quoted half spread (ask minus bid divided by two) for Heineken on January 2, 2008. To make activity measures comparable across stocks, we convert, e.g., the number of shares traded to a €amount by multiplying it with the average transaction price in the sample period. The second step is a panel data analysis on the 'box' with all stock-day results. Standard errors are based on residuals that are clustered by day so as to avoid 'double counting' in the presence of commonality and to explicitly recognize heteroskedasticity. The results are presented as weighted-averages across stocks where the weight corresponds to the stock's weight in the local index (see appendix with the list of all stocks). Also, results are reported separately for large and small stocks where the cutoff is the median index weight.

[insert Table 1 here]

Summary statistics. Table 1 presents summary statistics to illustrate Chi-X role in the trading of Dutch stocks. It leads to a couple of observations.

(i) Chi-X managed to obtain a nontrivial market share within one year of its existence. Chi-X' share of overall volume is 8.4% its share of trades is 13.6%. Its performance is particularly strong for large stocks.

(ii) The use of Chi-X in addition to Euronext leads to a substantial improvement of liquidity supply. The average quoted half spread is 3.70 basis points for Euronext and 5.09 basis points for Chi-X. Average depth is €108,100 for Euronext and €48,500 for Chi-X. The wider spread and lower depth in Chi-X does not necessarily imply that investors who demand liquidity/immediacy only focus on Euronext. The results are, for example, consistent with Chi-X always having a strictly better price on one side of the market, i.e., a strictly lower ask or a strictly higher bid. To assess Chi-X' contribution to liquidity supply one might calculate the lowest ask across markets minus the highest bid—the inside spread—and compare it to the Euronext spread. The inside spread is, effectively, what investors with 'smart routers' pay (see Foucault and Menkveld (2008)).

The inside spread however might lead one to overestimates liquidity supply improvement as the average Chi-X depth is lower than Euronext depth. To control for depth, we define the 'generalized' inside spread which adjusts both the bid and the ask quote for potentially better prices in Chi-X. For example, the adjusted ask is €29.995 if the Euronext ask is €30.00 with depth €100,000 and the Chi-X' ask is €29.99 with depth €50,000. The generalized inside spread is a conservative measure as it calculated for transaction sizes that consume full Euronext depth; smaller transaction sizes imply an even tighter spread.

The generalized inside spread is 2.86 basis points, which is a significant 1.02 basis points (-23%) lower than the Euronext-only spread of 3.70 basis points. A conservative t-value of this differential assumes perfect correlation and therefore equals 3.92. The differential is statistically significant for both large stocks (-24%) and small stocks (-16%).

(iii) A standard effective spread decomposition shows that, by far, its largest component is adverse selection (91%) which thus supports the focus on information asymmetry in the theoretical model. The effective spread is defined as the transaction price minus the midquote—the average of the bid and ask quote—at the time of trade. It can be decomposed into a component that is compensation for being adversely selected and the orthogonal component which is gross profit to the passive order submitter. A standard decomposition relies on 'waiting out' the time it takes until prices reflect the long-term information in the trade (see, e.g., Glosten (1987)) which we set to 30 minutes. Overall, we find that the average effective spread is 3.04 basis points which is the sum of a significant 2.78 adverse selection (91%) and an insignificant 0.26 basis points gross profit (9%). The adverse-selection component is higher for small stocks.

4.3 Caught on tape! a middleman

The anonymization scheme by market makes simple matching of broker IDs across markets impossible. Instead, we match pairs of broker IDs and find that one combination (say broker 7 and broker d) achieves mean-reversion in net position within the day. Also, both broker IDs trade very frequently. It thus matches the SEC's defition of 'high frequency trader' and appears to fit the profile of the middleman in our main theory.

[insert Figure 5 here]

Figure 5 illustrates the middleman's trading by plotting inventory in ING stock throughout January 30, 2008 assuming she starts off at zero. This inventory at any particular point in time is thus defined as the number of shares bought minus the number of shares sold since the start of the trading day. The two top graphs plot this inventory by market and show that the middleman is quite active and runs into positions of almost 40,000 shares. Yet, these time series also appear nonstationary which, by market, would not qualify these broker IDs as middlemen. But, if summed across markets, which is the bottom graph, the pattern does exhibit high-frequency mean-reversion and it seems that we did catch a middleman. Although hard to see from the graph, the inventory at the end of the day is exactly zero shares.

[insert Table 2 here]

In Table 2, Panels A and B generate statistics in support of the conjecture that the broker IDs underlying Figure 5 represent a middleman. Panel A reports that on almost half (0.46) of the stock-days in the sample the middleman's change in inventory across the day is exactly zero. On average, this daily inventory change is €-56,000. Panel B shows that the middleman trades 1.40 times per minute in Euronext and 0.96 times per minute in Chi-X. She trades an average €32,000 per minute in Euronext and €21,000 per minute in Chi-X. The average open-to-close inventory change is therefore of the same magnitude as the amount she trades in a minute which supports strong inventory mean-reversion. She is a substantial market participant as, based on these numbers, she is a counterparty in every third trade in Chi-X (35.6%) and every fourteenth trade (7.7%) in Euronext. Disaggregating across small and large stocks, it appears her participation rate is the same in Chi-X but substantially lower in Euronext. She also seems less eager to carry positions overnight as the fraction of days with a zero inventory change is 0.60 as opposed to 0.33 for large stocks.

Panel C of Table 2 reports that most often the middleman is at the passive side of a transaction. In Chi-X, 78.8% of her transactions was another broker's aggressive order executing against her limit orders waiting in the book. In Euronext, it was slightly lower, 74.0%. The standard errors, 0.7% and 1.0% respectively, show that this is a structural pattern as the distance to 50% is statistically significant. This predominant use of passive orders in addition to the inventory mean-reversion is consistent with dynamic inventory control models that have been proposed for market makers (see, e.g., Ho and Stoll (1981), Amihud and Mendelson (1980), and Hendershott and Menkveld (2009)). These models predict an intermediary to skew her quotes opposite to the direction of her inventory in order to mean-revert. This could explain why Chi-X quotes, where our middleman is in every third trade, often features strictly better prices on one side of the market only (see the discussion on the 'generalized inside spread' in Section 4.2). Interestingly, disaggregation across large and small stocks shows that the middleman is less passive for small stocks in Euronext (52.7%) which, along with her high fraction of days that she 'goes home flat', indicates that she often willingly pays the half spread to keep inventory close to zero.

Panel D of Table 2 reveals adverse selection is a relatively smaller component of the effective spread when the middleman is on the passive side of the trade relative to when she is not. The panel conditions the effective spread decomposition on whether or not the middleman was on the passive side of the trade. The middleman effective spread is 3.47% on average, which is significantly higher than the nonmiddleman effective spread of 2.96$ (conservative t-value is 3.92). The adverse-selection cost, however, is 2.75 basis points for middleman trades which is not significantly different from the 2.81 basis points for nonmiddleman trades. The remainder is gross profits to the passive side of the trade or so-call realized spread. It is 0.72 basis points for middleman trades which is significantly higher than the 0.15 basis points for nonmiddleman trades (t value is 1.97). Testing against zero reveals that gross profits are only significantly positive if the middleman is on the passive side of the trade. In relative terms, adverse selection is 79% of the effective spread for middleman trades vs. 95% for nonmiddleman trades. We note that this result should not be interpreted as evidence that the middleman is bad for the market as she appears to have significantly positive gross profits on her passive orders. First off, trading conditions might be worse when the middleman is on the passive side, e.g., volatility might be higher—Section 4.5 will provide evidence for this conjecture. But, any judgement on whether the middleman is good or bad for liquidity supply or trading in general is deferred until the diff-in-diff analysis of Section 4.6.

4.4 Information-processing speed

This section studies the theory's conjecture that the middleman has superior information-processing speed which makes her a cost-efficient limit-order submitter. The idea is that a fast computer with enormous processing power can follow all relevant public news and quickly cancel and resubmit limit orders to reflect it. This reduces the adverse-selection cost associated with limit orders. The theory captures this idea by allowing the middleman to condition her price on the common value innovation z.

