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Competition for Order Flow and Smart Order Routing Systems

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ABSTRACT

We study the rivalry between Euronext and the London Stock Exchange (LSE) in the Dutch stock market to test hypotheses about the effect of market fragmentation. As predicted by our theory, the consolidated limit order book is deeper after entry of the LSE. Moreover, cross-sectionally, we find that a higher trade-through rate in the entrant market coincides with less liquidity supply in this market. These findings imply that (i) fragmentation of order flow can enhance liquidity supply and (ii) protecting limit orders against trade-throughs is important.

THE PROLIFERATION OF ELECTRONIC TRADING venues raises new questions about the benefits and costs of market fragmentation. In the United States, this evolution triggered several debates on the organization of equity markets and culminated in new SEC rules, known as Regulation NMS.[1] This paper addresses two questions central in these debates: (i) Does centralization of order flow improve liquidity and (ii) should limit orders be protected against violations of price priority?

To this end, we study the entry of the London Stock Exchange into the Dutch equity market with the launch of EuroSETS, an electronic limit order market. Before entry, trading was largely centralized in NSC, a limit order

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[1] See, for instance, "Request for Comment on Issues Relating to Market Fragmentation" SEC Release no. 34 − 42459 and "Regulation NMS" SEC Release no. 34 − 51808.

market operated by Euronext. Thus, the introduction of EuroSETS gives us a way to study empirically whether switching from a centralized limit order book (CLOB) to a more fragmented environment impairs or improves liquidity.[2]

In a fragmented market, orders sometimes execute at a price worse than the best quoted price. Brokers should avoid these violations of price priority (so-called trade-throughs), but agency conflicts may induce them to not do so. For instance, brokers may give up an improvement in execution price to economize on monitoring costs and the time required for splitting orders.[3] In the United States, trade-throughs are prohibited for exchange-listed stocks and Regulation NMS expands this prohibition to all quotations accessible through automatic execution (e.g., Nasdaq quotes). The rationale is that trade-throughs discourage liquidity provision, but there is very little empirical evidence on this issue.[4] The introduction of EuroSETS offers a good opportunity to study how trade-throughs affect liquidity provision because there is no trade-through prohibition in the Dutch equity market.

Our testable hypotheses derive from Parlour and Seppi (2003). They focus on competition between a pure limit order market and a hybrid market (like the NYSE). We use their framework to analyze the case in which competitors are two pure limit order markets, namely an "incumbent" and an "entrant" market (like NSC and EuroSETS). We account for possible intermarket differences in order submission fees because EuroSETS and NSC charge different fees on limit orders. Moreover, we introduce two types of brokers: smart routers, who automate the routing decision to obtain the best execution price and nonsmart routers, who ignore quotes in the entrant market and thereby generate trade-throughs.

The model has two main testable predictions. First, other things equal, consolidated depth at a certain price (i.e., the sum of all shares available at that price or better in both markets) should be larger after EuroSETS entry. The absence of time priority across markets is key for this prediction.[5] It allows traders to jump ahead of the queue of limit orders in one market by submitting a limit order in the competing market. In this way, queue-jumping competes away the profits (due to price discreteness) earned on inframarginal limit orders (i.e., orders strictly ahead of the marginal order in the queue) and hence the price concession paid by liquidity demanders is smaller. Second, the model predicts that an increase in the proportion of smart routers (in the trader population)

[2] Institutions such as Morgan Stanley, Goldman Sachs, and Merrill Lynch have been prominent advocates of a CLOB. See "Don't CLOBber ECNs," *Wall Street Journal*, March 27, 2000 and "Sweeping Changes in Markets Sought," *Wall Street Journal*, February 29, 2000.

[3] Brokers could also decide to trade-through the best quote to secure faster execution or because they receive a payment when they direct orders to a specific market.

[4] Trade-throughs in the U.S. securities markets are documented in Bessembinder (2003), Battalio et al. (2004), and Hendershott and Jones (2005a).

[5] Parlour and Seppi (2003) find that competition between a hybrid market and a pure limit order market can increase or decrease consolidated depth. We obtain a different prediction because we focus on two pure limit order markets.

coincides with an increase of EuroSETS liquidity supply as it enlarges the execution probability of limit orders in this market.

We test these predictions using a sample of 22 stocks. For each stock, we build 5-minute snapshots of the consolidated limit order book (i.e., the "sum" of books across markets). We find that the consolidated limit order book is deeper after EuroSETS entry, after controlling for changes in market conditions. This increase is significant for almost all stocks. For instance, for the most actively traded stocks, we find that consolidated depth through the fourth tick behind the best quote increased by a significant 46.3% and 100.8% in our two sample periods following EuroSETS entry. This increase is partially due to increased depth in NSC, consistent with lower fees on NSC limit orders after EuroSETS entry.[6]

Next, we study the cross-sectional relationship between the proportion of smart routers and EuroSETS liquidity supply. In the model, the proportion of nonsmart routers is equal to the trade-through rate at the expense of the entrant market. We therefore identify the proportion of smart routers in the data through estimation of the trade-through rate. The proportion of smart routers appears small as the average trade-through rate exceeds 73%. As predicted, we find a positive cross-sectional relationship between the proportion of smart routers and EuroSETS competitiveness in terms of liquidity supply. That is, the EuroSETS bid-ask spread relative to that of NSC is significantly smaller for stocks with a large proportion of smart routers and EuroSETS contributes more to consolidated depth for these stocks. In other words, EuroSETS is relatively less competitive in stocks with high trade-through rates.

These findings have intriguing policy implications. They provide support to the claim that protecting limit orders against trade-throughs is important because trade-throughs discourage liquidity provision. They also imply that smart routers create a positive externality for other smart routers (smart routers make EuroSETS more liquid and thereby increase the benefit of using smart routers). Thus, trade-throughs can be self-sustaining: Few brokers adopt smart routing systems because gains are small, but they are small precisely because too few brokers are smart routers. This chicken and egg problem is a barrier to entry for fledgling markets like EuroSETS.[7]

Most related to our paper are comparisons of market liquidity before and after entry (or exit) of new trading venues (e.g., Battalio (1997), Board and

[6] Other things equal, the model implies that the entry of EuroSETS should reduce cumulative depth in NSC as it decreases the likelihood of execution for limit orders in this market. However, around the time of EuroSETS entry, there is a reduction in fees on limit orders in NSC. As shown by our model, such reduction could theoretically increase cumulative depth in NSC, even if this market attracts less order flow.

[7] The London Stock Exchange organized several meetings between brokers and developers of smart routers, presumably to solve this coordination problem. On the day following the introduction of EuroSETS, the *Financial Times* wrote: "The London Stock Exchange, which yesterday started an assault on Amsterdam stock, is drawing attention to traders' increasing need for smart order routing to take advantage of increased competition." ("LSE Tries the Smart Order Route," *Financial Times*, May 25, 2004).

Wells (2000), DeFontnouvelle, Fishe, and Harris (2003), Mayhew (2002), Battalio et al. (2004), Biais, Bisière, and Spatt (2004), Boehmer and Boehmer (2004), Hendershott and Jones (2005b)). More generally, our paper relates to the literature on market fragmentation (e.g., Hamilton (1979), Barclay, Hendershott, and McCormick (2003), Bessembinder (2003), Fink, Fink, and Weston (2004)). Our paper contributes to this literature in two ways. First, it considers the effect of competition between *pure* limit order markets, whereas previous papers generally consider different market structures. Second, the richness of our data enables us to analyze changes in consolidated depth at *and* behind the best quotes. This is important, as the effect of market fragmentation could differ throughout the limit order book.

The model is tailored to the institutional features of our event analysis. Thus, in our theory, the two markets have identical trading mechanisms (limit order markets) and there are no clientele effects (as in Hendershott and Mendelson (2000) or Viswanathan and Wang (2002)). To our knowledge, Glosten (1994) is the only theoretical analysis of competition between pure limit order markets. In his framework, consolidated depth is not affected by intermarket competition because limit order traders earn no rents. Glosten (1998), however, points out that this prediction depends on the allocation rule used to execute limit orders queuing at the same price. It does not hold if time priority is used and, in this case, Glosten (1998) argues that intermarket competition can improve liquidity by fostering competition between liquidity suppliers. Our assumptions are different from those in Glosten (1998) (e.g., there is no asymmetric information), but the theory delivers a similar insight.

We organize the remainder of the paper as follows. Section I presents a model of competition for order flow and derives testable hypotheses about the effect of EuroSETS entry. Section II tests these hypotheses and discusses the implications for the regulation of trade-throughs. Section III concludes.

I. Theory and Testable Hypotheses

In this section, we develop testable hypotheses on the liquidity effects of EuroSETS entry. These hypotheses are derived using an extension of the Parlour and Seppi (2003) model that focuses competition between pure limit order markets and allows for violations of price priority ("trade-throughs") across markets.

A. Model

A security trades in two limit order markets, the incumbent market, denoted I, and the entrant market, denoted E. In period 1, traders fill the limit order books in each market. In period 2, a broker executes a market order against the limit orders posted in period 1. In period 3, payoffs are realized. The expected payoff of the security is μ.

A.1. Limit Order Traders

Limit orders are submitted by risk-neutral traders who arrive at stochastic points in time during period 1. Traders must position their limit orders on a price grid $\{\ldots p_{-1,} p_0, p_1, p_2 \ldots\}$. Prices are indexed by their position relative to the asset value μ. We set $p_0 \equiv \mu$ and $p_{i+1} - p_i = \Delta > 0$, that is Δ is the tick size. In this model, it is never optimal to submit a sell (buy) limit order below (above) μ. Our predictions are derived for the "ask side" of the book (that is, prices $\{p_1, p_2, \ldots\}$). Symmetric results obtain for the "bid side." We denote by S_{jk} the number of shares offered for sale at price p_k $(k \geq 1)$ in market j, $Q_{jk} \overset{def}{=} Q_{jk-1} + S_{jk}(k \geq 1)$ the cumulative depth at price p_k in this market $(Q_{j0} = 0)$, and $Q_k \overset{def}{=} Q_{Ik} + Q_{Ek}(k \geq 1)$ the consolidated depth at price p_k, that is, the total number of shares offered up to this price aggregated across markets.

Limit orders in a given market are executed according to price and time priority, such that a buy market order in market j executes against the limit orders standing in this market at progressively higher prices until completion of the order, and limit orders standing at a given price are filled in the sequence in which they are submitted (time priority). These priority rules do not apply for limit orders posted in different markets.

A.2. Market Order Traders and Smart Routers

The broker arriving in period 2 must fill a market order. This order is a buy or a sell with equal probability and the cumulative distribution function for its size, $\tilde{X}$, is $F(.)$. A reservation price is attached to the order. We denote it p_m for a buy order $(p_m > p_1)$.[8]

The broker has one of two types: Either she is a smart router (probability γ), or she is not (probability $(1 - \gamma)$). The nonsmart router ignores offers in the entrant market to economize on monitoring costs and the time required for splitting orders. The smart router splits her order between markets I and E to minimize total trading costs. Thus, a smart router with order size $x \in [Q_{s-1}, Q_s]$ executes limit orders placed at prices $p_1, p_2, \ldots, p_s$ in each market. At the stop-out price, p_s, the smart router executes the residual portion of her order, $(x - Q_{s-1})$, using the following tie-breaking rule: With probability δ_j, she first executes limit orders at price p_s in market j and then the residual (if any) in the competing market.

Parameter γ is the proportion of trades intermediated by smart routers (henceforth, "the proportion of smart routers"). We interpret these trades as coming from brokers equipped with smart routing systems as multimarket trading is costless for them. The proportion of smart routers depends on the fraction of brokerage firms equipped with smart routing systems and smart routers' market share. These factors are fixed in the short run as it takes time for brokers to develop smart routers and for investors to realize which brokers achieve smaller costs. Thus, we take γ as given.

[8] The market order can be seen as a marketable limit order with price p_m. This assumption is innocuous as our results do not depend on p_m. It just guarantees that a buy order does not execute at a very large price because the limit order book is too thin.

A.3. Competitive Equilibrium

As in Parlour and Seppi (2003), we focus on competitive equilibria, which are defined by a zero-expected profit condition on the marginal order at each price. To define this notion formally, consider the last (submitted) share (henceforth, the marginal share) offered at price $p_k \leq p_m$ in market j.[9] Its expected payoff is

$$\Pi_{jk} = P_{jk}(p_k - f_j - \mu) - c_j, \tag{1}$$

where P_{jk} is the execution probability of the marginal share, $c_j > 0$ is a (per share) order entry cost, which is paid whether the order is filled or not, and f_j is a fee paid in case of execution. The order entry cost includes the costs associated with the time required to submit and then monitor the order and, possibly, an order entry fee charged by market j. For simplicity, we normalize the execution fee to zero as, qualitatively, its effect is similar to that of the order entry cost. Indeed, for a given execution probability, an increase in either type of costs reduces the expected profit on the marginal limit order at a given price and thereby the incentive to queue at this price. A strictly positive order entry cost implies that consolidated depth at each price is bounded, which is required to obtain predictions about consolidated depth. We interpret cross-market differences in the order entry cost as resulting from differences in fees charged by each market (other order handling costs are likely to be identical across markets). For instance, limit order traders pay an order entry fee on NSC, but not on EuroSETS.

Conditional on the arrival of a buy order, the marginal share at price p_k in market I executes when $\{\tilde{X} \geq Q_{Ik}\}$ (time priority) if the broker is not a smart router. If the broker is a smart router, the marginal share executes either if $\{\tilde{X} \geq Q_{k-1} + S_{Ik}\}$ (at the stop-out price, the broker gives priority to the incumbent market) or if $\{\tilde{X} \geq Q_k\}$ (at the stop-out price, the broker gives priority to the entrant market). We deduce that

$$\begin{aligned} P_{Ik}&(Q_{Ik-1}, Q_{k-1}, S_{Ik}, S_{Ek}) \\ &= 0.5[(1-\gamma)\bar{F}(Q_{Ik}) + \gamma(\delta_I \bar{F}(Q_{k-1} + S_{Ik}) + \delta_E \bar{F}(Q_k))], \end{aligned} \tag{2}$$

where $\bar{F}(x) \equiv \text{Prob}(\tilde{X} \geq x)$. Similar reasoning yields

$$P_{Ek}(Q_{k-1}, S_{Ik}, S_{Ek}) = 0.5\gamma[\delta_E \bar{F}(Q_{k-1} + S_{Ek}) + \delta_I \bar{F}(Q_k)]. \tag{3}$$

Other things equal, the execution probability of the marginal share at a given price decreases with the number of shares offered at this price. Hence, as the queue at price p_k in market j increases, the expected profit on the marginal share at this price decreases. When it is equal to zero, no trader finds it optimal to add depth at price p_k in market j. If this zero-profit condition holds at each price in each book, there are no profit opportunities left for liquidity

[9] Limit orders at prices strictly larger than p_m are never submitted because they have a zero execution probability.

suppliers and a competitive equilibrium is reached. A competitive equilibrium is therefore a set of depths $\{S^*_{Ik}, S^*_{Ek}\}_{k=1}^{m}$ that solves the following system of equations:

$$\begin{cases} P_{Ik}\left(Q^*_{Ik-1}, Q^*_{k-1}, S^*_{Ik}, S^*_{Ek}\right) = \dfrac{c_I}{(p_k - \mu)} & \text{if } S^*_{Ik} > 0, \\ P_{Ik}\left(Q^*_{Ik-1}, Q^*_{k-1}, S^*_{Ik}, S^*_{Ek}\right) \leq \dfrac{c_I}{(p_k - \mu)} & \text{if } S^*_{Ik} = 0, \\ P_{Ek}\left(Q^*_{k-1}, S^*_{Ik}, S^*_{Ek}\right) = \dfrac{c_E}{(p_k - \mu)} & \text{if } S^*_{Ek} > 0, \\ P_{Ek}\left(Q^*_{k-1}, S^*_{Ik}, S^*_{Ek}\right) \leq \dfrac{c_E}{(p_k - \mu)} & \text{if } S^*_{Ek} = 0. \end{cases} \tag{4}$$

A limit order book can feature prices at which no limit order is submitted ($S^*_{jk} = 0$), because the expected revenue is too small relative to the order submission cost. In particular, the order submission cost determines the first quote on the grid at which submitting a buy or sell limit order is profitable, that is, the bid-ask spread. For instance, the equilibrium conditions imply that the best ask in the consolidated market (i.e., the lowest ask across markets) is the lowest price on the grid such that

$$p_k > \mu + 2Min\left\{c_I, \frac{c_E}{\gamma}\right\}. \tag{5}$$

We focus on the case in which $2c_I < (p_1 - \mu)$, so that, in equilibrium, limit orders are posted at price p_1 in at least one of the two markets. This simplifies the exposition without affecting the implications.

In equilibrium, the expected profit on inframarginal shares at a given price is strictly positive because they have a larger execution probability than the zero-profit marginal share. The rent earned on inframarginal shares stems from price discreteness. To see this, suppose that the incumbent market operates alone and consider the expected profit on the first infinitesimal unit ("share") offered at price p_k (the expected profit per share declines as we move further into the queue). This unit has the same execution probability as the marginal share offered at $p_{k-1}(\bar{F}(Q^*_{Ik-1}))$, but it sells at a markup equal to the tick size. Thus, its expected profit is proportional to the tick size and is given by $\bar{F}(Q^*_{Ik-1})\Delta$, which is easily checked using the equilibrium conditions. Entry of a new market reduces this rent (and more generally the rent earned on inframarginal shares) because time priority is not imposed across markets. Thus, "late" limit order traders can jump ahead of the queue of limit orders at a given price in a given market by submitting a limit order in the other market.

Hence, price discreteness (combined with time priority) sustains strictly positive expected profits for liquidity suppliers and explains why the incumbent market is exposed to entry. It does not immediately follow, however, that two limit order markets can coexist. To study this point, we say that market j is dominant if its competitor does not attract any limit order (for all reservation

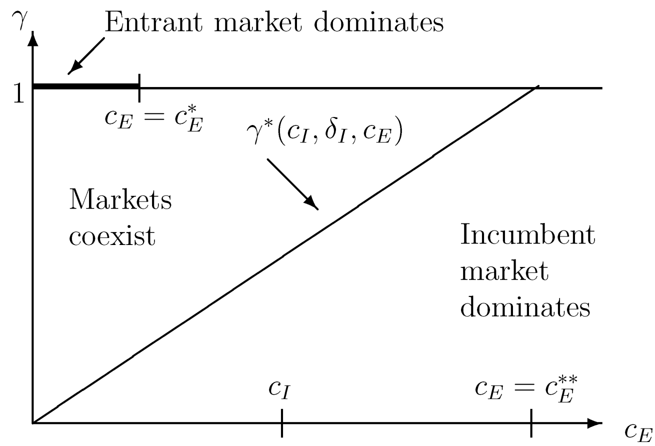

Figure 1. Potential equilibria—one market dominates or markets coexist. This figure illustrates for which values of (c_E,γ) both markets coexist. The alternative is that one market captures all order flow and, by our definition, dominates. c_j is the order submission cost in market j and γ is the proportion of smart routers.

prices). Otherwise, the two markets coexist. The next proposition derives the conditions under which markets I and E coexist (proofs are in Appendix A).

PROPOSITION 1:

- *If $\gamma^*\ (c_E, c_I, \delta_I) < \gamma < 1$, the two markets coexist. If $\gamma \le \gamma^*\ (c_E, c_I, \delta_I)$, then market I is dominant.*
- *If $\gamma = 1$, then both markets coexist if $c_E^* < c_E < c_E^{**}$. Else, market E is dominant if $c_E \le c_E^*$, and market I is dominant if $c_E \ge c_E^{**}$.*
- *The cutoffs γ^*, c_E^*, and c_E^{**} are given by $\gamma^*(c_E, c_I, \delta_I) \equiv Min\{\frac{c_E}{(2-\delta_I)c_I}, \frac{2c_E}{2\delta_I c_I + (1-\delta_I)\Delta}\}$, $c_E^* = Min\{\frac{c_I}{1+\delta_I}, \frac{2c_I - \delta_I \Delta}{2(1-\delta_I)}\}$, and $c_E^{**} = Max\{(2-\delta_I)c_I, \delta_I c_I + \frac{(1-\delta_I)\Delta}{2}\}$.*

Figure 1 depicts the set of values for γ and c_E such that market I dominates or the two markets coexist (for fixed values of c_I and δ_I).

When the proportion of smart routers is too small ($\gamma \le \gamma^*$), the expected revenue from submitting a limit order in the entrant market is smaller than the order entry cost in this market (at each price on the grid) because the likelihood of execution for limit orders in the entrant market is low. Entry is then impossible. It is therefore key for the entrant market to establish a critical mass of smart routers so that $\gamma > \gamma^*\ (c_E, c_I, \delta_I)$.

As $c_E^* < c_E^{**}$, both markets can coexist even when they charge different order entry fees and there is no captive base of users for the incumbent market ($\gamma = 1$). This result is puzzling. Why, in this case, does not trading gravitate entirely to the market with the lowest fee (as, for instance, in Pagano (1989))? The answer to this question lies in the interplay of two self-reinforcing forces. First, as the queue of limit orders in the market with the smallest entry cost gets large, execution probability in this market declines. Routing a limit order to the more expensive market is then a way to get a larger execution probability by bypassing time priority on limit orders in the cheaper market. Second, liquidity demanders optimally split their orders between the two markets if offers are available in each system. As a result, they sustain limit order traders' incentives for jockeying between queues.[10] For these two reasons, limit order traders use both markets provided that the difference in order submission costs is not too large ($c_E^* < c_E < c_E^{**}$).

Proposition 1 applies when the tick size, Δ, is strictly positive, the relevant case for the markets considered in our empirical analysis. For completeness, we briefly discuss the limit case in which the tick size goes to zero. In this case, total expected profits for limit order traders vanish and queue-jumping strategies are useless. Thus, trading gravitates to the market with the lowest order submission cost, unless some users are captive in the incumbent market ($\gamma < 1$). In this case, the analysis reveals that the two markets coexist when the order submission cost of the entrant market is sufficiently small compared to that of the incumbent market ($\frac{c_E}{\gamma} < c_I$).[11]

B. Testable Implications

We now use the restrictions imposed by the zero profit conditions (equation (4)) to develop testable hypotheses about (i) the effect of EuroSETS entry on consolidated depth and (ii) the impact of smart routers on liquidity provision.

B.1. Intermarket Competition and Depth

We first compare consolidated depth when markets E and I coexist to depth when the incumbent market operates alone. We also compare the depth of the incumbent market in these two cases. We denote by $Q_k^*(\gamma)$ the consolidated depth (up to price p_k) in equilibrium when the proportion of smart routers is γ. Similarly, $Q_{Ik}^*(\gamma)$ is the cumulative depth in the incumbent market. The case in which the incumbent market operates alone is tantamount to $\gamma = 0$.

PROPOSITION 2: *Other things equal, when the two markets coexist, (i) consolidated depth is larger and (ii) cumulative depth in the incumbent market is smaller than when the incumbent market operates alone, that is,* $Q_k^*(\gamma) \geq Q_k^*(0)$ *and* $Q_{Ik}^*(\gamma) \leq Q_{Ik}^*(0)$, *for* $k \geq 1$ *and* $\gamma \in [\gamma^*, 1]$.

Coexistence of two limit order markets allows for queue-jumping strategies and thereby intensifies competition between liquidity providers. Hence,

[10] Bloch and Schwartz (1978) develop a similar idea. Interestingly, the August 2004 issue of the EuroSETS newsletter mentions that: "some firms are using the relatively lower volumes on the spread offered by the Dutch Trading Service (i.e., EuroSETS) to 'queue-jump' rather than waiting elsewhere for execution" (EuroSETS newsletter, August 2004, 4).

[11] This condition is not obtained by setting $\Delta = 0$ in Proposition 1. Indeed, the case in which $\Delta = 0$ requires a separate analysis because in this case the tie-breaking parameter δ_I plays no role. Details can be obtained from the authors upon request.

it reduces the wealth transfer from liquidity demanders to liquidity providers, which means that consolidated depth increases. Thus, the first result is due to the interplay of price discreteness (which leaves rents to limit order traders) and the absence of time priority across markets. This effect of queue-jumping on consolidated depth is amplified when the fee of the entrant market is smaller than that of the incumbent market as liquidity provision becomes cheaper. For this reason, the result would still obtain with a continuous price grid because coexistence in this case requires a strictly smaller fee in the entrant market. Otherwise, when the tick size is strictly positive, a smaller fee in the entrant market is not necessary to obtain the first result.

The second part of the proposition is more intuitive. When the two markets coexist, part of the order flow executes against limit orders posted in the entrant market. Consequently, other things equal, execution probabilities of limit orders submitted to the incumbent market are smaller and this market therefore attracts less limit orders than when it operates alone.[12]

In summary, the model implies that, other things equal, the effect of EuroSETS entry on consolidated depth should be positive, whereas its impact on NSC depth should be negative. Testing these predictions is not straightforward because there are other factors influencing liquidity provision that may have changed at the time of EuroSETS entry. We now discuss these factors.

First, the improvement in depth following EuroSETS entry could induce liquidity demanders to submit large orders more frequently. This effect is not captured by our model since the distribution of market order size is exogenous. A full analysis would require that this distribution is endogenized, which is beyond the scope of the paper. In any case, more frequent large orders would amplify the improvement in consolidated depth due to EuroSETS entry. Indeed, a first order stochastic shift in market order size enlarges the likelihood of execution for limit orders and thereby the incentive to provide liquidity (see Seppi (1997) for a formal analysis in a related setting).

Second, fees on limit orders are smaller after EuroSETS introduction as EuroSETS fees are lower than NSC fees and EuroSETS entry prompted a fee reduction in NSC. As explained above, lower fees on limit orders amplify the positive effect of queue jumping on consolidated depth. The reduction of fees in NSC is more problematic for our second prediction as it makes liquidity provision in this market cheaper. This effect can more than offset the negative impact of EuroSETS entry on NSC depth, which leaves us with an ambiguous prediction for the evolution of cumulative depth in NSC.

The next parametric example illustrates this point for depth at the top of the book. In this example, $\tilde{X}$ has a uniform distribution on $[0, \bar{Q}]$, $\delta_I = 0.95$, $\Delta = 0.01$, and $c_E = 0.001$. We denote the order submission cost in the incumbent

[12] The absence of time priority is often viewed as deterring, instead of encouraging, liquidity provision (see Harris (1990)). The deterrence effect is present in our model: Traders submit less limit orders in the incumbent market because queue jumping reduces the likelihood of execution in this market. However, queue jumping facilitates "entry" of relatively slow bidders (those who submit orders at the end of the queue). This second effect encourages competition between limit order traders and outweighs the deterrence effect.

market before entry by c_I^b and after entry by c_I^a. We set $c_I^b = 0.004$ and we consider the case where $c_I^a = c_I^b$ and the case where $c_I^a < c_I^b$. For each case, the example shows how depth at the best quote changes after introduction of the entrant market, both for the incumbent and for the consolidated market.[13]

Numerical Example 1.

Proportion of Smart Routers (γ):	0.40	0.50	0.60	0.70	0.80	0.90	0.95
(a) $c_I^a = c_I^b = 0.004$							
Depth change incumbent market[a]	−3%	−5%	−7%	−9%	−12%	−14%	−15%
Depth change consolidated market[b]	154%	204%	237%	261%	279%	293%	298%
(b) $c_I^a = 0.003; c_I^b = 0.004$							
Depth change incumbent market[a]	99%	97%	96%	94%	92%	91%	90%
Depth change consolidated market[b]	159%	209%	243%	267%	285%	298%	304%

[a]: Defined as $\frac{Q_{I1}^*(\gamma) - Q_{I1}^*(0)}{Q_{I1}^*(0)} * 100\%$.

[b]: Defined as $\frac{Q_1^*(\gamma) - Q_{I1}\%^*(0)}{Q_{I1}^*(0)} * 100\%$.

First, observe that the magnitude of the depth improvement can be large even if γ is small and δ_I is large (0.95). This improvement is due to both the queue-jumping effect and the smaller order submission cost in the entrant market. Second, as implied by Proposition 2, the depth in the incumbent market declines after the arrival of the entrant market, other things equal ($c_I^a = c_I^b$). If, however, the order submission cost in the incumbent market is reduced following this arrival ($c_I^a = 0.003$), then depth in the incumbent market increases despite the loss of order flow to the entrant market. Moreover, the effect of entry on consolidated depth is strengthened.

Finally, we discuss the role of the tick size for our prediction regarding consolidated depth. The prediction regarding the direction of the change in consolidated depth following EuroSETS entry does not depend on the tick size. It just requires coexistence of the two markets after EuroSETS entry. The magnitude of the impact of EuroSETS entry on consolidated depth, however, depends on the tick size, because queue-jumping strategies become less profitable when the tick size is reduced. Moreover, time-series variation in the tick size for a given stock affects the rents on inframarginal limit orders and therefore affects consolidated depth, above and beyond the effect of EuroSETS entry. In our empirical analysis, we control for this tick size effect in two ways. First, we focus on stocks for which the (absolute) tick size does not change after EuroSETS entry. Second, we control for changes in the relative tick size by adding price as a control variable.

B.2. Liquidity and Smart Routers

Even if the proportion of brokers with smart routing systems is fixed and equal across stocks, the fraction of order flow channeled through these brokers,

[13] The numerical values are obtained by computing the quoted depth at price p_1 in each market using equilibrium conditions when the order size has a uniform distribution. Closed-form solutions in this case are easily derived and can be obtained from the authors upon request.

which we define as the proportion of smart routers, could vary across stocks. Other things equal, limit orders in EuroSETS are more likely to be executed for stocks with a large proportion of smart routers. Thus, if limit order traders care about execution probabilities, we expect liquidity provision in EuroSETS to increase in the proportion of smart routers.