The middleman's ability to avoid picking-off risk in real markets is not perfect as not all (public) information is 'hard'. We believe the middleman is particularly well-positioned to quickly do the 'statistics' and inference a security's change in fundamental value by tracking price series that correlate with it, e.g., the index level, same industry stocks, foreign exchange rate, etc. We label such information 'hard' information. The middleman is at a disadvantage for 'soft' information which is, for example, an assessment of the quality of a new management team, the value of a new patent, etc.

The econometric challenge is to test the prediction that the middleman's quotes reveal hard information on a stock's fundamental value before anyone can pick her off. A data limitation is that her quotes are not observed. Instead, we conjecture that Chi-X quotes are more revealing of middleman quotes than Euronext quotes as Chi-X is the most friendly venue for their activity (see passive order and speed discussion in Section 4.1). The identified middleman's higher participation rate in Chi-X supports it. Midquotes in the highly active index futures market are used to trace an important piece of hard information that matters for a security's fundamental value.

We believe the most appropriate analysis of whether Chi-X (read: middlemen) quotes are more likely to reflect hard information inbetween trades requires a cointegration model that identifies the information in the trade. But, leading up to such model we first perform two analyses on the raw data to measure (i) the speeed with which both markets' quotes reveal index futures information and (ii) to what extent their quote updates inbetween trades correlate with the long-term information in the trade.

[insert Table 3 here]

Simple raw data analysis. Table 3 shows that Chi-X quotes are more responsive to changes in the Dutch index futures market than are Euronext quotes. A natural and simple approach is to consider all events where the index future midquote changes and count how often a stock midquote adjusts in the same second. This comparison, however, includes ‘mechanical’ stock midquote changes that are the result of executions that knock off stale quotes rather than the result of quote updates. It is for this reason that the analysis further conditions down on index changes that are not accompanied by stock transactions one second before, during, or one second after the change. The results show that same-second Chi-X stock quote updates happen three times more often than Euronext quote updates and their correlation with the index change is significantly more positive. Both these observations are statistically significant.

[insert Table 4 here]

Panel A of Table 4 shows that Chi-X quote updates appear more informed than Euronext quote updates. First, midquote changes strictly inbetween trades are calculated[16], i.e., the log midquote one second after trade (t-1) is subtracted from the log midquote one second prior to trade t (prices are expressed as log prices whenever price changes are analyzed throughout the study). These are then correlated with the long-term information revealed in the trade interval which is proxied by transaction price (t+10) minus transaction price (t-1). This correlation is 0.050 for Chi-X quote updates which is significantly higher than the Euronext correlation of 0.013. A drawback of this approach is that it does not recognize and strip out transient effects in quotes due to, e.g., dynamic inventory control. And, it cannot assess to what extent an informational advantage reflects ‘hard’ information. This is why we turn to a cointegration approach.

A cointegration model. A cointegration model is proposed to gauge quote update informativeness in both the Euronext and the Chi-X market. The approach extends Hasbrouck (1995) to include the market index so that quote informativeness can be decomposed into an index-correlated part (hard information) and a remainder part (which arguably is a mix of hard and soft information). This enables us to quantify Chi-X quote informativeness and compare it to Euronext quote informativeness. Moreover, it allows for to decompose any such differential into an index and a nonindex differential to test the conjecture that Chi-X quote informativeness is particularly strong for hard information.

The cointegration model is defined as:

$$\Delta p_t := [index_t \quad midquote\_euronext_{t^-} \quad midquote\_chi\_x_{t^-} \quad trade\_price_t]' \tag{49}$$

[16]The transaction clock used in this table aggregates across markets; it does not distinguish between Chi-X and Euronext trades.

where t runs over the transaction clock, t^- indicates that the quote snapshot is taken one second prior to the transaction, *index* is the midquote price in the local index futures, $trade\_price_t$ is the transaction price, and $midquote\_X_{t^-}$ indicates the midquote price in market X.

$$p_t = \varphi_1 \Delta p_{t-1} + \varphi_2 \Delta p_{t-2} + \cdots + \beta(A' p_{t-1}) + \varepsilon_t \tag{50}$$

$$\beta' = \begin{pmatrix} 0 & \beta_{22} & \beta_{32} & \beta_{42} \\ 0 & \beta_{21} & \beta_{31} & \beta_{41} \end{pmatrix} \quad A' = \begin{pmatrix} 0 & 1 & -1 & 0 \\ 0 & 1 & 0 & -1 \end{pmatrix}$$

The vector error correction term $\beta A' p_{t-1}$ in equation (50) reflects the presence of two random walks, one associated with the market index and the other with the security's 'efficient price'. This common efficient price disciplines differentials across both midquote price series and the trade price series to be stationary with mean zero. Price changes are assumed to be covariance stationary which implies that they can be expressed as a vector moving average (VMA):

$$\Delta p_t = \theta_1 \varepsilon_{t-1} + \theta_2 \varepsilon_{t-2} + \cdots = \theta(L)\varepsilon_t \tag{51}$$

where L is the lag operator. The two random walks now show up in the coefficient polynomial $\theta(L)$ evaluated at 1 which reflects the long-term response of prices to an error term impulse. This matrix has rank 2, i.e., the second, third, and fourth row are equal as all three are security prices that in the long-term agree on what the current shock's impact is on the efficient price. A useful econometric proxy for this efficient price is the best long-term linear forecast of prices conditional on all historical price information up until and including time t:

$$f_t \coloneqq \lim_{t\to\infty} E^*[p_{t+k}|p_t, p_{t-1}, \ldots] \tag{52}$$

where the asterisk indicates that it is the best *linear* forecast. Hasbrouck (2007, Ch.8) shows that the forecast innovation from (t-1) to t for the efficient price is:

$$\Delta f_t = [\theta(1)]_2 \varepsilon_t \tag{53}$$

where $[.]_i$ indicates 'the ith row of the matrix in brackets'.

The forecast innovations Δf_t are a natural measure for the theory's common value changes in between trades and linear projections allows for further analysis of these common-value innovations. For ease of exposition, let $P_x(y)$ be the best linear projection of the random variable y on random variable x. In regression terms,

$$P_x(y) := x'\beta \tag{54}$$

where β is the coefficient of a standard linear regression of y on x. The projections allow for the following analysis.

(i) Quote informativeness inbetween is naturally measured by the variance of the efficient price projection onto the quote innovation, e.g., $var(P_e(\Delta f_t))$ where P_e projects onto the Euronext quote innovation $[\varepsilon]_2$. In other words, how much information in the intertrade interval can be learned from obtaining a market's quote update? This measure is zero in a Glosten and Milgrom (1985) type of model and equal to the full Δf_t variance if liquidity demanders are uninformed.

(ii) The variance of efficient price changes (as measured by Δf_t) and its projection onto quote innovations can be decomposed into an index-correlated component (hard information) and an orthogonal component. For example, $var(P_m \circ P_e(\Delta f_t))$ where m corresponds to $[\varepsilon]_1$ indicates how much of Euronext quote informativeness reflects the index innovation. If Euronext quote updates are uncorrelated with index innovations this measure is zero. P_{-m} is defined to be the orthogonal part, i.e., $y = (P_m + P_{-m})(y)$ by construction.

Panel B of Table 4 provide empirical support for Chi-X quotes being significantly more informative on hard information. The proxy for such information is the index-correlated part of efficient price changes which amounts to 42% (=100%*4.02/9.48). By Roll's standards these firms are large and this percentage corresponds to his finding that most large U.S. firm are in the 40% to 50% range (see Roll (1988, p.545)). Projecting efficient price changes onto Euronext and Chi-X quotes reveals that Chi-X quotes are more informative (3.83 vs 3.54 basis points squared) but this difference is not significant. If, however, this differential is decomposed into index and nonindex components, Chi-X is significantly more informative on the index component (0.30 vs. 0.05 basis points squared with a t value of 5.0 for the differential).