To study this point, we use two measures of the "liquidity share" of the entrant market: (i) $R^d(\gamma) \equiv \frac{Q^*_{E1}(\gamma)}{Q^*_1(\gamma)}$, which is the ratio of entrant depth at price p_1 to consolidated depth at this price, and (ii) $R^s(\gamma)$, which is the ratio of the incumbent bid-ask spread to the entrant bid-ask spread. This second measure complements the first as the two markets may coexist without both being active at the consolidated best ask (in which case $R^d(\gamma) = 1$ or $R^d(\gamma) = 0$). As we focus on the sell side of the book, we define the bid-ask spread in market j as the difference between the best ask price in this market, $a^*_j(\gamma)$, and the value of the security, μ. Thus, $R^s(\gamma) \equiv \frac{a^*_I(\gamma)-\mu}{a^*_E(\gamma)-\mu}$.

PROPOSITION 3: *Other things equal, when the two markets coexist,*

- *The entrant's contribution to consolidated depth at price p_1 (weakly) increases with the proportion of smart routers (i.e., $\frac{\partial R^d(\gamma)}{\partial \gamma} \geq 0$).*
- *The ratio of the bid-ask spread in the incumbent market to the bid-ask spread in the entrant market (weakly) increases with the proportion of smart routers (i.e., $\frac{\partial R^s(\gamma)}{\partial \gamma} \geq 0$).*

This proposition establishes that the liquidity share of the entrant market increases with the proportion of smart routers. The intuition is that the likelihood of execution for limit orders in the entrant market improves as the proportion of smart routers enlarges. Thus, traders post more aggressive quotes in this market and its queue of limit orders increases. In response, the likelihood of execution for limit orders in the incumbent market declines and the queue of orders in this market shortens. Thus, the entrant market contributes relatively more to liquidity provision.

The net effect of an increase in the proportion of smart routers on consolidated depth is ambiguous, however, and depends on parameter values.[14] To see this, consider again the case in which $\tilde{X}$ has a uniform distribution on $[0, \bar{Q}]$. The numerical example below reports the consolidated quoted depth at price p_1 (as a fraction of the maximal order size $\bar{Q}$) and the contribution of the entrant market to consolidated depth when $c_I = 0.003$, $c_E = 0.001$, and $\Delta = 0.01$ for two different values of δ_I.

As implied by Proposition 3, the contribution of the entrant market to quoted depth ($R^d_1(\gamma)$) increases with the proportion of smart routers. The effect of smart routers on total quoted depth, however, is less clear-cut and depends on the tie-breaking rule, δ_I. For $\delta_I = 0.50$, it first increases with γ for $\gamma \leq 0.80$ but

[14] This point does not contradict Proposition 2. This proposition states that consolidated depth is smaller when $\gamma \leq \gamma^*$ (only the incumbent market is active) than when $\gamma > \gamma^*$ (both markets are active), not that consolidated depth should always increase in γ in the range $[\gamma^*, 1]$.

Numerical Example 2.

Proportion of Smart Routers (γ):	0.40	0.50	0.60	0.70	0.80	0.90	0.95
(a) $\delta_I = 0.50$							
Consolidated depth at best ask, $\frac{Q_1^*(\gamma)}{\bar{Q}}$	67%	74%	78%	80.5%	81.2%	81%	80%
Depth share entrant market, $R_1^d(\gamma)$	50%	62%	70%	77%	85%	92%	95%
(b) $\delta_I = 0.95$							
Consolidated depth at best ask, $\frac{Q_1^*(\gamma)}{\bar{Q}}$	52%	62%	69%	73%	77%	80%	80%
Depth share entrant market, $R_1^d(\gamma)$	24%	36%	43%	47%	50%	52%	53%

afterwards it decreases with γ. In contrast, for $\delta_I = 0.95$, quoted depth monotonically increases with γ. The last observation suggests that the effect of γ on quoted depth can be signed for δ_I large enough. This is indeed the case as shown by the next proposition.

PROPOSITION 4: *There exists a threshold $\delta_I^* < 1$ such that if $\delta_I > \delta_I^*$, then consolidated depth at price p_1 increases with the proportion of smart routers (i.e., $\frac{\partial Q_1^*(\gamma)}{\partial \gamma} > 0$ for $\delta_I > \delta_I^*$).*

The intuition for this result is as follows. For large values of δ_I, an increase in the proportion of smart routers results in a small loss of order flow at the best quotes for the incumbent market. Indeed, it only loses the order flow of smart routers who give priority to the entrant market in case of a tie, that is, a fraction $(1 - \delta_I)$ of the order flow. In contrast, the entrant market gains new users whether these users give priority to the entrant market or not in case of a tie. Thus, for δ_I large enough, the improvement in quoted depth in the entrant market dominates the decrease in quoted depth in the incumbent market when γ increases.

II. Empirical Analysis

In this section, we test the two main implications of the model: The consolidated limit order book should be deeper after EuroSETS entry, and EuroSETS liquidity supply should increase with the proportion of smart routers in the cross-section of stocks. We also analyze the effect of EuroSETS entry on NSC depth and the relationship between the proportion of smart routers and consolidated depth.

A. Background, Data, and Methodology

A.1. Market Structure

Euronext operates the main electronic trading platform for Dutch stocks, NSC, since the merger of the Amsterdam Stock Exchange and the Paris Bourse in 2001. On October 14, 2003, the London Stock Exchange announced that it would introduce a competing platform, EuroSETS, for the stocks in the two major Dutch indices, the AEX and AMX. This introduction was encouraged by the Dutch brokerage community to prompt a cut in Euronext trading fees.[15] Euronext did indeed cut its fees by 50% on April 23, 2004. Trading in EuroSETS began on May 24, 2004.

The organization of trading in NSC and EuroSETS is close to that considered in our model. The two systems operate over the same trading hours (9:00 a.m. to 5:30 p.m.) and they are both organized as continuous electronic limit order markets. Price-time priority is enforced within each market, but not across markets. As both systems are fully automated, they offer the same speed of execution. Moreover, they have the same transparency: Participants see all limit orders (except for hidden orders) and trading is anonymous. Also, EuroSETS and NSC use the same tick size, €0.01, for stocks that trade below €50.

The two platforms have almost the same membership and use the same clearing house. Moreover, in contrast to U.S. equity markets, practices such as payment for order flow or preferencing, which could systematically tilt routing decisions in favor of one market, do not exist in the Dutch equity market. Overall, these features imply that routing decisions should depend on the prices available in EuroSETS and NSC and the labor costs of using both systems, rather than clientele effects, as assumed in the model.

For these reasons, the introduction of EuroSETS provides an excellent laboratory to test the empirical implications of the model.

A.2. Data

We compare liquidity measures before and after EuroSETS entry. We select a pre-entry period and two post-entry periods of 21 trading days. The pre-entry period starts on April 23 and lasts until May 21, 2004 (the day before entry). To identify permanent equilibrium effects of EuroSETS entry and to account for possible changes in the proportion of smart routers over time, we consider two post-entry periods: August 2–August 30, 2004 and January 3–January 31, 2005.

Our sample includes all 25 stocks of the AEX index. To avoid confounding effects, we remove stocks with a price higher than €50 (above this price, the tick size is not the same across markets), stocks that drop out of or enter the index during the sample period, and stocks that implement or cancel an ADR program during the sample period. This leaves us with a sample of 22 stocks. As explained in Section I.B.2, we expect cross-sectional variation in the effect of EuroSETS entry on consolidated depth. To document such variation, we group stocks into quartiles based on trading volume, with Q1 containing the most actively traded stocks. The classification is based on 2003 volume to ensure an exogenous ranking. The composition of the quartiles is given in Appendix B.

[15] See "Discontented Dutch Brokers Prompt Foreign Intervention," *Euromoney*, December 2003 or "Dutch Auction: Can the LSE Snatch Dutch Equities Trading from Euronext?" *The Economist*, March 6, 2004.

We use two types of data, namely, limit order book snapshots and a time-stamped record of trades and best bid and ask quotes in both markets (including quoted depth for EuroSETS).[16] The snapshot data contain the five best bid and ask quotes and the number of shares offered at these quotes sampled every 5 minutes in both EuroSETS and NSC. We also aggregate these data across markets and create a snapshot of the consolidated limit order book. We use the trade and quotes data to estimate the proportion of smart routers (see Section II.B.2).

Our data have some limitations. First, we do not have data on trades occurring in venues other than NSC and EuroSETS. There are three main alternative venues: (i) an OTC market that, effectively, is an upstairs market, (ii) "Xetra star," a trading platform operated by Deutsche Börse (introduced in 2003), and (iii) foreign markets where the stocks are cross-listed. The market share of Xetra star is very small. Half of the stocks in our sample have ADRs in the United States. We expect the U.S. brokerage firms to be more active in these stocks. As these firms are used to trade in a more fragmented environment (the U.S. equity market), they are more likely to be equipped with smart routing technology (see Hallam and Idelson (2003)) or, at least, to behave like smart routers.

Second, we do not have data on iceberg orders, that is, orders that display only a fraction of total size. Both NSC and EuroSETS authorize these orders. Thus, we can measure the change in displayed consolidated depth following EuroSETS entry, not the change in overall (hidden and displayed) consolidated depth. The change in displayed depth could therefore underestimate or overestimate overall depth change. We address this problem by analyzing the evolution of effective spreads in NSC (see below).

A.3. Methodology and Summary Statistics

Below we compare various variables (e.g., consolidated depth) before and after EuroSETS entry. We estimate the means of these variables, changes in these means, and test for the statistical significance of these changes using panel data techniques.

The econometric specification assumes that the variable of interest, y_{it}, for stock i on day t (e.g., consolidated depth) is the sum of a stock-specific mean (μ_i), an event effect (θ_i), potential control variables (X_{it}), and an error term (ε_{it}):

$$y_{it} = \mu_i + \theta_i \mathbf{1}_{[t \text{ in post-entry period}]} + \beta' X_{it} + \varepsilon_{it}, \tag{6}$$

$$\varepsilon_{it} = \xi_t + \eta_{it}, \tag{7}$$

where $\mathbf{1}_{[A]}$ is a dummy variable that is one if A is true, and ξ_t is a common factor across all stocks that captures, for example, the widely documented

[16] The continuous time data are obtained from data sets distributed by Euronext and the LSE. The EuroSETS snapshots are made available to us by the LSE. The NSC snapshots are downloaded (with permission of Euronext and Alex) from a Dutch retail broker, Alex, who offers a live feed to the Euronext trading platform.

commonality in liquidity. To save space, we do not report separate estimates for each stock, but instead report the average values of the coefficients of interest for each quartile. In particular, we define:

$$\mu_q \overset{def}{=} \frac{1}{N_q}\sum_{i\in I_q}\mu_i \quad \text{(quartile mean pre-entry)}, \tag{8}$$

$$\theta_q \overset{def}{=} \frac{1}{N_q}\sum_{i\in I_q}\theta_i \quad \text{(quartile change: post-entry vs. pre-entry)}, \tag{9}$$

where q is a quartile index that runs from one (most active) to four, N_q is the number of stocks in quartile q, and I_q is the set of stocks in quartile q. We are particularly interested in θ_q, which measures the impact of EuroSETS entry on the dependent variable for each quartile. Following Petersen (2005), our t-statistics are based on Rogers standard errors to account for heteroskedasticity and nonzero (stock-specific) autocorrelation in the error term (η_{it}). [17]

Using this methodology, Table I provides summary statistics on daily volume, number of trades, average trade size, realized volatility (based on 5-minute midquote returns), and average price level. It also gives EuroSETS and NSC market shares (in terms of trading volume and number of trades) for each quartile. The first column reports the average values in the pre-entry period and testifies to the heterogeneous nature of the sample. For instance, the average daily trading volume ranges from €167.33 million for Q1 to €9.4 million for Q4. Realized volatility (annualized) is 35.25% for Q4 and declines to 19.13% for Q1. We observe a significant drop in trading activity (−13% for volume) and volatility (−7%) in the first post-entry period. Trading activity in the second post-entry period is not significantly different from pre-entry levels, but volatility is significantly lower (−36%).

The evolution of the distribution of aggregate market order size after EuroSETS entry is of interest for reasons discussed in Section I.B.1 We do not find economically large changes in this distribution (findings are not shown for brevity).[18] For instance, the median trade size is €28,000 in the pre-entry period and €29,000 (€27,000) in the first (second) post-entry period for stocks in Q1. We obtain similar conclusions for other quantiles of the empirical distribution of aggregate market order sizes and for other stocks. Thus, the assumption that the distribution of market order sizes is unchanged before and after entry seems reasonable in our sample.

On average, EuroSETS daily market share in terms of total number of trades is 3.5% (2.0%) in the first (second) post-entry period. For Q1, EuroSETS market share is 6.1% (3.6%) in the first (second) post-entry period. This market share

[17] Rogers standard errors are similar to Newey-West standard errors but are designed for panel data analysis. The main difference is in the weights of the cross-terms. See Petersen (2005) for details.

[18] After EuroSETS entry, we aggregate transactions occurring at the same time in NSC and EuroSETS into one transaction to obtain the empirical distribution of market order sizes (i.e., we assume that transactions occurring at the same time in NSC and EuroSETS originate from order-splitting traders).

Table I

Summary Statistics

This table reports summary statistics for the 22 Dutch index stocks in our sample. We group them into volume quartiles, where Q1 contains the most actively traded stocks. We report volume, number of trades, volatility, and price. For both post-entry periods, we disaggregate volume and the number of trades to report EuroSETS market share. All statistics are based on quotes and trades through the limit order book, that is, off-market block trades are excluded. The pre-entry period runs from April 23 through May 21, 2004, post-entry 1 from August 2 through August 30, 2004, and post-entry 2 from January 3 through January 31, 2005. For all four variables, we calculate the difference between the pre- and post-entry levels and add a "*" to the post-entry levels if these are significantly different at the 99% level. In the test, we use standard errors that control for commonalities across stocks, heteroskedasticity, and nonzero stock-specific autocorrelation (see Section II.A.3).