Disaggregating according to large and small stocks reveals a cross-sectional heterogeneity as Chi-X quotes are significantly more informative for large stocks, but significantly less informative for small stocks. For large stocks, Chi-X quote innovations reveal 3.70 basis points squared of the intertrade innovation which is a significant 28% higher than the 2.90 basis points squared for Euronext. For small stocks on the other hand, Chi-X quote updates reveal 4.60 basis points squared which a significant 37% lower than Euronext the informativeness of Euronext quote updates. Decomposing according to index and nonindex information reveals that Chi-X quote appear significantly more informative on the index part for both types of stocks, but are significantly less informative on the nonindex for small stocks. For large stocks the nonindex part is not significantly different across markets (although Chi-X informativeness is slightly higher for this part).

4.5 Middleman participation: which stocks and when?

[insert Table 5 here]

This section studies middleman participation in both the cross-section (through 'between' correlations) and in the time dimension (through 'within' correlations). Table 5 presents these correlations of various trading variables which lead to the following observations.

[insert Figures 6 here]

The relative size of hard information as proxied by the 'R^2 of a single factor CAPM' correlates positively with middleman trade participation (0.67 between and 0.46 within) and Chi-X share of trades (0.64 between and 0.23 within). Figure 6 illustrates the 0.46 within correlation by plotting middleman participation against the size of hard information. It reveals that this strong correlation does not appear to be driven by outliers and is based on considerable time variation in both variables, double-digit percentages. The increase in Chi-X share of trades is not surprising given that it is a middleman's preferred habitat (low fees and a fast system). The table also shows that middleman participation correlates positively with Chi-X trade share (0.89 between and 0.41 within) which is further evidence that the relationship between Chi-X and middlemen appears symbiotic.

[insert Figure 7 here]

The differential between Chi-X and Euronext price-quote informativeness correlates positively with the relative amount of hard information (0.64 between and 0.23 within). A market's price-quote informativeness is defined as the predictive power of midquote price changes for the amount of information that is revealed inbetween trades. The methodology is based on linear projections $(P_e - P_i)(\Delta f)$ and a cointegration model (see Section 4.4). Figure 7 illustrates the cross-sectional relationship by plotting the size of hard information against both market's price-quote informativeness for each stock. The black dots represent Chi-X, the white dots represent Euronext, and dot size corresponds to stock's overall volume. The graph leads to the following two observations. First, black dots appear to be above white dots on the right-hand side of the graph, below them on the left-hand side. This illustrates the positive between-correlation of hard information size and Chi-X minus Euronext price-quote informativeness. Second, dot size is generally larger on the right-hand side of the graph. Hard information is relatively more important for active stocks.

[insert Figure 8 here]

Figure 8 replots Figure 7 but decomposes price-quote informativeness into an index-related part (top graph) and an orthogonal part (bottom graph). It illustrates that Chi-X price-quote informativeness is higher than Euronext quote informativeness across all stocks for the hard information (black dots are generally above with dots in the top graph) and results are mixed for the nonindex part which is likely to be a combination of hard and soft information. The latter result illustrates that it is not only index information that drives Chi-X quote efficiency.

4.6 The counterfactual: what if middlemen had not been introduced?

As we cannot rerun trading in the first 77 days of 2008 without Chi-X and the identified middleman, we revert to a diff-in-diff approach as a second best. As discussed in Section 4.2, additional data have been collected to create a pre-event sample of the first 77 trading days of 2007 to compare before and after Chi-X introduction. This difference for the 'treated' sample is then compared to the difference for an untreated sample of Belgian stocks. Belgium is a natural choice as it a neighboring country whose stocks also trade in the Euronext system. The difference in difference ('Δ Dutch - Δ Belgian') identifies a treatment effect.

[insert Table 6 here]

The diff-in-diff results of Table 6 (Panel A) reveal that Chi-X introduction raises liquidity supply, does not affect the number of trades, and lowers trading volume. Before discussing these results, we like to point out that the comparison across Dutch and Belgian stocks is not perfect as the latter typically trade less actively, 3.71 vs. 11.05 trades per minute in the post-event period. Yet, volatility increase is comparable across markets; realized volatility increases slightly less for Dutch stocks (64% vs. 69%) whereas the increase of intertrade volatility based on the cointegration model is not significantly different across markets (41% vs 39%). Bearing this in mind, the table leads to the following observations:

(i) The generalized inside spread which equals the Euronext spread in the absence of Chi-X has increased by 35% in Belgian stocks (reflecting the higher volatility), yet stayed put for Dutch stocks (0%). The treatment effect is a significant 35%. Depth at this quote has declined by 13% more for Dutch stocks but we consider this effect to be second order as this decrease does not undo the large price discount. If one were to transact the 13% at one tick behind the best price quote this implies a 175% worse price[17] and the overall effect is thus still a spread improvement of 100%*(1-(0.87*0.65+0.13*0.65*1.75))=29%. The significant treatment effect of minus 13% for effective spread further supports a general increase in liquidity supply on the introduction of Chi-X/ middlemen.

(ii) The number of trades in Dutch stock increases by 53% which is not significantly different from the increase of 55% witnessed for Belgian stocks. The number of trades in Dutch stocks has been corrected for double-counting of trades due to the presence of the new middleman that has been identified (see Table 2). In other words, if a security that in the past traded directly between investor A and B now travels via the middleman this would artificially inflate trade activity.

(iii) Volume increases by only 5% for Dutch stocks, which is a significant 15% less than the 21% increase in Belgian stocks. Again, this volume was corrected for double-counting.

5 Conclusion

We model high-frequency traders in electronic markets. We base this conclusion on the introduction of Chi-X, an HFT-hospitable market, and on being able to compare the post Chi-X entry change in the trading of Dutch stocks which do trade on Chi-X, and similar Belgian stocks that do not. We showed evidence that

[17]This calculation is based on a one cent tick size and an average share price of ~€20 which imply a 5 basis points worse price on a one tick move. This is a 175% increase relative to the 2.86 basis points average half spread (see Table 1).

middlemen are better informed about recent news than the average investor, in that their reaction times were faster and in the right direction.

Being better informed, middlemen still can make a positive or a negative contribution to welfare. On the one hand, they can raise welfare by solving a pre-existing adverse-selection problem. In that case their entry should be accompanied by a rise in trade and a fall in bid-ask spreads. Our simple model indicates that in this case and they can raise welfare by up to 30% of the gap between its equilibrium level and its first-best level. On the negative side, they can create or exacerbate a pre-existing adverse-selection problem, in which case bid-ask spreads should rise and trade declines.

Our evidence on the welfare contribution of middlemen is mixed. On the one hand, middlemen's participation lowers bid-ask spreads but, on the other, it also lowers volume. The net effect is uncertain.

Our theoretical analysis and the mixed evidence on welfare suggest that there is room for optimal market design. Regulators and market operators should think carefully about how adverse-selection risk affects the various participants. For example, the speed privilege that HFTs can buy into, co-location, might require a differentiated order-fee schedule. Passive orders submitted through this pipe might optimally be rewarded more whereas aggressive orders might have to be charged more. The reason is that passive orders come with the positive externality of liquidity supply to others whereas aggressive orders have a negative externality of creating adverse selection for non-co-located participants. The latter is, in spirit, similar to the old NYSE market structure where specialists were not allowed to have a live data feed of market-index information into their system. Also, markets might want to enable limit-order submitters to peg their order to, e.g., the market index (cf. Black (1995)).

Appendix I

PROOF OF LEMMA 1: We shall first complete the square in the expression

$$\phi\left(\frac{p-y}{\sigma}\right)\phi(y-1) = \frac{1}{2\pi}\exp\left(-\frac{1}{2\sigma^2}\left[(p-y)^2+\sigma^2(y-1)^2\right]\right)$$

Then

$$\begin{aligned}(p-y)^2+\sigma^2(y-1)^2 &= p^2+y^2-2py+\sigma^2\left(y^2+1-2y\right)\\ &= \left(1+\sigma^2\right)y^2-2\left(p+\sigma^2\right)y+p^2+\sigma^2\\ &= \left(1+\sigma^2\right)\left[y^2-2\frac{p+\sigma^2}{1+\sigma^2}y+\frac{p^2+\sigma^2}{1+\sigma^2}\right]\end{aligned}$$

Now for any constant A, we have $y^2-2Ay=(y-A)^2-A^2$, and therefore,

$$\begin{aligned}(p-y)^2+\sigma^2(y-1)^2 &= \left(1+\sigma^2\right)\left[\left(y-\frac{p+\sigma^2}{1+\sigma^2}\right)^2-\left(\frac{p+\sigma^2}{1+\sigma^2}\right)^2+\frac{p^2+\sigma^2}{1+\sigma^2}\right]\\ &= \left(1+\sigma^2\right)\left[\left(y-\frac{p+\sigma^2}{1+\sigma^2}\right)^2+\left(\frac{p+\sigma^2}{1+\sigma^2}\right)\left(1-\frac{p^2+\sigma^2}{1+\sigma^2}\right)\right]\\ &= \left(1+\sigma^2\right)\left[\left(y-\frac{p+\sigma^2}{1+\sigma^2}\right)^2+\left(\frac{p+\sigma^2}{1+\sigma^2}\right)\frac{1-p^2}{1+\sigma^2}\right]\end{aligned}$$

Therefore

$$\begin{aligned}-\frac{1}{2\sigma^2}\left[(p-y)^2+\sigma^2(y-1)^2\right] &= -\frac{1+\sigma^2}{2\sigma^2}\left[\left(y-\frac{p+\sigma^2}{1+\sigma^2}\right)^2+\left(\frac{p+\sigma^2}{1+\sigma^2}\right)\frac{1-p^2}{1+\sigma^2}\right]\\ &= -\frac{1+\sigma^2}{2\sigma^2}\left(y-\frac{p+\sigma^2}{1+\sigma^2}\right)^2-\frac{1-p^2}{2\sigma^2}\left(\frac{p+\sigma^2}{1+\sigma^2}\right)\\ &= -\frac{1+\sigma^2}{2\sigma^2}\left(y-\frac{p+\sigma^2}{1+\sigma^2}\right)^2+C\end{aligned}$$

where

$$C=\frac{p^2-1}{2\sigma^2}\left(\frac{p+\sigma^2}{1+\sigma^2}\right) \tag{55}$$

Therefore

$$\begin{aligned}\phi\left(\frac{p-y}{\sigma}\right)\phi(y-1) &= \frac{1}{2\pi}\exp\left(-\frac{1+\sigma^2}{2\sigma^2}\left(y-\frac{p+\sigma^2}{1+\sigma^2}\right)^2+C\right)\\ &= \frac{1}{2\pi}e^C\exp\left(-\frac{1}{2\frac{\sigma^2}{1+\sigma^2}}\left(y-\frac{p+\sigma^2}{1+\sigma^2}\right)^2\right)\\ &= \frac{\sqrt{\frac{\sigma^2}{1+\sigma^2}}}{\sqrt{2\pi}}e^C\frac{1}{\sqrt{2\pi\frac{\sigma^2}{1+\sigma^2}}}\exp\left(-\frac{1}{2\frac{\sigma^2}{1+\sigma^2}}\left(y-\frac{p+\sigma^2}{1+\sigma^2}\right)^2\right)\\ &= \frac{\alpha}{\sqrt{2\pi}}e^C\frac{1}{\alpha\sqrt{2\pi}}\exp\left(-\frac{1}{2\alpha^2}\left(y-\alpha^2-\frac{p}{1+\sigma^2}\right)^2\right)\end{aligned}$$

where

$$\alpha = \sqrt{\frac{\sigma^2}{1+\sigma^2}}$$

Therefore

$$\phi\left(\frac{p-y}{\sigma}\right)\phi(y-1) = \frac{\alpha}{\sqrt{2\pi}} e^C \frac{1}{\alpha}\phi\left(\frac{y-\alpha^2-\frac{p}{1+\sigma^2}}{\alpha}\right)$$

Let

$$B = \frac{\alpha}{\sqrt{2\pi}}\frac{e^C}{\sigma} \tag{56}$$

Then B multiplies a normal density of y that has mean $\alpha^2 + \frac{p}{1+\sigma^2}$ and variance α^2. Therefore in (11)

$$\int_{-\infty}^{\infty} \frac{x-y}{\sigma}\phi\left(\frac{p-y}{\sigma}\right)\phi(y-1)\,dy = B\left(x-\alpha^2-\frac{1}{1+\sigma^2}p\right)$$

Therefore (11) reads

$$0 = \int_{-\infty}^{\infty}\left[1-\Phi\left(\frac{p-y}{\sigma}\right)\right]\phi(y-1)\,dy + B\left(x-\alpha^2-\frac{1}{1+\sigma^2}p\right).$$

Rearranging and using (12) we get the probability of trade being

$$\tau = B\left(\frac{1}{1+\sigma^2}p+\alpha^2-x\right). \tag{57}$$

Using (56), we get (13).

Appendix II: List of all stocks

This table lists all stocks that have been analyzed in this manuscript. It reports the official isin code, the company's name, and the index weight which has been used throughout the study to calculate (weighted) averages.

Dutch index stocks / 'treated' sample			Belgium index stocks / 'untreated' sample		
isin code	security name	index weight[a]	isin code	security name	index weight[a]
NL0000303600	ing groep	22.3%	BE0003801181	fortis	17.5%
NL0000009470	royal dutch petrol	20.1%	BE0003565737	kbc	15.8%
NL0000009538	kon philips electr	12.1%	BE0003796134	dexia	13.5%
NL0000009355	unilever	11.3%	BE0003793107	interbrew	9.5%
NL0000303709	aegon	7.5%	BE0003470755	solvay	6.5%
NL0000009082	koninklijke kpn	7.4%	BE0003797140	gpe bruxel.lambert	5.7%
NL0000009066	tnt	4.8%	BE0003562700	delhaize group	5.4%
NL0000009132	akzo nobel	4.2%	BE0003810273	belgacom	4.4%
NL0000009165	heineken	3.0%	BE0003739530	ucb	4.1%
NL0000009827	dsm	2.4%	BE0003845626	cnp	2.9%
NL0000395903	wolters kluwer	2.2%	BE0003775898	colruyt	2.3%
NL0000360618	sbm offshore	1.2%	BE0003593044	cofinimmo	2.2%
NL0000379121	randstad	1.1%	BE0003764785	ackermans and van haaren	2.2%
NL0000387058	tomtom	0.6%	BE0003678894	befimmo-sicafi	2.1%
			BE0003826436	telenet	2.1%
			BE0003735496	mobistar	1.5%
			BE0003780948	bekaert	1.1%
			BE0003785020	omega pharma	1.0%

[a]: The index weights are based on the true index weights of December 31, 2007. The weights are rescaled to sum up to 100% as only stocks are retained that were a member of the index throughout the sample period. This allows for fair comparisons through time.

References

Amihud, Y. and H. Mendelson (1980). Dealership market: Market-making with inventory. *Journal of Financial Economics 8*, 31–53.

Baricz, A. (2008). Mills' ratio: Monotonicity patterns and functional inequalities. *Journalof Math. Anal. Appl. 340*, 1362–1370.

Biais, B., P. Hillion, and C. Spatt (1995). An empirical analysis of the limit order book and the order flow in the paris bourse. *Journal of Finance 50*, 1655–1689.

Black, F. (1995). Equilibrium exchanges. *Financial Analysts Journal 51*, 23–29.

Chaboud, A., B. Chiquoine, E. Hjalmarsson, and C. Vega (2009). Rise of the machines: Algorithmic trading in the foreign exchange market. Manuscript, Federal Reserve Board.

Duffie, D., N. Gârleanu, and L. Pedersen (2005). Over-the-counter markets. *Econometrica 73*, 1815–1847.

Duffie, D., S. Malamud, and G. Manso (2009). Information percolation with equilibrium search dynamics. *Econometrica 77*, 1513–1574.

Engle, R. (2002). A dynamic conditional correlation: A simple class of multivariate generalized autoregressive conditional heteroskedasticity models. *Journal of Business & Economic Statistics 20(3)*, 339–350.

Foucault, T. and A. J. Menkveld (2008). Competition for order flow and smart order routing systems. *Journal of Finance 63*, 119–158.

Foucault, T., A. Roëll, and P. Sandas (2003). Market making with costly monitoring: An analysis of the soes controversy. *Review of Financial Studies 16*, 345–384.