		Pre-Entry	Post-Entry 1			Post-Entry 2		
			Consolidated	Change	EuroSETS	Consolidated	Change	EuroSETS
Daily volume[a] (€ mio)	Q1	167.33	147.36	−19.98*	5.1%	176.03	8.70	3.6%
	Q2	57.12	48.85	−8.27*	0.3%	58.07	0.95	0.2%
	Q3	25.29	19.43	−5.87*	0.3%	25.85	0.55	0.1%
	Q4	9.40	9.25	−0.15	0.2%	9.26	−0.14	0.1%
	All	69.10	60.03	−9.07	3.5%	71.82	2.72	2.4%
Daily # Trades[a] (1,000 trades)	Q1	4.84	4.33	−0.51*	6.1%	4.88	0.04	3.6%
	Q2	2.23	2.02	−0.21*	0.4%	2.20	−0.02	0.1%
	Q3	1.39	1.22	−0.16*	0.2%	1.41	0.02	0.1%
	Q4	0.76	0.68	−0.08	0.2%	0.83	0.06	0.1%
	All	2.42	2.17	−0.25*	3.5%	2.44	0.02	2.0%
Annualized Volatility[b] (%)	Q1	19.13	17.21	−1.92*		12.21	−6.92*	
	Q2	22.61	21.38	−1.23*		15.39	−7.31*	
	Q3	27.13	26.05	−1.07		16.42	−10.71*	
	Q4	35.25	32.02	−3.24		23.04	−12.21*	
	All	25.57	23.72	−1.85*		16.49	−9.10*	
Price (€)	Q1	21.22	20.44	−0.78		22.67	1.45	
	Q2	16.17	14.10	−2.08*		15.40	−0.78	
	Q3	19.30	18.76	−0.53		21.06	1.77	
	Q4	11.20	10.34	−0.86*		13.04	1.84	
	All	17.13	16.04	−1.10*		18.13	1.00	

[a]The trade statistics are based on all trades through the limit order book, that is, off-market block trades are not included.
[b]This is realized volatility based on 5-minute midquote returns. We annualize using 225 trading days per year.
*Significant at the 99% significance level.

is similar to that of the most active regional exchanges in the United States (see Bessembinder (2003)). For the other quartiles, it is less than 1%. Market share in terms of volume gives similar results.

Low EuroSETS market share for stocks in Q2, Q3, and Q4 does not mean that this market is completely inactive in these stocks. First, some trades do occur in these stocks (see Table I). Second, EuroSETS share of liquidity supply is nontrivial as shown in Figure 2.

This figure gives the frequencies with which EuroSETS and NSC are present at the best ask in the consolidated market, and the depth each market offers *conditional* on matching the best ask price. Similar findings (not shown) are obtained for the bid side. For the most actively traded stocks, EuroSETS is frequently present at the best ask (76.88% (87.97%) of the time in the first (second) post-entry period), with a depth equal to €27,000 (in both periods). This is substantial since the average trade size for Q1 stocks is about €35,000 in each post-entry period. NSC is also at the best ask for a large fraction of time (90.34% (95.01%)), with considerably more depth than EuroSETS. Yet, this implies that 9.64% (4.99%) of the time EuroSETS is alone at the best ask price. For the other quartiles, EuroSETS presence at the inside is lower as it ranges from 4.91% to 32.60% across both post-entry periods. These frequencies are similar to the frequency with which regional exchanges match the best bid and offer in the U.S. equity market. For instance, Bessembinder (2003) finds that these frequencies range from 17.4% (Chicago Stock Exchange) to 6.44% (Philadelphia Stock Exchange).

To sum up, EuroSETS "liquidity share" (its contribution to overall displayed liquidity supply) is substantially larger than its market share. The model suggests two explanations: (i) a relatively low proportion of smart routers and/or (ii) a tie-breaking rule very favorable to NSC (large δ_I). We study these explanations in more detail below.

B. Testing the Predictions

B.1. The Effect of Intermarket Competition on Market Depth

Consolidated depth. Our first prediction is that depth should increase throughout the consolidated limit order book (Proposition 2) after EuroSETS entry. To test this prediction, we compute the value (number of shares times the midquote) offered up to k ticks behind the best quotes before and after the entry of EuroSETS.

Table II reports these values for consolidated depth at the best ask price (*Depth0*) and up to four ticks behind this price (*Depth4*). Results are identical for consolidated depth at intermediate price steps and for the bid side. Consistent with our prediction, consolidated depth is larger after EuroSETS entry both at and behind the best ask. Moreover, the increase in depth is significant in almost all quartiles in both post-entry periods.

As explained in Section I.B.1, these changes in consolidated depth may in part be due to variations in the relative tick size (the tick size divided by the stock price) and more generally to other factors affecting liquidity supply not captured by our model (such as trading volume or price volatility). Hence, to isolate the role of EuroSETS entry, we run regression (6) with the price level, volume, and volatility as control variables. The results are reported in Table III.

The coefficient of interest is θ_q, which measures, for a given quartile, the impact of EuroSETS introduction on consolidated depth. Overall, the analysis

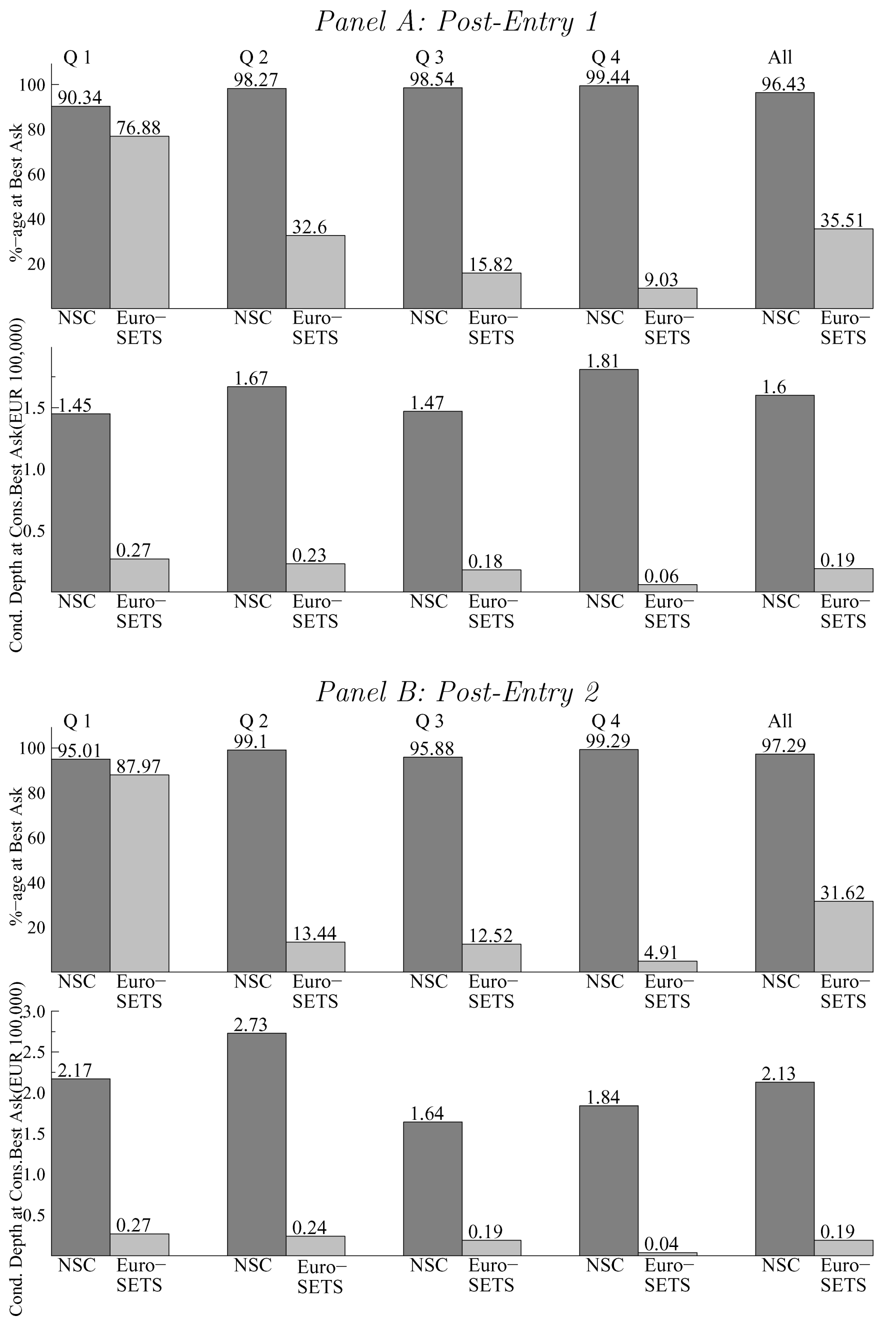

Figure 2. Frequency at best (consolidated) ask and conditional depth. This figure illustrates how often a market is at the best ask in the consolidated market and, at the best ask, how much depth (in €100,000) it offers at that quote. These statistics are based on 5-minute order book snapshots and are therefore time-weighted averages.

Table II

Spread and Depth Pre- and Post-Entry

This table reports spread and depth for volume-ranked quartiles, where Q1 contains the most actively traded securities. We report quoted spread, (visible) depth at the best ask using the midquote to calculate the value (Depth0), cumulative depth up until four ticks behind the best ask (Depth4), and effective spread. We compare post-entry liquidity in the consolidated market with pre-entry liquidity. For completeness, we also report spread and depth in EuroSETS only. The pre-entry period runs from April 23 through May 21, 2004, post-entry 1 from August 2 through August 30, 2004, and post-entry 2 from January 3 through January 31, 2005. For all four liquidity measures, we calculate the difference between the pre- and post-entry levels for the consolidated and the NSC-only market and add a "*/**" to the post-entry levels if these are significantly different at the 95%/99% level. In the test, we use standard errors that control for commonalities across stocks, heteroskedasticity, and nonzero stock-specific autocorrelation (see Section II.A.3).

		Pre-Entry	Post-Entry 1			Post-Entry 2		
			Consolidated	NSC-Only	EuroSETS-Only	Consolidated	NSC-Only	EuroSETS-Only
Quoted Spread (basispoints)	Q1	7.91	6.65**	7.80	9.64	5.59**	6.05**	6.91
	Q2	13.80	13.55	13.86	27.78	10.89**	11.03**	29.80
	Q3	21.43	24.80	25.13	55.64	17.93	18.19	49.17
	Q4	43.48	46.28	46.41	112.36	32.60**	32.86**	88.01
	All	20.67	21.66	22.17	48.39	15.98**	16.26**	41.19
Depth0 (basispoints)	Q1	1.21	1.72**	1.44**	0.78	2.65**	2.30**	0.65
	Q2	1.35	1.80*	1.62	1.05	2.87**	2.78*	1.48
	Q3	0.93	1.24	1.15	1.13	1.54*	1.59*	1.41
	Q4	1.14	1.69*	1.63	0.71	1.93*	1.92*	0.77
	All	1.17	1.63**	1.47**	0.92	2.30**	2.19**	1.08
Depth4 (basispoints)	Q1	7.71	13.37**	9.36**	4.32	17.52**	15.06**	2.62
	Q2	7.76	11.93**	9.50	2.64	18.98**	17.07*	2.13
	Q3	5.84	8.66**	6.84	2.16	9.47**	9.56*	2.05
	Q4	8.23	11.08**	9.77	1.54	11.85**	13.30*	1.12
	All	7.42	11.39**	8.92**	2.74	14.80**	13.96**	2.01
Eff. Spread[a] (basispoints)	Q1	7.12	6.41**	7.24	7.27	5.30**	5.80**	5.91
	Q2	11.93	12.26	12.51*	18.44	10.44**	10.52**	21.52
	Q3	18.29	22.02	22.27	32.84	17.27	17.38	34.16
	Q4	39.03	42.50*	47.70*	91.39	31.69**	31.83**	41.17
	All	18.22	19.76	20.15*	32.57	15.42**	15.63**	24.89

[a]The effective spread is twice the difference between the trade price and the contemporaneous midquote. In case of multiple trades in the same second, the trade price is defined as the volume-weighted average price. The reason is that orders that run up the book are reported as separate trades by the exchanges. For the consolidated market, we use the midquote in the consolidated market and aggregate market buys (sells) across both markets. For the "NSC only" or "EuroSETS only" market, we use the market's own midquote.

*/** Significant at the 95%/99% significance level.

confirms the univariate findings of Table II. Consolidated depth increases substantially after EuroSETS entry across all quartiles. The increases are statistically significant for the most active stocks (Q1 and Q2) and predominantly insignificant for the least active stocks (Q3 and Q4). In all cases, they are quite large in economic terms. For instance, the improvement in quoted depth is well in excess of 30% for all quartiles and both periods.

Table III

Liquidity Change with Controls for Volume, Volatility, and Price

This table reports time-weighted liquidity change by comparing pre- and post-entry order books with the controls volume, realized volatility, and price. For the post-entry books, both the consolidated and the NSC-only book are considered. We analyze three liquidity measures: quoted spread, depth at the best ask (Depth0), and cumulative depth up until four ticks behind the best ask (Depth4). The econometric specification assumes that the variable of interest y_{it} (e.g., quoted spread) for stock i on day t can be expressed as the sum of a stock-specific mean (μ_i), an event effect (θ_i), control variables (X_{it}), and an error term (ε_{it}):

$$y_{it} = \mu_i + \theta_i \, 1_{t\,\text{in post-entry period}} + \beta' X_{it} + \varepsilon_{it} \varepsilon_{it} = \xi_t + \eta_{it},$$

where $1_{[A]}$ is an indicator function that is one if A is true, zero otherwise, and ξ_t is a (potential) common factor across all stocks. We calculate quartile means and event-effects based on the model estimates. Section II.A.3 describes the methodology in more detail. The pre-entry period runs from April 23 through May 21, 2004, post-entry 1 from August, 2 through August 30, 2004, and post-entry 2 from January 3 through January 31, 2005. For all four liquidity measures, we calculate the difference between the pre- and post-entry levels and add a "*/**" to the post-entry levels if these are significantly different at the 95%/99% level. In the test, we use standard errors that control for commonalities across stocks, heteroskedasticity, and nonzero stock-specific autocorrelation (see Section II.A.3).

	Post-Entry 1						Post-Entry 2					
	Spread		Depth0		Depth4		Spread		Depth0		Depth4	
	Consolidated	NSC	Consolidated	NSC	Consolidated	NSC	Consolidated	NSC	Consolidated	NSC	Consolidated	NSC
Change Q1 ($\theta 1$)	−1.16**	−0.13	0.56**	0.30**	6.00**	2.11**	−1.05**	−0.62	1.22**	0.90**	8.17**	6.25**
Rel. Change Q1[a]	−14.7%	−1.6%	46.3%	24.8%	77.8%	27.4%	−13.3%	−7.8%	100.8%	74.4%	106.0%	81.1%
Change Q2 ($\theta 2$)	−0.28	−0.05	0.65**	0.43	5.12**	2.49*	−1.88**	−1.74**	1.32*	1.21*	9.75**	7.88*
Rel. Change Q2[a]	−2.0%	−0.4%	48.1%	31.9%	66.0%	32.1%	−13.6%	−12.6%	97.8%	89.6%	125.6%	101.5%
Change Q3 ($\theta 3$)	3.49	3.79	0.33	0.24	2.92**	1.07	−1.74	−1.42	0.33	0.39	1.59	2.11
Rel. Change Q3[a]	16.3%	17.7%	35.5%	25.8%	50.0%	18.3%	−8.1%	−6.6%	35.5%	41.9%	27.2%	36.1%
Change Q4 ($\theta 4$)	3.11	3.21	0.57**	0.50*	2.90**	1.52*	−9.06**	−8.73**	0.51	0.50	1.54	3.43
Rel. Change Q4[a]	7.2%	7.4%	50.0%	43.9%	35.2%	18.5%	−20.8%	−20.1%	44.7%	43.9%	18.7%	41.7%
R^2	0.53	0.53	0.78	0.52	0.46	0.28	0.51	0.51	0.18	0.14	0.23	0.14
#Obs	920	920	920	920	920	920	920	920	920	920	920	920

[a] Relative to pre-entry levels.