Glosten, L. (1987). Components of the bid ask spread and the statistical properties of transaction prices. *Journal of Finance 42*, 1293–1307.

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

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

Grossman, S. and J. Stiglitz (1980). On the impossibility of informationally efficient markets. *American Economic Review 70(3)*, 393–408.

Haile, P. A. (2003). Auctions with private uncertainty and resale opportunities. *Journal of Economic Theory 108*, 72–110.

Hasbrouck, J. (1995). One security, many markets: Determining the contributions to price discovery. *Journal of Finance 50*, 1175–1199.

Hasbrouck, J. (2007). *Empirical Market Microstructure*. New York: Oxford University Press.

Hendershott, T., C. M. Jones, and A. J. Menkveld (2010). Does algorithmic trading improve liquidity? *Journal of Finance (forthcoming)*.

Hendershott, T. and A. J. Menkveld (2009). Price pressures. Manuscript, VU University Amsterdam.

Hendershott, T. and R. Riordan (2009). Algorithmic trading and information. Manuscript, University of California, Berkeley.

Ho, T. and H. R. Stoll (1981). Optimal dealer pricing under transaction cost and return uncertainty. *Journal of Financial Economics 9*, 47–73.

Hollifield, B., R. A. Miller, P. Sandås, and J. Slive (2006). Estimating the gains from trade in limit order markets. *Journal of Finance 61*, 2753–2804.

Kyle, A. (1985). Continuous auctions and insider trading. *Econometrica 53*, 1315–1335.

Lagos, R., G. Rocheteau, and P.-O. Weill (2009). Crashes and recoveries in illiquid markets. Manuscript, UCLA.

Li, Y. (1996). Middlemen and private information. *Journal of Monetary Economics 42*, 131–159.

Masters, A. (2007). Middlemen in search equilibrium. *International Economic Review 48*, 343–362.

Milgrom, P. and N. Stokey (1982). Information, trade and common knowledge. *Journal of Economic Theory 26*, 17–27.

Myerson, R. and M. A. Satterthwaite (1983). Efficient mechanisms for bilateral trading. *Journal of Economic Theory 29*, 265–281.

Roll, R. (1988). R^2. *Journal of Finance 43*, 541–566.

Rubinstein, A. and A. Wolinsky (1987). Middlemen. *Quarterly Journal of Economics 102*, 581–593.

Table 1: Summary statistics

This table provides summary statistics on a sample of 14 Dutch index stocks that trade both in the incumbent market Euronext and in the entrant Chi-X (Chi-X). The sample runs from Jan 1, 2008 through April 23, 2008. The table reports weighted averages where weights are based on a stock's local index weight. Time-clustered standard errors account for commonality and heteroskedasticity and are reported in parentheses.

variable (units)	large	small	all
Euronext volume (€1000/min)	524.4 (19.9)	128.1 (4.3)	466.6 (17.4)
Chi-X volume (€1000/min)	49.4 (2.0)	4.5 (0.2)	42.8 (1.8)
Chi-X share volume (%)	8.6	3.4	8.4
Euronext #trades (/min)	19.03 (0.62)	9.30 (0.21)	17.61 (0.55)
Chi-X #trades (/min)	3.16 (0.12)	0.57 (0.03)	2.78 (0.10)
Chi-X share #trades (%)	14.2	5.7	13.6
Euronext time-weighted quoted half spread (basis points)	3.47 (0.07)	5.00 (0.14)	3.70 (0.08)
Chi-X time-weighted quoted half spread (basis points)	3.44 (0.10)	14.76 (0.98)	5.09 (0.20)
time-weighted generalized inside half spread[a] (basis points)	2.63 (0.18)	4.20 (0.24)	2.86 (0.18)
Euronext time-weighted quoted depth (€1000)	121.4 (2.4)	30.6 (0.3)	108.1 (2.0)
Chi-X time-weighted quoted depth (€1000)	53.3 (1.2)	21.0 (1.1)	48.5 (1.0)
trade-weighted effective half spread (basis points)	2.89 (0.06)	3.90 (0.10)	3.04 (0.06)
trade-weighted adverse selection, 30 min (basis points)	2.62 (0.14)	3.74 (0.21)	2.78 (0.14)
trade-weighted realized spread, 30 min (basis points)	0.28 (0.14)	0.16 (0.17)	0.26 (0.13)
N=1078 (14 stocks, 77 days)			

[a]: defined as a Chi-X adjusted Euronext half spread in the sense that it is the cost of demanding the full Euronext depth but re-routing (part of) the order to Chi-X if Chi-X has strictly better prices; it is a 'generalized' inside spread since it controls for depth; for example, the adjusted ask is €29.995 if the Euronext ask is €30.00 with depth €100,000 and the Chi-X' ask is €29.99 with depth €50,000

Table 2: Caught on tape! a middleman

This table produces statistics on middleman trading for Dutch index stocks from January 1 through April 23, 2008. The middleman is discovered as a combination of an anonymous Chi-X broker ID and an anonymous Euronext broker ID that achieves high-frequency trading and mean-reversion in inventory across markets. Figure 5 plots middleman inventory for a single stock on a representative day to illustrate her trading. Time-clustered standard errors account for commonality and heteroskedasticity and are reported in parentheses.

	large	small	all
Panel A: middleman inventory			
average net change in middleman inventory (€1000)	−75.6	55.1	−56.5
	(93.3)	(19.6)	(79.8)
standard deviation net change in middleman inventory (€1000)	1,417.2	298.4	1,314.6
	(186.7)	(33.5)	(172.3)
fraction of days with zero net change in inventory	0.33	0.60	0.46
Panel B: middleman activity			
middleman Euronext volume (€1000/min)	36.8	4.3	32.0
	(1.8)	(0.3)	(1.6)
middleman Chi-X volume (€1000/min)	24.2	1.9	21.0
	(1.8)	(0.2)	(1.6)
middleman Euronext #trades (/min)	1.56	0.43	1.40
	(0.07)	(0.03)	(0.06)
middleman Chi-X #trades (/min)	1.09	0.19	0.96
	(0.08)	(0.02)	(0.07)
middleman participation rate Euronext trades (%)	8.2	4.8	7.7
	(0.3)	(0.3)	(0.3)
middleman participation rate Chi-X trades (%)	35.7	35.2	35.6
	(1.8)	(2.3)	(1.8)
Panel C: middleman order types			
middleman relative use of passive orders in Euronext (%)	78.6	53.5	74.9
	(0.8)	(2.7)	(0.9)
middleman relative use of passive orders in Chi-X (%)	76.9	84.8	78.0
	(0.5)	(0.8)	(0.5)
Panel D: middleman vs nonmiddleman effective spread and its decomposition			
middleman trade-weighted effective half spread (basis points)	3.25	4.72	3.47
	(0.06)	(0.11)	(0.07)
nonmiddleman trade-weighted effective half spread (basis points)	2.81	3.81	2.96
	(0.06)	(0.10)	(0.06)
middleman trade-weighted adverse selection, 30 min (basis points)	2.54	3.98	2.75
	(0.17)	(0.66)	(0.17)
nonmiddleman trade-weighted adverse selection, 30 min (basis points)	2.64	3.78	2.81
	(0.15)	(0.21)	(0.14)
middleman trade-weighted realized spread, 30 min (basis points)	0.72	0.74	0.72
	(0.17)	(0.62)	(0.16)
nonmiddleman trade-weighted realized spread, 30 min (basis points)	0.17	0.03	0.15
	(0.14)	(0.17)	(0.13)
N=1078 (14 stocks, 77 days)			

Table 3: Speed comparison across markets

This table compares Euronext and Chi-X in terms of how quickly their price quotes for stocks reflects changes in the Dutch local index (AEX) future. A natural approach is to consider all events where the index future midquote (the average of the bid and ask quote) changes and count how often the stock midquote is adjusted in the same second. This comparison, however, includes ‘mechanical’ stock midquote changes that are the result of executions that knock off stale quotes rather than quote updates. It is for this reason that the analysis further conditions down on index future midquote updates that show no stock transactions one second before, during, or one second after the index futures quote update. The sample Dutch index consists of Dutch index stocks from January 1 through April 23, 2008. Time-clustered standard errors account for commonality and heteroskedasticity and are reported in parentheses.

	large	small	all
count of Euronext and index futures quote change in same second (/day)	426	637	457
	(24)	(40)	(25)
count of Chi-X and index futures quote change in same second (/day)	1256	1257	1256
	(52)	(58)	(50)
correlation Euronext quote change and index futures quote change	0.33	0.16	0.31
	(0.01)	(0.01)	(0.01)
correlation Chi-X quote change and index futures quote change	0.46	0.15	0.41
	(0.02)	(0.01)	(0.01)
14 stocks, 77 days			

Table 4: Euronext and Chi-X quote informativeness

This table analyzes to what extent midquote (the average of the bid and ask quote) updates inbetween trades reveal the information that arrives in the intertrade intervals. The observation clock runs in transaction time. Panel A correlates log midquote changes strictly inbetween trades with the information revealed in the trade interval which is proxied by the the log trade price (t+10) minus log trade price (t-1). Panel B is based on cointegration model which stacks all price series of interest into a single price vector

$$\Delta p_t := [index_t \quad midquote\_euronext_{t^-} \quad midquote\_chi\_x_{t^-} \quad trade\_price_t]'$$

where t runs over the transaction clock, t^- indicates that the quote snapshot is taken one second prior to the transaction, *index* is the midquote in the local index futures, $trade\_price_t$ is the transaction price, and $midquote\_X_{t^-}$ indicates the midquote in market X. The price series is modeled as a vector error correction model (VECM) to capture cointegration:

$$p_t = \varphi_1 \Delta p_{t-1} + \varphi_2 \Delta p_{t-2} + \cdots + \beta(A' p_{t-1}) + \varepsilon_t$$

$$\beta' = \begin{pmatrix} 0 & \beta_{22} & \beta_{32} & \beta_{42} \\ 0 & \beta_{21} & \beta_{31} & \beta_{41} \end{pmatrix} \quad A' = \begin{pmatrix} 0 & 1 & -1 & 0 \\ 0 & 1 & 0 & -1 \end{pmatrix}$$

The $\beta A' p_{t-1}$ reflects the presence of two random walks, one associated with the market index and the other with the security's 'efficient price' which is naturally defined as

$$f_t := \lim_{t \to \infty} E^*[p_{t+k} | p_t, p_{t-1}, \dots]$$

where the asterisk indicates that it is the best *linear* forecast (see Hasbrouck (2007, Ch.8)). The extent to which Chi-X and Euronext quotes reveal efficient prices and whether it is the index or the nonindex component is established through linear projection of Δf_t on the price innovation vector ε_t where P_m denotes a projection on the first element which captures the market-index innovation (and P_{-m} is its residual), P_e projects onto the second element which is the Euronext quote innovation, and P_c projects onto the third element which is the Chi-X quote innovation. The sample Dutch index consists of Dutch index stocks from January 1 through April 23, 2008. Time-clustered standard errors account for commonality and heteroskedasticity and are reported in parentheses.

	large	small	all
Panel A: correlations based on raw data[a]			
correlation Euronext midquote return and long-term price impact of (signed) trade	0.007	0.046	0.013
	(0.003)	(0.003)	(0.003)
correlation Chi-X midquote return and long-term price impact of (signed) trade	0.052	0.039	0.050
	(0.004)	(0.003)	(0.003)
Panel B: cointegration analysis[a]			
overall efficient price innovation			
variance efficient price innovation inbetween trades, Δf	8.19	16.98	9.47
	(0.49)	(1.16)	(0.58)
variance efficient price innovation correlated with market index, $P_m(\Delta f)$	3.74	5.66	4.02
	(0.28)	(0.51)	(0.30)
variance efficient price orthogonal to market index, $P_{-m}(\Delta f)$	4.45	11.32	5.45
	(0.28)	(0.75)	(0.33)

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	large	small	all
efficient price innovation correlated with the Euronext midquote return			
variance efficient price innovation inbetween trades, $P_e(\Delta f)$	2.90 (0.17)	7.25 (0.45)	3.54 (0.21)
variance efficient price innovation correlated with market index, $P_m \circ P_e(\Delta f)$	0.05 (0.00)	0.08 (0.01)	0.05 (0.00)
variance efficient price orthogonal to market index, $P_{-m} \circ P_e(\Delta f)$	2.85 (0.17)	7.18 (0.45)	3.48 (0.21)
efficient price innovation correlated with the Chi-X midquote return			
variance efficient price innovation inbetween trades, $P_c(\Delta f)$	3.70 (0.17)	4.60 (0.44)	3.83 (0.20)
variance efficient price innovation correlated with market index, $P_m \circ P_c(\Delta f)$	0.33 (0.02)	0.14 (0.02)	0.30 (0.02)
variance efficient price orthogonal to market index, $P_{-m} \circ P_c(\Delta f)$	3.37 (0.16)	4.47 (0.43)	3.53 (0.19)
14 stocks, 77 days			

[a]: based on midquotes that are sampled strictly inbetween trades (i.e. one second after the last trade and one second ahead of the next trade) in order to avoid spurious correlation due a trade knocking off the best bid or ask quote

Table 5: Correlation daily variables

This table presents correlations for a panel dataset of trading variables that are calculated by stock-day. It distinguished 'between' and 'within' correlations which study variable interdependence in the cross-section and through time, respectively. The within correlation is based on time means: $\overline{x}_i = \frac{1}{T}\sum_{t=1}^{T} x_{it}$. The between correlation is based on day t's deviation relative to the time mean: $x_{it}^{*} = x_{it} - \overline{x}_i$. The sample Dutch index consists of Dutch index stocks from January 1 through April 23, 2008. Standard errors are reported in parentheses (within correlation standard errors account for commonality and heteroskedasticity).

variable (units)	corr type	variance eff price innovation	middleman participation rate	#trades	Chi-X share #trades	middleman relative use of passive orders	Chi-X minus Euronext quote informativeness, $(P_c - P_e)(\Delta f)$
relative size index component[a] (%)	between[b]	−0.50 (0.27)	0.67* (0.27)	0.55* (0.27)	0.75** (0.27)	0.07 (0.27)	0.64* (0.27)
	within[c]	0.13 (0.10)	0.46** (0.05)	−0.09 (0.08)	0.13** (0.04)	0.04 (0.07)	0.23** (0.08)
variance eff price innovation inbetween trades, Δf	between[b]		−0.73** (0.27)	−0.62* (0.27)	−0.61* (0.27)	−0.64* (0.27)	−0.88** (0.27)
	within[c]		0.15** (0.05)	0.55** (0.12)	−0.15* (0.07)	0.03 (0.06)	−0.04 (0.08)
middleman participation rate (%)	between[b]			0.64* (0.27)	0.89** (0.27)	0.53* (0.27)	0.78** (0.27)
	within[c]			0.11* (0.05)	0.41** (0.05)	0.08 (0.05)	0.20** (0.05)
#trades (/min)	between[b]				0.73** (0.27)	0.34 (0.27)	0.40 (0.27)
	within[c]				0.01 (0.06)	−0.05 (0.07)	−0.29** (0.06)
Chi-X share #trades (%)	between[b]					0.23 (0.27)	0.67* (0.27)
	within[c]					−0.15** (0.05)	0.05 (0.04)
middleman relative use of passive orders (%)	between[b]						0.52* (0.27)
	within[c]						−0.02 (0.04)
14 stocks, 77 days							

[a]: size of the index component in the efficient price innovation

[b]: based on the time means: $\overline{x}_i = \frac{1}{T}\sum_{t=1}^{T} x_{it}$

[c]: based on day t's deviation relative to the time mean: $x_{it}^{*} = x_{it} - \overline{x}_i$

$^{*}/^{**}$: significant at a 95/99% level

Table 6: Diff-in-diff analysis trading variables

This table compares trading variables based on Dutch index stocks before and after the introduction of Chi-X and the advent of middlemen (e.g., the ID of the middleman we identified in Table 2 did appear in the pre-event period). It compares the first 77 trading days of 2007 (through April 20) and 2008 (through April 23). This serves as the 'treated' sample. The same comparison is done for Belgian index stocks which creates an 'untreated' sample as Chi-X had not yet been introduced. Belgium is a natural choice as it a neighboring country whose stocks also trade in the Euronext system. A diff-in-diff analysis then identifies the treatment effect. The percentage change was determined based on the log series. Time-clustered standard errors account for commonality and heteroskedasticity and are reported in parentheses.