*/** Significant at the 95%/99% significance level.

The strong increase in consolidated depth might not be an overall liquidity improvement if, at the same time, the bid-ask spread increases. Table III, however, indicates that the relative inside spread in the consolidated market (i.e., the best ask minus the best bid across both markets divided by the price level) is either significantly smaller or not significantly different in both post-entry periods. More importantly, the spread changes are economically small (one (five) basis point(s) in the first (second) post-entry period). Nevertheless, to account for variation in bid-ask spreads, we also calculate the price impact (from the midquote) of hypothetical market orders of various sizes that we execute against the consolidated limit order book (as smart routers would do). The average price impacts (not shown) are generally smaller after EuroSETS entry, which confirms that indeed the deeper books are associated with a reduction in trading costs.

NSC depth. Table III also documents the impact of EuroSETS entry on cumulative depth in NSC after controlling for volume, volatility, and price level changes (see Table II for the univariate results). In general, the findings for NSC depth are similar to those for consolidated depth. First, cumulative depth increases throughout the limit order book for all quartiles and for both post-entry periods. Second, in economic terms, the increase is substantial. For instance, for Q1 stocks, NSC depth increases by 24.8% in the first post-entry period and by 74.4% in the second post-entry period. Third, the change in NSC depth is statistically significant for Q1 and Q2 stocks and predominantly insignificant for Q3 and Q4 stocks.

Why does depth increase in NSC? Our sample periods are chosen so that the NSC fee structure is fixed throughout, but the pre-entry period starts when Euronext reduces its fee by 50% (April 23, 2004). NSC depth should therefore increase on April 23, 2004 and then decrease after EuroSETS entry. However, the effect of the fee cut may not fully materialize in the pre-entry period. In this case, the positive effect of the fee reduction in NSC can offset the negative effect of EuroSETS entry on NSC depth (as explained in Section I.B.1.). The reported increase in NSC depth is consistent with this interpretation, which suggests that the fee reduction on limit orders plays a role in our findings.

A lagged response to the Euronext fee reduction can also explain the moderate bid-ask spread decline *combined* with the substantial depth increase following EuroSETS entry. Indeed, in the model, a fee reduction can simultaneously trigger a spread decrease (see equation (5)) and a depth increase because it makes liquidity provision cheaper. To see this point, consider again the case in which the size of market orders has a uniform distribution with $\Delta = 0.01$, $\gamma = 0.4$, $c_E = 0.001$, and $\delta_I = 0.95$. The incumbent market charges an order entry fee equal to $c_I^b = 0.008$ before entry and $c_I^a = 0.003$ after entry. In this case, before entry, the (half) bid-ask spread is equal to two ticks (equation (5)) and the quoted depth represents 20% of the maximum order size. After entry, the bid-ask spread is equal to one tick and the quoted depth in the incumbent (consolidated) market represents 40% (52%) of the maximum order size (see numerical example 2).

Still, NSC depth might have decreased after entry if reduced hidden depth outweighs increased displayed depth. In this case, the price impact of market orders executed in NSC should be unchanged or even larger after entry. We measure price impacts on market orders by the effective spread, defined as twice the amount by which the average (volume-weighted) execution price of a buy (sell) market order exceeds (is below) the contemporaneous midquote. In the second post-entry period, we find a decrease in effective spreads in NSC (see Table II). For the first post-entry period, however, effective spreads in NSC are larger, but the increase is significant only for Q2 and Q4 stocks. Overall, the effective spread analysis does not suggest that the NSC depth increase reflects a substitution of hidden depth by displayed depth.

To sum up, following EuroSETS entry, consolidated depth has increased. This finding is consistent with the first main prediction of the model. In theory, the increase in consolidated depth can be due to both the queue-jumping effect and the fee reduction on limit orders following EuroSETS entry. The strong increase in NSC depth suggests that the fee reduction plays a significant role.

B.2. The Effect of Smart Routers on EuroSETS Liquidity Supply

Proxy for proportion of smart routers. We now test our cross-sectional prediction about the effect of smart routers on EuroSETS liquidity supply. To do so, we need a proxy for the proportion of smart routers in each stock. For a given stock, consider the case in which the entrant posts a strictly lower ask (higher bid) than the incumbent. Conditional on the arrival of a market buy (sell), the likelihood of observing a trade in the entrant market is equal to γ in the model. Thus, a proxy for this parameter is the proportion of market buys (sells) executed in EuroSETS when the ask (bid) is strictly worse in NSC. We denote this proxy by $\hat{\gamma}_1$ and we estimate it for each stock in each post-entry period.

Panel A of Table IV reports, for both post-entry periods, the average value of $\hat{\gamma}_1$ for the whole sample and for each quartile. On average, the proportion of smart routers is 27% (18%) in the first (second) post-entry period. Q1 stocks stand out with the highest proportion, 54% in both periods, as opposed to less than 23% for the other quartiles. We find a high positive correlation between $\hat{\gamma}_1$ and a dummy equal to one if the stock is cross-listed in the United States ($\rho = 0.63$ (0.44) for the first (second) post-entry period), as expected.

The proxy $\hat{\gamma}_1$ implicitly assumes that nonsmart routers never trade in the entrant market. In reality, they may occasionally check quotes in EuroSETS. If so, $\hat{\gamma}_1$ overestimates the proportion of smart routers (γ). Hence, for robustness, we propose a second proxy for γ. We use Probit to model the likelihood of observing a buy (sell) order executed in EuroSETS conditional on EuroSETS posting a strictly better ask (bid) price, as a function of variables that capture relevant market conditions (discussed below). We then use the likelihood of observing a trade in EuroSETS under very adverse conditions as a more conservative proxy for γ, denoted $\hat{\gamma}_2$. Intuitively, trades occurring in these

Table IV

Estimates for Smart Router Proportion (γ_i) and the Tie-Breaking Rule (δ)

This table reports estimates of the model's parameters: the proportion of smart routers (Panels A and B) and the tie-breaking rule (Panel C). For the smart router proportion, we condition on all transactions that execute at times of strictly better EuroSETS prices, that is, market buys on strictly lower EuroSETS asks and markets sells on strictly higher EuroSETS bids. For these transactions, the proportion that materializes on EuroSETS, $\hat{\gamma}_{1i}$, is a first proxy for smart router proportion. $\hat{\gamma}_{1i}$ might overstate the proportion of smart routers, as nonsmart routers might be willing, under some conditions, to incur the "search cost" of checking EuroSETS and (also) trade there if prices are better. To identify these conditions, we estimate a PROBIT model with a vector of explanatory variables X_{it} for trade t of stock i:

$$\gamma_{it} = \mathrm{P}_t[\text{Trade on EuroSETS}|\text{Strictly Better EuroSETS Quote}]$$
$$= \mathrm{E}[\alpha_i + \beta' X_{it} + \varepsilon_{it} > 0], \quad \varepsilon_{it} \sim \mathrm{IIN}(0, 1),$$

where α_i is a stock-specific dummy and X_{it} contains EuroSETS quoted depth, order size, the number of trades in the prior 10 minutes, and volatility based on the midquote high minus low in the prior 10 minutes. A more refined gamma estimate, $\hat{\gamma}_{2i}$, is the proportion of EuroSETS trades *conditional* on adverse market conditions for EuroSETS. We use the following *fixed* values for these factors: zero for EuroSETS quoted depth and the 0.90-quantile of the unconditional (full-sample) distribution of order size, the number of trades, and volatility:

$$\hat{\gamma}_{2i} = \hat{\gamma}_{it}(X_{it} = X^*) = \Phi(\hat{\alpha}_i + \hat{\beta}' X^*), \quad X^* = [0,\ Q_{0.90}(X_2),\ Q_{0.90}(X_3),\ Q_{0.90}(X_4)]',$$

where hats indicate coefficient estimates and $Q_{0.90}(.)$ indicates the 0.90-quantile of the unconditional (full-sample) distribution. Panel A reports both $\hat{\gamma}_{i1}$ and $\hat{\gamma}_{i2}$. Panel B reports the PROBIT coefficient estimates, t-values, the probability slope, which is the estimated change in probability for a one-unit change in the variable, the j^{th} variable average ($\bar{X}_j$), and the product of the last two to indicate economic significance. Panel C reports estimates of the tie-breaking rule, δ_I, which is the proportion of traders who start in the incumbent market when both markets are tied in terms of price. To identify δ_I, we condition on market buys (sells) at times that ask (bid) prices are equal across markets and further require that the order size be smaller than EuroSETS depth. The proportion of these orders (buy or sell) that execute on NSC identifies δ_I, as this proportion equals $\kappa = (1 - \hat{\gamma}) + \hat{\gamma}\delta_I$. In the calculations, we use $\hat{\gamma}_{1i}$ as our proxy for $\hat{\gamma}$.

Panel A: Overall and Quartile-Specific Estimate[a] of γ_i

	Post-Entry 1				Post-Entry 2			
	$\hat{\gamma}_{1i}$ Proportion EuroSETS Trades	$\hat{\gamma}_{2i}$ Proportion EuroSETS Trades for Adverse Market Conditions	$\sigma_{\hat{\gamma}_{2i}}$	#Obs	$\hat{\gamma}_{1i}$ Proportion EuroSETS Trades	$\hat{\gamma}_{2i}$ Proportion EuroSETS Trades for Adverse Market Conditions	$\sigma_{\hat{\gamma}_{2i}}$	#Obs
Q1	0.54	0.37	0.01	22,239	0.54	0.37	0.01	12,688
Q2	0.22	0.15	0.02	677	0.11	0.05	0.02	475
Q3	0.10	0.05	0.05	423	0.04	0.02	0.01	298
Q4	0.23	0.20	0.08	72	0.01	0.01	0.02	72
All	0.27	0.19	0.05	23,411	0.18	0.11	0.02	13,533
$\sigma_{\hat{\gamma}_i}$[b]	0.24	0.19			0.23	0.16		

Table IV—*Continued*

Panel B: Control Variable Coefficients

	Coef	t-value	P-Slope	$\bar{X}$	P-Slope*$\bar{X}$
Quoted Depth EuroSETS (€ 100,000)	0.211	26.27	0.084	0.984	0.082
Order Size[c] (€100,000)	−0.267	−23.80	−0.107	0.518	−0.055
#Trades in Prior 10 Minutes (1,000 trades)	−0.356	−2.08	−0.142	0.070	−0.010
Volatility[d] (basispoints)	−0.003	−7.86	−0.001	26.424	−0.030

Panel C: Estimates of the Tie-Breaking Rule Parameter (δ_I)

	Post-Entry 1					Post-Entry 2				
	Q1	Q2	Q3	Q4	All	Q1	Q2	Q3	Q4	All
$\hat{\kappa} = (1 - \hat{\gamma}_1) + \hat{\gamma}_1 \delta_I$	0.975	0.997	0.999	0.998	0.992	0.981	0.982	0.985	0.997	0.986
#Obs	80,911	15,383	4,552	1,860	102,706	129,957	7,989	2,539	653	141,138
$\hat{\delta}_I$	0.954	0.988	0.991	0.989	0.981	0.964	0.834	0.630	0.710	0.784
$\sigma(\hat{\delta}_I)$[e]	0.001	0.003	0.007	0.009	0.003	0.001	0.035	0.148	0.384	0.103

[a]The quartile-specific and overall estimate of γ_i is based on equally weighted averages over all stocks in the quartile and sample, respectively.
[b]Cross-sectional dispersion in the γ_i estimates.
[c]All transactions at the same second are aggregated into one order, as exchanges report orders running up the book as separate transactions.
[d]Volatility is defined as the maximum minus the minimum midquote in the previous 10 minutes scaled by the average midquote.
[e]We calculate an approximate standard error based on linearization, recognizing that both $\hat{\kappa}$ and $\hat{\gamma}_1$ are subject to estimation error.

conditions must come from traders who only pay attention to prices, that is, smart routers.

We expect brokers who handle orders manually to prefer executing orders in single trades (as opposed to splitting orders into multiple trades), and to suffer high opportunity cost of checking EuroSETS quotes in fast markets. The single-trade preference suggests considering EuroSETS depth at the best quote and trade size as explanatory variables in the Probit model. The opportunity cost argument suggests two additional explanatory variables that capture trade intensity, namely, the number of trades and volatility in the 10 minutes prior to submission of the market order.

The Probit estimates in Panel B of Table IV show that all explanatory variables are statistically significant and carry the expected sign. We use these estimates to calculate the likelihood of observing a market order routed to EuroSETS on strictly better EuroSETS quotes under very adverse conditions for EuroSETS (i.e., low depth in EuroSETS, a large market order, high trading activity). The estimates for this proxy, $\hat{\gamma}_2$, are reported in Panel A of Table IV (2[nd] column). By construction, $\hat{\gamma}_2$ is a conservative estimate relative to $\hat{\gamma}_1$ ($\hat{\gamma}_2 < \hat{\gamma}_1$), but it is clear from Table IV that the two proxies are highly correlated cross-sectionally.[19]

Smart routers and EuroSETS's contribution to liquidity supply. For each stock and each post-entry period, we compute the average "spread ratio" that is, the ratio of NSC spread to EuroSETS spread, and the average "depth ratio", that is, the ratio of the number of shares offered in EuroSETS to the total number of shares offered, both at the best consolidated ask. The model predicts that both ratios increase with the proportion of smart routers (Proposition 3). We test this prediction by running cross-sectional regressions in each post-entry period, where the dependent variable is either the depth or the spread ratio and the explanatory variables include the smart router proxy ($\hat{\gamma}_1$ or $\hat{\gamma}_2$) with and without volume and volatility as control variables.

The results in Table V are consistent with our predictions. For the spread ratio (Panel A), we find a significantly positive coefficient for both proxy $\hat{\gamma}_1$ and $\hat{\gamma}_2$. In the univariate regressions, we find that these proxies explain between 47% and 89% of the cross-sectional variation. The result is robust to adding volume and volatility as control variables. Hence, as implied by Proposition 3, EuroSETS quotes are more competitive for stocks for which the proportion of smart routers is large. For the depth ratio (Panel B), we also find that it is positively related to the proportion of smart routers, as predicted. For this ratio, however, the relationship is statistically significant only in the second post-entry period and the explanatory power is lower (the proxies explain between 10% and 63% of the cross-sectional variation).

Smart routers and consolidated depth. The relationship between the proportion of smart routers and consolidated depth cannot be signed unambiguously in the model. It is positive if δ_I is close to one, that is, if smart routers usually give priority to NSC when the markets are tied in terms of price. To estimate δ_I, consider all market buys (sells) that occur when (i) both the entrant and the incumbent are at the best consolidated ask and (ii) the entrant depth at the best ask is larger than the size of the trade. In our model, the fraction of these market orders that executes (at least partially) in the incumbent market is

$$\kappa = (1 - \gamma) + \gamma\delta_I. \tag{10}$$

Thus, the estimate of κ combined with our estimate of γ, say $\hat{\gamma}_1$, allows us to calculate δ_I.