variable (units)	Netherlands/'treated'			Belgium/'untreated'			diff-in-diff[a]
	pre	post	Δ	pre	post	Δ	$\Delta\Delta$
Panel A: Full sample							
20-min realized volatility (bp/min)	3.9	7.6	64%**	4.1	8.3	69%**	−4%*
	(0.1)	(0.3)	(4%)	(0.1)	(0.4)	(4%)	(2%)
volatility efficient price innovation inbetween trades, Δf (bp)	1.9	2.9	41%**	3.5	5.0	39%**	2%
	(0.0)	(0.1)	(3%)	(0.1)	(0.1)	(3%)	(2%)
time-weighted generalized inside half spread[a] (basis points)	2.93	2.86	0%	5.00	6.86	35%**	−35%**
	(0.03)	(0.18)	(2%)	(0.08)	(0.16)	(2%)	(2%)
time-weighted quoted depth (€1000)	213	108	−62%**	67	46	−49%**	−13%**
	(2)	(2)	(2%)	(1)	(0)	(2%)	(2%)
trade-weighted effective half spread (basis points)	2.61	3.04	13%**	3.99	5.07	27%**	−13%**
	(0.02)	(0.06)	(2%)	(0.07)	(0.12)	(2%)	(1%)
trade-weighted adverse selection, 30 min (basis points)	1.89	2.78	32%**	3.16	5.23	54%**	−21%**
	(0.09)	(0.14)	(6%)	(0.11)	(0.22)	(5%)	(7%)
#trades (/min)	11.05	20.39	59%**	3.71	6.89	55%**	3%
	(0.34)	(0.63)	(3%)	(0.12)	(0.21)	(3%)	(2%)
#trades after removing middleman's trades (/min)	11.05	19.80	56%**	3.71	6.89	55%**	0%
	(0.34)	(0.61)	(3%)	(0.12)	(0.21)	(3%)	(2%)
volume (€1000/min)	446	509	10%*	72	100	21%**	−10%**
	(16)	(18)	(4%)	(2)	(4)	(4%)	(2%)
volume after removing middleman's volume (€1000/min)	446	496	8%	72	100	21%**	−13%**
	(16)	(18)	(4%)	(2)	(4)	(4%)	(2%)
#observations 4746, 14+18=32 stocks, 77+77=154 days							

[a]: defined as the Netherlands differential (post minus pre) minus the Belgium differential

*/**: significant at a 95/99% level (only applied to differentials)

Figure 5: Middleman inventory

These graphs plot the middleman's intraday inventory for ING stock on January 30 starting her off with zero shares (by assumption). They plot inventory both by market (top two graphs) and aggregated across markets (bottom graph). The middleman is discovered as a combination of an anonymous Chi-X broker ID and an anonymous Euronext broker ID that achieves high-frequency trading and mean-reversion in inventory across markets. The graphs illustrate this trading pattern for one stock-day and Table 2 produces middleman statistics for the full sample.

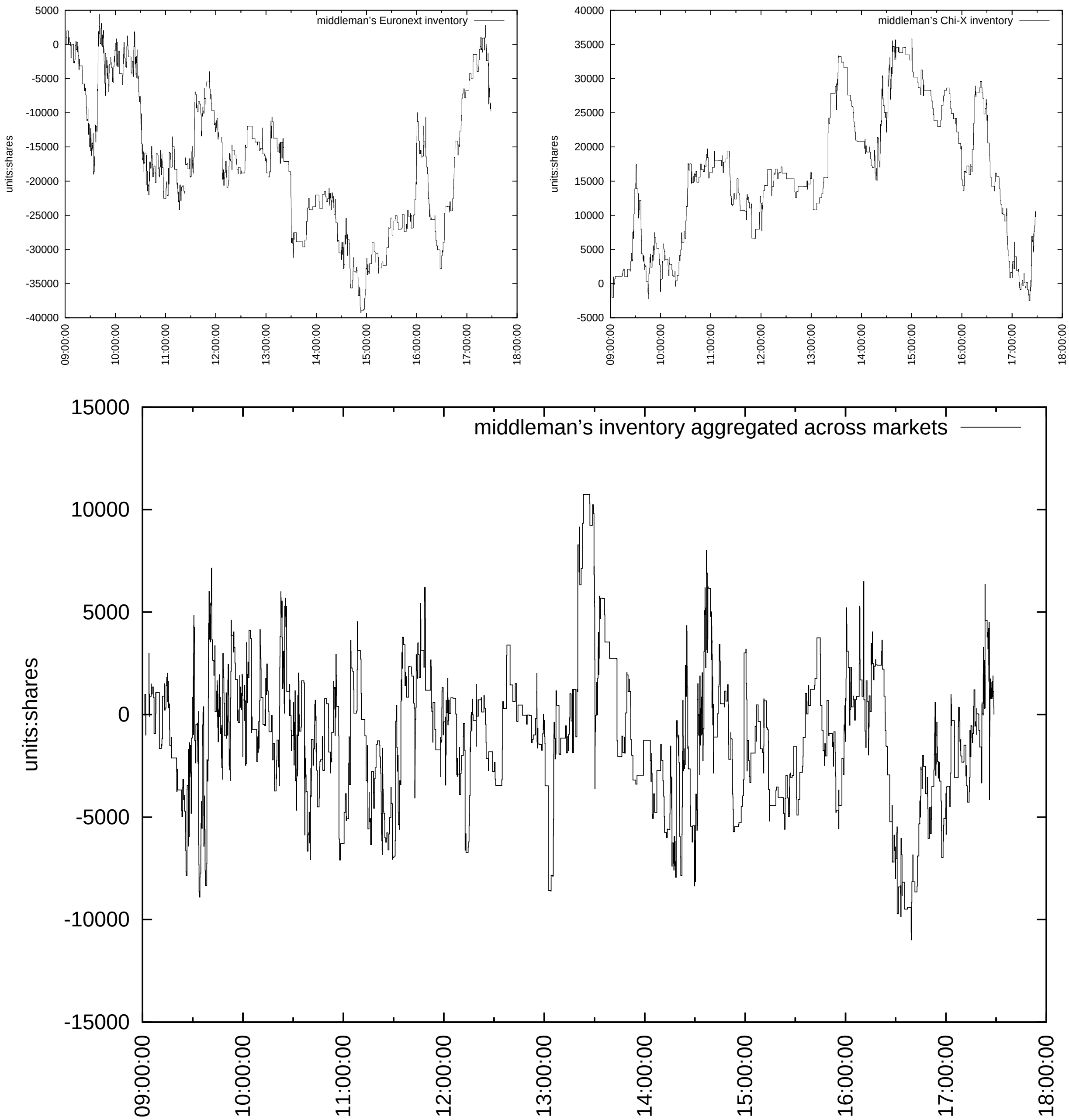

Figure 6: Scatter plot of middleman activity versus amount of hard information

This figure contains a scatter plot of the trade participation by the identified middleman (see Table 2) against a proxy for the relative importance of ‘hard’ information defined as any public information that can be processed by machines (e.g., price changes in the index futures, same industry stocks, foreign exchange rate). The conjecture is that middlemen operating with fast machines have an edge when such information is a larger part of total information. A proxy for the relative size of hard information is the ‘R^2’ of a regression of stock return on index return. This proxy is constructed for each stock-day in the sample based on the cointegration model results of Table 4. Middleman trade participation is also calculated for each stock-day. Both variables are demeaned by stock to only focus on the time variation (and not have the results be driven by unobserved heterogeneity across stocks). The scatterplot of these series thus illustrates the within correlation presented in Table 5.