Panel C of Table IV reports the δ_I estimates for all quartiles and both post-entry periods. We find that $\hat{\delta}_I$ is high, especially for the first post-entry period, where, for all quartiles, it exceeds 0.95. One possible reason is that NSC charges smaller fees on market orders than EuroSETS. In this case, if markets are tied

[19] Our approach requires the data feed for NSC and EuroSETS to be synchronized. Time latencies in trade and quote reporting in either market would bias our measures. This problem is unlikely as we use data from fully electronic markets and time stamps should therefore be accurate. However, as a robustness check, we also apply our method only to trades occurring when EuroSETS has a strictly better price than NSC for at least 20 seconds around the time of the trade. We obtain very similar estimates (omitted for brevity) for $\hat{\gamma}_1$ and $\hat{\gamma}_2$ as those reported in Table IV.

Table V

Can the Proportion of Smart Routers Explain EuroSETS's Share of Liquidity Cross-sectionally?

This table reports cross-sectional regressions that relate two measures of EuroSETS's share of liquidity to our two measures of the proportion of smart routers: $\hat{\gamma}_{1i}$ and $\hat{\gamma}_{2i}$. Panel A reports results for the first measure: the ratio of the time-weighted NSC spread and the EuroSETS spread. Panel B reports the results for the second measure: the ratio of EuroSETS depth at the best ask in the consolidated market (EuroSETS depth at this ask could, therefore, be zero) and total depth at the best ask in the consolidated market. In a second set of regressions, we add two control variables: average daily volume and annualized volatility. t-statistics are in brackets.

	Post-Entry 1 ($N = 21$)[a]					Post-Entry 2 ($N = 22$)				
	$\hat{\gamma}_{1i}$ Proportion EuroSETS Trades	$\hat{\gamma}_{2i}$ Proportion EuroSETS Trades for Adverse Market Conditions	Volume (€100,000)	Annualized Volatility (%)	R^2	$\hat{\gamma}_{1i}$ Proportion EuroSETS Trades	$\hat{\gamma}_{2i}$ Proportion EuroSETS Trades for Adverse Market Conditions	Volume (€100,000)	Annualized Volatility (%)	R^2
Panel A: Dependent Variable Is the Ratio of NSC Spread and EuroSETS Spread										
(1)	0.529**				0.60	1.018**				0.88
	(5.33)					(12.01)				
(2)		0.586**			0.47		1.452**			0.89
		(4.09)					(13.06)			
(3)	0.393**		0.001**	−0.004*	0.77	1.012**		0.000	0.003	0.89
	(4.23)		(2.17)	(−1.74)		(6.75)		(0.49)	(1.29)	
(4)		0.417**	0.001**	−0.004*	0.72		1.424**	0.000	0.002	0.90
		(3.45)	(2.68)	(−1.57)			(7.28)	(0.49)	(0.97)	
Panel B: Dependent Variable Is the Ratio of EuroSETS Depth and Consolidated Depth										
(1)	0.150*				0.14	0.254**				0.63
	(1.77)					(5.86)				
(2)		0.155			0.10		0.352**			0.61
		(1.42)					(5.55)			
(3)	0.093		0.000	−0.004*	0.34	0.203**		0.000	−0.002	0.68
	(1.02)		(0.59)	(−1.79)		(2.71)		(0.29)	(−1.51)	
(4)		0.088	0.000	−0.004*	0.32		0.269**	0.000	−0.002*	0.67
		(0.81)	(0.81)	(−1.76)			(2.57)	(0.40)	(−1.65)	

[a] For VRSA we do not have any transaction conditional on strictly better EuroSETS prices and therefore cannot identify $\hat{\gamma}_i$.

*/** Significant at the 90%/95% significance level.

in terms of quoted price, a router that optimizes based on net prices (i.e., net of fee) starts execution on NSC.[20]

As $\hat{\delta}_I$ is close to one, we expect to find a positive relationship between the effect of EuroSETS entry on consolidated depth at the best quotes (measured by θ_i in equation (6)) and the proportion of smart routers. The model also suggests that the magnitude of the effect of EuroSETS entry should be smaller for stocks with small relative tick sizes (as the queue-jumping effect is smaller in these stocks). We therefore regress the change in consolidated depth due to EuroSETS entry, that is, the θ_i estimate, on the proportion of smart routers with and without the price level as a control variable.

Table VI shows that the change in consolidated depth due to EuroSETS entry increases with the proportion of smart routers in the cross-section. This relationship is significant for depth at the best ask for both γ proxies and for both post-entry periods (see Panel A). The proportion of smart routers appears economically significant as it explains from 23% up to 39% of the cross-sectional variation in depth change. This finding is robust to the use of the price level as a control variable. Interestingly, as expected, there is an inverse and significant relationship between the change in consolidated depth due to EuroSETS entry and the stock price (i.e., the effect of EuroSETS entry is smaller for stocks with a small relative tick size).

The effect of smart routers on depth up to four ticks behind the best ask is also positive but not significant (see Panel B), maybe because limit order traders update their orders further into the book less frequently than at the best quotes.

We also find no significant cross-sectional relationship between the bid-ask spread in the consolidated market and the proportion of smart routers (see Panel C of Table VI). This is not surprising for two reasons. First, empirically, there is less cross-sectional variation in the bid-ask spread change as compared to the depth changes.[21] It is, therefore, more difficult to identify an effect of smart routers on the spread. Second, the model predicts a weak (negative) relationship between these two variables in the first place. To see this, recall that the consolidated (half) spread is equal to $2Min\{c_I, \frac{c_E}{\gamma}\}$ rounded up to the nearest tick on the grid (see equation (5)). Thus, the bid-ask spread is a decreasing step function of γ, that is, many values of γ yield the same level for the bid-ask spread.

EuroSETS liquidity share vs. EuroSETS market share. Our findings help us understand why EuroSETS market share is low compared to its share of liquidity supply. In theory, the entrant contribution to liquidity can be significant even if δ_I is large and γ is small, as we find (see numerical example 2). Yet, under these conditions, the likelihood of a trade occurring in EuroSETS is small. Suppose, for instance, that market orders execute only at the best quote (either

[20] In reality, it is unclear whether routing decisions are made based on raw or net prices as there are practical difficulties in building quote montages based on net prices (see McCleskey (2004) for a discussion). In the model, we ignore the fee on market orders, because in practice this fee per share is small compared to the tick size. Therefore, it only affects brokers' routing decisions when there is a tie.

[21] The standard deviation of the bid-ask spread change is 16% (19%) for the first (second) post-entry period vs. 26% (49%) for depth at the best ask.

Table VI

Can the Proportion of Smart Routers Explain Liquidity Change Cross-sectionally?

This table reports cross-sectional regressions that relate three measures of liquidity change—the bid-ask spread and two depth measures—to our two proxies of the proportion of smart routers: $\hat{\gamma}_{1i}$ and $\hat{\gamma}_{2i}$. We use the liquidity change on a stock-by-stock basis, where changes in volume, volatility, and price are controlled (see Table III for methodology). We add the average pre-entry price level to control for tick size. Panel A reports results for the change in depth at the best ask ("Depth0"). Panel B reports results for the change in cumulative depth up until four ticks behind the best ask ("Depth4"). Panel C reports results for the change in quoted bid-ask spread.

	Post-Entry 1 ($N = 21$)[a]				Post-Entry 2 ($N = 22$)			
	$\hat{\gamma}_{1i}$ Proportion EuroSETS Trades	$\hat{\gamma}_{2i}$ Proportion EuroSETS Trades for Adverse Market Conditions	Price[b] (€)	R^2	$\hat{\gamma}_{1i}$ Proportion EuroSETS Trades	$\hat{\gamma}_{2i}$ Proportion EuroSETS Trades for Adverse Market Conditions	Price[b] (€)	R^2
Panel A: Dependent Variable Is Depth at the Best Quote (€100,000)								
(1)	0.67**			0.39	1.08**			0.25
	(3.45)				(2.58)			
(2)		0.81**		0.36		1.46**		0.23
		(3.28)				(2.41)		
(3)	0.54**		−0.01**	0.60	1.43**		−0.03**	0.69
	(3.25)		(−3.11)		(5.00)		(−5.16)	
(4)		0.63**	−0.01**	0.56		1.94**	−0.03**	0.65
		(2.86)	(−2.89)			(4.55)	(−4.85)	
Panel B: Dependent Variable Is Cumulative Depth through Tick 4 (€100,000)								
(1)	0.01			0.00	0.53			0.03
	(0.04)				(0.73)			
(2)		0.03		0.00		0.52		0.01
		(0.08)				(0.5)		
(3)	0.12		0.01	0.08	0.47		0.00	0.03
	(0.36)		(1.27)		(0.62)		(0.33)	
(4)		0.19	0.01	0.09		0.42	0.01	0.02
		(0.46)	(1.3)			(0.39)	(0.38)	
Panel C: Dependent Variable Is the Quoted Bid-Ask Spread (in Basispoints)								
(1)	−0.08			0.02	0.22			0.07
	(−0.54)				(1.18)			
(2)		−0.06		0.00		0.30		0.06
		(−0.3)				(1.15)		
(3)	−0.20*		−0.01**	0.47	0.29		−0.01*	0.18
	(−1.69)		(−3.95)		(1.59)		(−1.66)	
(4)		−0.23	−0.01**	0.46		0.40	−0.01*	0.18
		(−1.49)	(−3.86)			(1.55)	(−1.64)	

[a]For VRSA we do not have any transaction conditional on strictly better EuroSETS prices and therefore cannot identify $\hat{\gamma}_i$.
[b]Average price in the pre-entry period.
*/**Significant at the 90%/95% significance level.

in NSC or in EuroSETS). This is a reasonable approximation as, in reality, a large fraction of orders does not walk up the book. Furthermore, suppose that there is a probability p_E^{strictly} (p_E^{jointly}) that the quotes in EuroSETS are better than or equal to those in NSC. In this case, the likelihood of observing a market order routed to EuroSETS is

$$p_E^{\text{strictly}}\gamma + p_E^{\text{jointly}}(1-\delta_I)\gamma.$$

Clearly, this likelihood is small when γ is small and δ_I is large, even if EuroSETS is frequently at the inside (i.e., $p_E^{\text{strictly}} + p_E^{\text{jointly}}$ is large). For instance, for Q1 stocks in the first post-entry period, we have $p_E^{\text{strictly}} \simeq 10\%$, $p_E^{\text{jointly}} \simeq 67\%$ (see Figure 2), $\gamma \simeq 54\%$, and $\delta_I \simeq 98\%$. Hence, the likelihood that EuroSETS is at the inside is 77%, yet the likelihood that it attracts a market order is $(0.10 \times 0.54 + 0.67 \times 0.02 \times 0.54) \times 100\% = 6.1\%$, which is very close to its actual market share (in number of trades) for Q1 stocks.

C. Implications for Trade-Through Regulation

Trade-throughs occur when a trade executes in one market at a price worse than the best consolidated price. Thus, in our analysis, $(1-\hat{\gamma}_1)$ is the trade-through rate at the expense of EuroSETS. Regulation NMS has specific provisions for preventing the occurrence of trade-throughs in the U.S. equity markets. These provisions have been much debated and we now discuss the implications of our findings for this controversy.

In our study, the average trade-through rate is 73% in the first post-entry period and 77% in the second period (see Table IV). These levels are high relative to those reported for the U.S. equity market. For instance, Bessembinder (2003) finds an average trade-through rate of 1.5% for trades in exchange listed stocks with sizes smaller than quoted depth. This is not surprising as trade-throughs are prohibited in the U.S. equity market, but not in the Dutch equity market.[22] More specifically, in the United States, trading venues that participate in the Intermarket Trading System (ITS) must reroute incoming market orders to the market posting the best quote. The "Order Protection Rule" in Regulation NMS extends this requirement to all quotations accessible for automatic execution (e.g., those in Nasdaq). The main rationale for this rule is that trade-throughs discourage liquidity provision, as stressed by the SEC in its 2005 release on Regulation NMS (p. 36):

> Price protection encourages the display of limit orders by increasing the likelihood that they will receive an execution in a timely manner and helping preserve investors' expectations that their orders will be executed when they represent the best displayed quotation.

[22] Guidelines provided by the Dutch regulator require brokers in the Dutch market to consider all venues they have access to at the time of execution, unless they have strong reason not to (e.g., very high automation cost). Thus, in practice, brokers can claim high automation cost as an excuse for not checking EuroSETS quotes.

This reasoning is similar to the economic intuition behind Proposition 3 and is supported by our empirical findings. Indeed, we find a positive and significant relationship between EuroSETS's contribution to liquidity and $\hat{\gamma}_1$. Thus, liquidity provision in EuroSETS is negatively related to the trade-through rate *at the expense of this market*.

Regulation NMS advocates the development of intermarket linkages to avoid trade-throughs. Stoll (2006) suggests instead using smart routing technologies to integrate fragmented markets. Our findings suggest one obstacle. In deciding to use smart routing technologies, brokers trade off the reduction in expected trading costs with the cost of developing a smart router. We find that entrant liquidity supply increases with the proportion of smart routers (γ). Thus, each broker's decision to adopt a smart routing system strengthens the benefit of being a smart router for the remaining brokers. This positive externality creates a coordination problem among brokers that results in two types of self-fulfilling equilibria, namely, a high- and a low-intensity competition equilibrium.[23] In the high-intensity competition equilibrium, many brokers invest in smart routers because they expect large reductions in trading costs and these reductions are indeed large, as many brokers are smart routers. In the low-intensity equilibrium, few brokers invest in smart routers as the expected gains are small and the gains are indeed small as few brokers are smart routers.

The large trade-through rate in our experiment suggests that EuroSETS and NSC are indeed locked in this low-intensity competition equilibrium in which the benefits of smart routing are small. To estimate these benefits, we identify all buy (sell) orders routed to NSC that execute at an average price strictly larger (smaller) than the contemporaneous best ask (bid) in EuroSETS. For each of these orders, we compute the difference between (i) the average execution price of the market order and (ii) the average price that could have been achieved by executing the market order against the consolidated limit order book. This difference times the size of the order is the opportunity cost of ignoring EuroSETS quotes for these trades. We refer to them as generalized trade-throughs, as they include regular trade-throughs but also orders walking up the book in NSC, while a better price is posted in EuroSETS.

Our data only allow us to find a lower bound for total opportunity cost as, in continuous time, we only have the top of the book for EuroSETS, and we do not observe hidden depth in EuroSETS.

Table VII reports a monthly estimate of the opportunity cost of generalized trade-throughs in our sample, before and after subtracting additional trading fees (based on fee schedules released by EuroSETS and NSC). The opportunity cost net of trading fees is smaller, as, generally, the fees on market orders are smaller in NSC.[24] The findings show that the opportunity cost for Q1 shares is much higher than for any of the other quartiles. For example, in the first

[23] In the model, this claim can be established by adding a stage in which brokers can choose, at a cost, to adopt a smart router just after the introduction of the entrant market.

[24] As NSC charges smaller fees on market orders, our identification of generalized trade-throughs based on raw prices may misclassify trades. For instance, EuroSETS can have a strictly lower ask, yet trading at this price might not be optimal as the execution fee might be higher. Hence, in

Table VII

Lower Bound Opportunity Cost of Nonsmart Routers

This table reports estimates of the monthly opportunity cost for NSC-only traders based on generalized trade-throughs. We screen all market orders executed on NSC and, ex post, reallocate (part of) the order to EuroSETS to optimize execution. The table reports both gross savings and the savings net of execution fee. These fees are retrieved from documents released by the LSE and Euronext. For instance, for a median-sized market order (1,500 shares) in a median-price stock (€15), the NSC fee is about €0.0006 per share for a broker submitting less than 60,000 orders per month. This is half the fee that EuroSETS charges on a similar order. We also calculate the total savings if we reallocate optimally *net* of execution fees and find that the results are similar (less than 0.2% difference) and therefore decide not to report them here. Post-entry 1 runs from August 2 through August 30, 2004 and post-entry 2 from January 3 through January 31, 2005.

	Post-Entry 1					Post-Entry 2				
	Q1	Q2	Q3	Q4	All	Q1	Q2	Q3	Q4	All
# Sub-Optimal Orders	16,374	1,172	769	185	18,500	10,691	657	514	212	12,074
Fraction of Total	0.07	0.01	0.01	0.01	0.04	0.04	0.01	0.01	0.01	0.02
Monthly Savings[a] (€1,000)	313	39	24	8	385	172	17	11	9	208
Monthly Net Savings[a] (€1,000)	271	37	23	8	338	143	16	10	9	177

[a]We miss three days in post-entry 1 and one day in post-entry 2. We use appropriate scaling factors to estimate the amount for the full 21 trading days.

post-entry period, the opportunity cost net of fees is equal to €271,000 for Q1 stocks and is less than €40,000 for stocks in the other quartiles. This finding stems from a much larger number of generalized trade-throughs for Q1 stocks. The small number of generalized trade-throughs in the other quartiles (about 1%) reflects the smaller presence of EuroSETS at the best quotes for these quartiles. It does not follow that prohibiting trade-throughs would have little effects for stocks in these quartiles. Rather, the logic of Proposition 3 (and the empirical findings in Table IV) suggests that it is actually the high likelihood of being traded-through that discourages aggressive quoting in these stocks.

On a per-order basis, the average net cost of a generalized trade-through is €18.27 and €14.66 for the first and second post-entry period, respectively. It is very likely that this cost is spread over a large number of brokerage firms. Moreover, the opportunities to use smart routers are still few in the European equity market, as it is little fragmented. Hence, for a single firm, the cost savings associated with smart routing technology appear small, consistent with the idea that EuroSETS and NSC are trapped in a low-intensity competition equilibrium.

Switching from a low- to a high-intensity competition equilibrium is difficult as brokers' evaluation of smart order routing systems is based on current market conditions, not those that would prevail if they could coordinate to all use smart routers. In line with this idea, we find no decline in the trade-through

addition to identifying generalized trade-throughs based on raw prices, we also repeat the analysis with net prices. Findings are very similar (because the tick size is large relative to the fee per share) and omitted for brevity.

rate when comparing the first and the second post-entry period (see Table IV). In such a case, regulatory intervention (or threat thereof) might be needed to coordinate brokerage firms on the high-intensity competition equilibrium (see Dybvig and Spatt (1983) for the role of regulation in solving coordination problems). For instance, Battalio et al. (2004) show that trade-throughs decreased considerably across United States' option markets between June 2000 and January 2002, when these markets were under strong pressures from the SEC to develop intermarket linkages enforcing price priority.

III. Conclusion

We study the introduction of a new limit order market, EuroSETS, in the Dutch equity market to test various hypotheses about the effect of market fragmentation. Prior to EuroSETS entry, trading in Dutch stocks was largely centralized in NSC, a limit order market operated by Euronext. Our testable hypotheses derive from a model in which liquidity suppliers trade off their revenue in case of execution with order submission costs, as in Parlour and Seppi (2003) or Seppi (1997). Our main findings are as follows.

First, the consolidated limit order book is significantly deeper after EuroSETS entry. This finding is consistent with the model in which the introduction of a new limit order market intensifies competition among limit order traders and thereby reduces liquidity providers' rents. This reduction results in smaller trading costs (a deeper market) for liquidity demanders.

Second, NSC depth is larger after EuroSETS entry. This finding is surprising as the introduction of EuroSETS means a loss of order flow for NSC and, therefore, a smaller execution probability for a limit order in this market. However, Euronext responded to EuroSETS entry with a fee reduction on limit orders. As shown in the model, such reduction leads to a depth improvement in the incumbent market, which might more than offset the depth decrease due to the loss of order flow to the entrant market. The observed increase in NSC depth therefore suggests a strong elasticity of liquidity provision to fees charged by exchanges.

Third, we examine the cross-sectional relationship between liquidity supply in EuroSETS and trade-throughs at the expense of this market. The model predicts a negative relationship as an increase in trade-throughs reduces the likelihood of execution for limit orders in EuroSETS. The empirical evidence supports this prediction as we find that (i) the ratio of the NSC and the EuroSETS bid-ask spreads, and (ii) the fraction of quoted depth contributed by EuroSETS are both inversely related to the trade-through rate.

The third finding implies that limit order traders care about execution probabilities and that protecting them against trade-troughs is important. Given the features of the Dutch equity market, we interpret trade-throughs as being due to a lack of automation of routing decisions. Prior to EuroSETS entry, smart order routing systems were not necessary as trading was essentially centralized in NSC. After entry, the benefit of using smart routers is not large because limit orders in EuroSETS are not aggressive enough. But the lack of automation might actually be the reason that limit orders are less aggressive in EuroSETS. This chicken and egg problem is likely to be more severe in markets where there is no installed base of smart routers. This is the case in the European equity market because it has traditionally been little fragmented. In such a situation, trade-through prohibitions are important as they lessen barriers to entry in the provision of trading services and help to integrate competing markets.

Our findings identify one benefit of intermarket competition: It improves consolidated depth because, as the model suggests, it intensifies competition among liquidity providers and forces market organizers to cut their fees. However, it does not immediately follow that intermarket competition is always good because market fragmentation has some costs. First, in our model, intermarket competition hurts nonsmart routers when it leads to a decline in the incumbent market cumulative depth. Second, it reduces liquidity providers' total expected profits. In some situations, this effect could trigger an exit of some liquidity providers (an effect that is absent in the model) and reduce liquidity. Future work should study this possibility in more detail. Last, as shown in several papers (e.g., Pagano (1989)), market fragmentation diminishes welfare in the presence of participation externalities. Whether the advent of smart routing technologies, which considerably diminish the cost of multimarket participation, reduces the importance of participation externalities is another interesting question for future research.

As is usual in the literature on competition for order flow (e.g., Chowdhry and Nanda (1991) or Parlour and Seppi (2003)), we focus on traders' decisions given the trading rules and the trading fees of competing markets. This is appropriate as traders know these variables when they make their decisions. However, a complete analysis of intermarket competition requires the market structure that competing exchanges choose be endogenized. Such an analysis could help us understand under which conditions markets choose to differentiate their trading systems and their fees. This is important as competing markets often have different trading rules and serve clienteles with different needs.

Appendix A. Proofs

Proof of Proposition 1:

Part 1. We show that market I is dominant iff $\gamma \leq \gamma^*$. In this case, $S^*_{Ek} = 0, \forall k$. This situation is an equilibrium if and only if the following conditions are satisfied (see conditions (4) in the main text)

$$\gamma\left(\delta_E \bar{F}\left(Q^*_{Ik-1}\right) + \delta_I \bar{F}\left(Q^*_{Ik}\right)\right) \leq \frac{2c_E}{(p_k - \mu)}, \forall k \geq 1. \tag{A1}$$

$$\bar{F}\left(Q^*_{Ik}\right) = \frac{2c_I}{(p_k - \mu)}, k \geq 1. \tag{A2}$$

Substituting the last expression in equation (A1), we deduce that an equilibrium in which market I dominates obtains if and only if

$$\gamma\left(\delta_E+\frac{2\delta_I c_I}{(p_1-\mu)}\right)\le\frac{c_E}{(p_1-\mu)}\,, \tag{A3}$$

$$\text{and } \gamma\left(\frac{\delta_E c_I}{(p_{k-1}-\mu)}+\frac{\delta_I c_I}{(p_k-\mu)}\right)\le\frac{c_E}{(p_k-\mu)},\ \forall k\ge 2. \tag{A4}$$

Let γ_1 and γ_2 be such that

$$\gamma_1\equiv\frac{2c_E}{2\delta_I c_I+(1-\delta_I)\Delta}\text{ and }\gamma_2\equiv\frac{c_E}{(2-\delta_I)c_I}. \tag{A5}$$

Condition (A3) is equivalent to $\gamma\le\gamma_1$ and condition (A4) is equivalent to $\gamma\le\gamma_2$. We deduce that an equilibrium in which market I dominates can be sustained iff

$$\gamma\le\gamma^*=\text{Min}\{\gamma_1,\gamma_2\}. \tag{A6}$$

Part 2. We deduce (from Part 1) that market I cannot dominate when $\gamma^*<\gamma<1$. This leaves us with two possibilities: (a) either market E dominates or (b) both markets coexist. If market E dominates, then in equilibrium $Q^*_{Ik}=0, Q^*_k=Q^*_{Ek}$ and (see conditions (4) in the main text):

$$(1-\gamma)+\gamma\left(\delta_I\bar{F}\left(Q^*_{Ek-1}\right)+\delta_E\bar{F}\left(Q^*_{Ek}\right)\right)\le\frac{2c_I}{(p_k-\mu)}. \tag{A7}$$

Using the fact that $\bar{F}(Q^*_{Ek})=\frac{2c_E}{\gamma(p_k-\mu)}$ for $k\ge 1$ if $S^*_{Ij}=0,\forall j\le k$, we rewrite condition (A7) as

$$(1-\gamma)+\frac{2\delta_I c_E}{(p_{k-1}-\mu)}+\frac{2\delta_E c_E}{(p_k-\mu)}\le\frac{2c_I}{(p_k-\mu)}\text{ for }k\ge 2, \tag{A8}$$

$$\text{and }(1-\gamma)+\gamma\delta_I+\frac{2\delta_E c_E}{(p_1-\mu)}\le\frac{2c_I}{(p_1-\mu)}\quad\text{for }\ k=1. \tag{A9}$$

When $\gamma=1$, inequalities (A8) and (A9) are satisfied if and only if

$$c_E\le\frac{c_I}{1+\delta_I},\qquad\text{and}\qquad 2c_E\le\frac{2c_I-\delta_I\Delta}{1-\delta_I}. \tag{A10}$$

Thus, when $\gamma=1$, market E dominates in equilibrium iff $c_E\le\text{Min}\{\frac{c_I}{1+\delta_I},\frac{2c_I-\delta_I\Delta}{2(1-\delta_I)}\}$. By symmetry, we deduce that market I dominates iff $c_I\le\text{Min}\{\frac{c_E}{1+\delta_E},\frac{c_E-\delta_E\Delta}{2(1-\delta_E)}\}$ or, equivalently, market I dominates iff $c_E\ge\text{Max}\{(2-\delta_I)c_I,\delta_I c_I+\frac{(1-\delta_I)\Delta}{2}\}$. We deduce from these observations that, when $\gamma=1$, the two markets coexist iff $c_E\in(c^*_E,c^{**}_E)$.

When $\gamma<1$, the left-hand side of inequality (A7) is strictly greater than zero. The right-hand side of inequality (A7) decreases with k and goes to zero as k becomes large. Thus, we conclude that when $\gamma < 1$, there always exists a finite value $k_0(\gamma)$ such that inequality (A7) does not hold for $k \geq k_0(\gamma)$. Using conditions (A8) and (A9), it is easily shown that $k_0(\gamma) = 1$ iff $\gamma \leq \gamma_3$ and that $k_0(\gamma)$ weakly increases with γ for $\gamma > \gamma_3$, where $\gamma_3 \equiv \frac{\Delta - 2c_I + 2(1-\delta_I)c_E}{(1-\delta_I)\Delta}$. This means that condition (A7) cannot be satisfied for all k when $\gamma < 1$ and, therefore, market E cannot dominate in this case.

Part 3. Additional Remarks. If $\text{Min}\{\gamma_1, \gamma_2\} < \gamma < 1$, the two markets coexist. In this case limit orders are posted at price p_1 in at least one of the two markets (as $2c_I < \Delta$), but not necessarily in both markets. Let $a_j^*(\gamma)$ be the best ask price in market j. From Part 2 we know that $a_I^*(\gamma) = p_{k_0(\gamma)}$. Moreover, we know that (i) $k_0(\gamma) = 1$ if $\gamma < \gamma_3$, (ii) $k_0(\gamma) > 1$ if $\gamma \geq \gamma_3$, and (iii) $\frac{\partial k_0(\gamma)}{\partial \gamma} \geq 0$. We deduce that (i) $a_I^*(\gamma) = p_1$ for $\gamma \leq \gamma_3$, (ii) $a_I^*(\gamma) > p_1$ for $\gamma > \gamma_3$, and (iii) $\frac{\partial a_I^*(\gamma)}{\partial \gamma} \geq 0$. It is also easily shown that (i) $\gamma > \gamma_1$ is a sufficient and necessary condition for $S_{E1}^* > 0$ and that (ii) $\gamma_2 < \gamma < \gamma_1$ is a sufficient and necessary condition for $S_{E1}^* = 0$ and $S_{E2}^* > 0$. We deduce that $a_E^*(\gamma) = p_1$ if $\gamma > \gamma_1$ and $a_E^*(\gamma) = p_2$ if $\gamma_2 < \gamma < \gamma_1$ (this interval is empty if $\gamma_1 < \gamma_2$). Last, we observe that $a_I^*(\gamma) = a_E^*(\gamma) = p_1$ for $\gamma_1 < \gamma < \gamma_3$. Q.E.D.

Proof of Proposition 2:

Part 1. When exchange I operates alone, the consolidated depth up to price p_k, $Q_k^*(0)$, solves

$$\bar{F}\left(Q_k^*(0)\right) = \frac{2c_I}{(p_k - \mu)}. \tag{A11}$$

We have $Q_k^*(0) > 0, \forall k \in [1, m]$, since $2c_I < p_k - \mu, \forall k$.