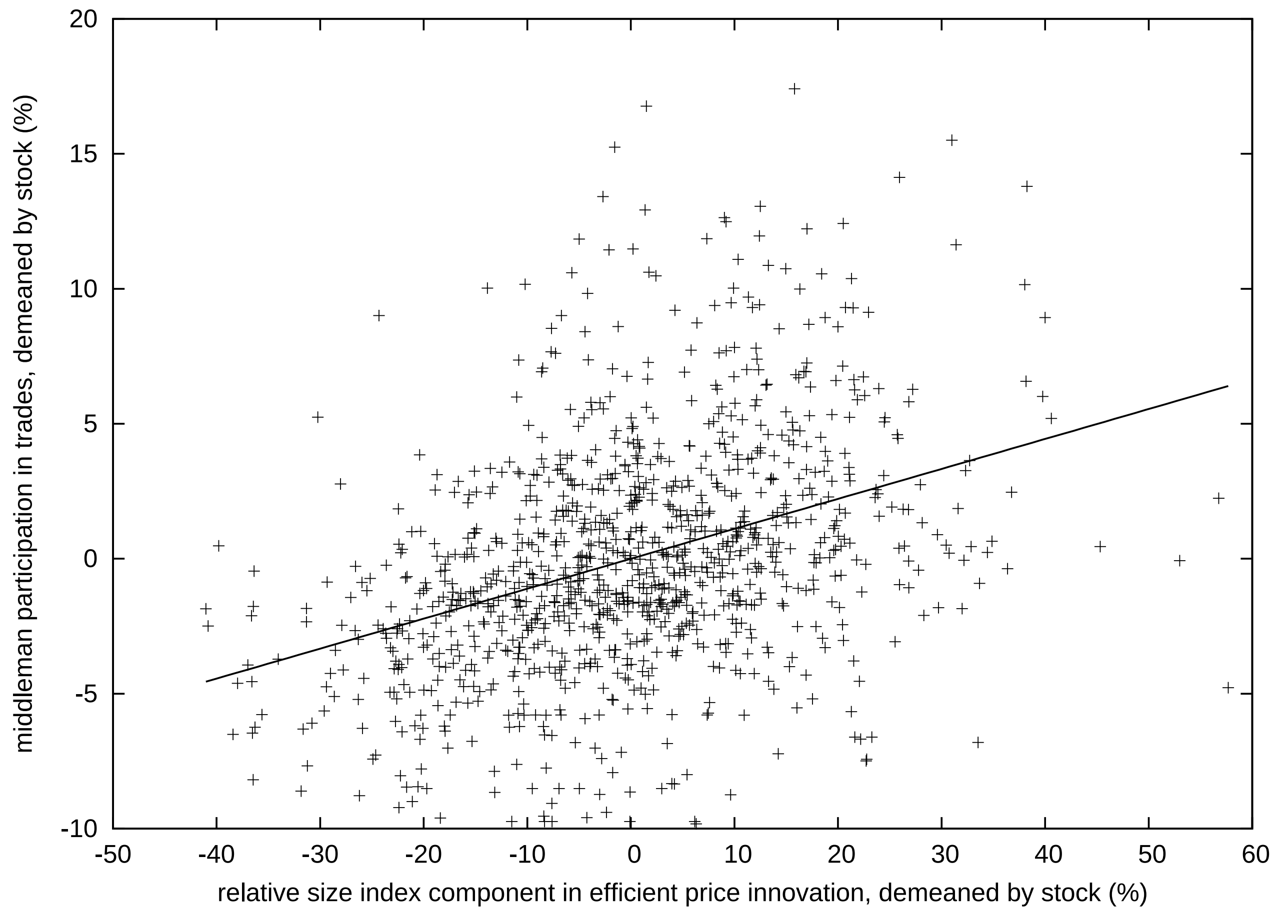

Figure 7: Chi-X and Euronext price-quote informativeness in the cross-section

This figure graphs Chi-X and Euronext price-quote informativeness against a proxy for the relative importance of 'hard' information defined as any public information that can be processed by machines (e.g., price changes in the index futures, same industry stocks, foreign exchange rate). Price quote informativeness is defined as the predictive power of midquote (average of the bid and ask quote) price changes for the amount of information that is revealed inbetween trades. The methodology is based on linear projections $(P_e - P_i)(\Delta f)$ and a cointegration model (see Section 4.4). The variables are calculated as averages per stock and the graphs represent dispersion in the cross-section. The size of the dot corresponds to average stock volume.

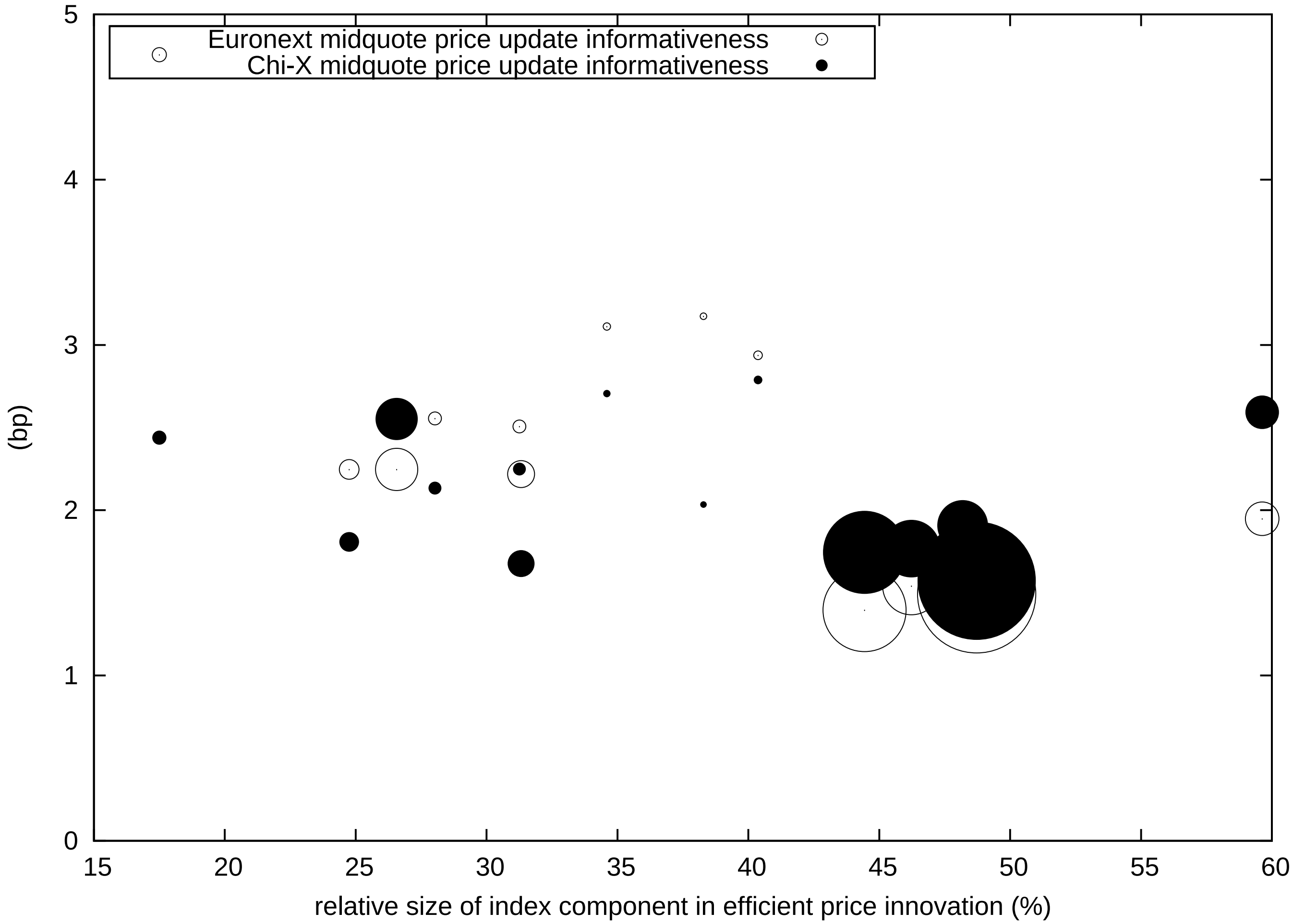

Figure 8: Price quote informativeness: index vs nonindex component

This figure decomposes the bottom graph of Figure 7 into the price-quote informativeness of the index-correlated component of the predictability and an orthogonal component.