Part 2. When the two markets coexist, there exists $k \leq m$ such that $S_{Ek}^* > 0$. Let k_0 be the smallest integer such that this inequality holds true. For $k < k_0$, the equilibrium cumulative depth in the incumbent market solves (see conditions (4) in the main text):

$$\bar{F}\left(Q_{Ik}^*(\gamma)\right) = \frac{2c_I}{(p_k - \mu)}. \tag{A12}$$

Thus, $Q_{Ik}^*(\gamma) = Q_k^*(0)$ (see equation (A11)) for $k < k_0$. Moreover, as $S_{Ek}^* = 0$ for $k < k_0$, we have $Q_k^*(\gamma) = Q_{Ik}^*(\gamma)$ for $k < k_0$. Hence, $Q_k^*(\gamma) = Q_k^*(0)$ for $k < k_0$. For $k \geq k_0$, equilibrium conditions impose:

$$(1-\gamma)\bar{F}\left(Q_{Ik}^*(\gamma)\right) + \gamma\left(\delta_I \bar{F}\left(Q_{k-1}^*(\gamma) + S_{Ik}^*(\gamma)\right) + \delta_E \bar{F}\left(Q_k^*(\gamma)\right)\right) \leq \frac{2c_I}{(p_k - \mu)}. \tag{A13}$$

As $S_{Ek_0}^*(\gamma) > 0$ and $Q_{k_0-1}^*(\gamma) = Q_{Ik_0-1}^*(\gamma)$, we have

$$Q_{Ik_0}^*(\gamma) = Q_{k_0-1}^*(\gamma) + S_{Ik_0}^*(\gamma) < Q_{k_0}^*(\gamma). \tag{A14}$$

Thus, for $k \geq k_0$,

$$Q^*_{Ik}(\gamma) < Q^*_k(\gamma), \tag{A15}$$

because $Q^*_k(\gamma) = Q^*_{Ik}(\gamma) + Q^*_{Ek}(\gamma)$ and $Q^*_{Ek}(\gamma) > 0$ (since $S^*_{Ek_0}(\gamma) > 0$). But then, as $\bar{F}(.)$ decreases and $\delta_E = 1 - \delta_I$, condition (A13) imposes

$$\bar{F}\big(Q^*_k(\gamma)\big) < \frac{2c_I}{(p_k - \mu)} < \bar{F}\big(Q^*_{Ik}(\gamma)\big),\ \forall k \geq k_0, \tag{A16}$$

which can be rewritten (using equation (A11)) as

$$\bar{F}\big(Q^*_k(\gamma)\big) < \bar{F}\big(Q^*_k(0)\big) < \bar{F}\big(Q^*_{Ik}(\gamma)\big),\ \forall k \geq k_0. \tag{A17}$$

As $\bar{F}(.)$ decreases, this implies $Q^*_k(\gamma) > Q^*_k(0) > Q^*_{Ik}(\gamma)$ for $k \geq k_0$. Thus, $Q^*_k(\gamma) \geq Q^*_k(0) \geq Q^*_{Ik}(\gamma)$ with a strict inequality for $k \geq k_0$. Q.E.D.

Proof of Proposition 3:

Part 1. We have $R^s(\gamma) < 1$ when $a^*_E(\gamma) > a^*_I(\gamma)$, that is, when $S^*_{E1} = 0$. Moreover, the ratio $R^s(\gamma)$ is well defined iff the two markets coexist. These two requirements (the two markets coexist and $S^*_{E1} = 0$) are satisfied iff $\gamma_2 \leq \gamma \leq \gamma_1$, where the thresholds γ_1 and γ_2 are defined in the proof of Proposition 1. In this interval, $a^*_E(\gamma) = p_2$ and $a^*_I(\gamma) = p_1$ (see Part 3 in the proof of Proposition 1). Hence, $R^s(\gamma) = 0.5$ for $\gamma_2 \leq \gamma \leq \gamma_1$. We have $R^s(\gamma) > 1$ when $a^*_E(\gamma) < a^*_I(\gamma)$, that is, when $S^*_{I1} = 0$. This occurs iff $\gamma_3 \leq \gamma \leq 1$ (see Part 3 of the proof of Proposition 1). In this case, the smallest offer at which some limit orders are posted in market I, $a^*_I(\gamma)$ (weakly) increases in γ and $a^*_E(\gamma) = p_1$ (see Part 3 in the proof of Proposition 1). Thus, $R^s(\gamma)$ (weakly) increases in γ for $\gamma \geq \gamma_3$. To sum up: (i) $R^s(\gamma) = 0.5$ when $\gamma_2 \leq \gamma \leq \gamma_1$, (ii) $R^s(\gamma) = 1$ when $\gamma_1 < \gamma < \gamma_3$, and (iii) $R^s(\gamma) > 1$ and $\frac{\partial R^s}{\partial \gamma} \geq 0$ when $\gamma_3 \leq \gamma < 1$. Hence, $R^s(\gamma)$ increases with γ when the two markets coexist. Cases (i) or (iii) may not happen as the conditions $\gamma_2 < \gamma_1$ or $\gamma_3 < 1$ are not satisfied for all values of the parameters.

Part 2. By definition

$$R^d(\gamma) \equiv \frac{Q^*_{E1}(\gamma)}{Q^*_{E1}(\gamma) + Q^*_{I1}(\gamma)}. \tag{A18}$$

Part 1 of this proof implies that (i) $R^d(\gamma) = 0$ when $\gamma_2 < \gamma < \gamma_1$ and (ii) $R^d(\gamma) = 1$ when $\gamma_3 < \gamma < 1$. Moreover, we prove below that $\frac{\partial Q^*_{E1}(\gamma)}{\partial \gamma} > 0$ and $\frac{\partial Q^*_{I1}(\gamma)}{\partial \gamma} < 0$ for $\gamma \in [\gamma_1, \gamma_3]$. Overall, this implies $\frac{\partial R^d(\gamma)}{\partial \gamma} \geq 0$.

When $\gamma \in [\gamma_1, \gamma_3]$, $Q^*_{E1}(\gamma) > 0$ and $Q^*_{I1}(\gamma) > 0$. Thus, the equilibrium conditions impose

$$(1-\gamma)\bar{F}\big(Q^*_{I1}(\gamma)\big) + \gamma\big(\delta_I \bar{F}\big(Q^*_{I1}(\gamma)\big) + \delta_E \bar{F}\big(Q^*_1(\gamma)\big)\big) = \frac{2c_I}{(p_k - \mu)}, \tag{A19}$$

and

$$\gamma\left(\delta_E \bar{F}\left(Q^*_{E1}(\gamma)\right) + \delta_I \bar{F}\left(Q^*_1(\gamma)\right)\right) = \frac{2c_E}{(p_1-\mu)}. \tag{A20}$$

By differentiating these conditions with respect to γ, we obtain

$$\delta_E\left(\bar{F}\left(Q^*_1(\gamma)\right) - \bar{F}\left(Q^*_{I1}(\gamma)\right)\right) + \left((1-\gamma\delta_E)\frac{\partial \bar{F}(Q^*_{I1})}{\partial x}\frac{\partial Q^*_{I1}}{\partial \gamma} + \gamma\delta_E \frac{\partial \bar{F}(Q^*_1)}{\partial x}\frac{\partial Q^*_1}{\partial \gamma}\right) = 0, \tag{A21}$$

$$\frac{2c_E}{\gamma(p_1-\mu)} + \gamma\left[(1-\delta_I)\frac{\partial \bar{F}(Q^*_{E1})}{\partial x}\frac{\partial Q^*_{E1}}{\partial \gamma} + \delta_I \frac{\partial \bar{F}(Q^*_1)}{\partial x}\frac{\partial Q^*_1}{\partial \gamma}\right] = 0. \tag{A22}$$

Equation (A21) implies that $\frac{\partial Q^*_1}{\partial \gamma} > 0$ and $\frac{\partial Q^*_{I1}}{\partial \gamma} \geq 0$ is impossible since $\bar{F}(Q^*_1(\gamma)) - \bar{F}(Q^*_{I1}(\gamma)) < 0$ and $\frac{\partial \bar{F}(x)}{\partial x} < 0$. Now suppose (to be contradicted) that $\frac{\partial Q^*_{E1}(\gamma)}{\partial \gamma} \leq 0$. In this case, equation (A22) implies that $\frac{\partial Q^*_1}{\partial \gamma} > 0$ (as $\frac{\partial \bar{F}(x)}{\partial x} < 0$). But then $\frac{\partial Q^*_{I1}}{\partial \gamma} \geq 0$ since $\frac{\partial Q^*_{E1}(\gamma)}{\partial \gamma} \leq 0$, which leads to a contradiction. We conclude that in equilibrium, $\frac{\partial Q^*_{E1}(\gamma)}{\partial \gamma} > 0$. Hence, $\frac{\partial Q^*_{I1}(\gamma)}{\partial \gamma} < 0$ since $\frac{\partial Q^*_1}{\partial \gamma} > 0$ and $\frac{\partial Q^*_{I1}}{\partial \gamma} \geq 0$ is impossible. Q.E.D.

Proof of Proposition 4: Consider a value of γ such that both markets are active at the best quotes (i.e., $\gamma \in [\gamma_1, \gamma_3]$; for other values quoted depth is independent of γ or increases in γ). For these values, the equilibrium conditions impose (see equation (A22)):

$$\frac{2c_E}{\gamma(p_1-\mu)} + \gamma\left[(1-\delta_I)\frac{\partial \bar{F}(Q^*_{E1})}{\partial x}\frac{\partial Q^*_{E1}}{\partial \gamma} + \delta_I \frac{\partial \bar{F}(Q^*_1)}{\partial x}\frac{\partial Q^*_1}{\partial \gamma}\right] = 0. \tag{A23}$$

Thus, in equilibrium, we have that

$$\frac{\partial Q^*_1}{\partial \gamma} = -\frac{\dfrac{2c_E}{\gamma(p_1-\mu)} + \gamma(1-\delta_I)\dfrac{\partial \bar{F}(Q^*_{E1})}{\partial x}\dfrac{\partial Q^*_{E1}}{\partial \gamma}}{\gamma\delta_I \dfrac{\partial \bar{F}(Q^*_1)}{\partial x}}. \tag{A24}$$

As $\frac{\partial \bar{F}}{\partial x} < 0$, we deduce that $\frac{\partial Q^*_1}{\partial \gamma} > 0$ if

$$\delta_I > \delta^*_I = 1 + \frac{\dfrac{2c_E}{(p_1-\mu)}}{\left(\dfrac{\partial \bar{F}(Q^*_{E1})}{\partial x}\dfrac{\partial Q^*_{E1}}{\partial \gamma}\right)\gamma^2}. \tag{A25}$$

Observe that $\delta^*_I < 1$ since $\frac{\partial \bar{F}}{\partial x} < 0$ and $\frac{\partial Q^*_{E1}}{\partial \gamma} > 0$. Q.E.D.

Appendix B. Composition of Quartiles

This appendix presents the composition of quartiles with stock names, codes, volume, and market capitalization. We start with the 25 AEX index stocks and eliminate Unilever as it exceeds the €50 bound where Euronext tick size changes. We further remove Gucci as it drops from the index on May 5, 2004, and Numico as it cancels its ADR program on July 22, 2004. The remaining 22 stocks are ranked based on out-of-sample 2003 volume to ensure an exogenous ranking.

	Name	Euronext Code	2003 Volume (bln €)	2004 Volume (bln €)	2004 Market Cap (bln €)
Q1	Royal Dutch	RDA	73.2	83.5	85.2
	ING Group	INGA	43.8	46.9	38.9
	Philips	PHIA	39.6	42.2	29.9
	ABN AMRO	AABA	32.7	32.8	29.8
	Aegon	AGN	25.7	23.8	16.2
	Fortis	FORA	19.1	19.3	23.2
Q2	ASML	ASML	18.7	27.2	6.45
	Ahold	AH	17.8	14.6	9.66
	KPN	KPN	17.4	18.7	14.6
	AKZO Nobel	AKZA	8.6	8.3	8.53
	Heineken	HEIA	8.4	7.3	14.7
	Reed Elsevier	REN	7.7	7.8	8.55
Q3	VNU	VNUA	7.0	7.1	5.86
	DSM	DSM	5.6	5.3	3.98
	Wolters Kluwer	WKL	5.3	4.5	4.09
	TPG	TPG	5.3	7.4	8.63
	Getronics	GTN	1.9	5.1	1.13
Q4	IHC Caland	IHC	1.8	2.4	1.29
	Versatel	VRSA	1.4	3.9	0.89
	Hagemeijer	HGM	1.3	3.5	0.92
	Buhrmann	BUHR	1.4	1.7	1.00
	Van der Moolen	MOO	1.1	0.5	0.25

REFERENCES

Barclay, Michael J., Terrence Hendershott, and Timothy D. McCormick, 2003, Competition among trading venues: Information and trading on electronic communications networks, *Journal of Finance* 58, 2637–2666.

Battalio, Robert, 1997, Third market broker-dealers: Cost competitors or cream-skimmers, *Journal of Finance* 52, 241–252.

Battalio, Robert, Brian Hatch, and Robert H. Jennings, 2004, Towards a National Market System for U.S. exchange-listed equity options, *Journal of Finance* 54, 933–962.

Bessembinder, Hendrik, 2003, Quote-based competition and trade execution costs in NYSE-listed stocks, *Journal of Financial Economics* 70, 385–422.

Biais, Bruno, Christophe Bisière, and Chester Spatt, 2004, Imperfect competition in financial markets, Working paper, Toulouse University.

Bloch, Ernest, and Robert A. Schwartz, 1978, The great debate over NYSE rule 390, *Journal of Portfolio Management* Fall, 5–8.

Board, John, and Stephen Wells, 2000, Liquidity and best execution in the U.K.: A comparison of SETS and Tradepoint, Working paper, Financial Markets Group.

Boehmer, Beatrice, and Ekkehart Boehmer, 2004, Trading your neighbor's ETFs: Competition or fragmentation, *Journal of Banking and Finance* 27, 1667–1703.

Chowdhry, Bhagwan, and Vikram Nanda, 1991, Multimarket trading and market liquidity, *Review of Financial Studies* 4, 483–511.

DeFontnouvelle, Patrick, Raymond P.H. Fishe, and Jeffrey H. Harris, 2003, The behavior of bid-ask spreads and volume in options markets during the competition for listings in 1999, *Journal of Finance* 58, 2437–2464.

Dybvig, Philip H., and Chester S. Spatt, 1983, Adoption externalities as public good, *Journal of Public Economics* 20, 231–247.

Fink, Jason D., Kristin Fink, and James P. Weston, 2004, Competition on the Nasdaq and the growth of electronic communication networks, Working paper, Rice University.

Glosten, Lawrence R., 1994, Is the electronic order book inevitable? *Journal of Finance* 49, 1127–1161.

Glosten, Lawrence R., 1998, Competition, design of exchanges and welfare, Working paper, Columbia University.

Hallam, Nicholas, and Nick Idelson, 2003, Breaking the barriers: A technological study of the obstacles to a pan-European best execution in equities, Working paper, Tradeserve.

Hamilton, James L., 1979, Marketplace fragmentation, competition, and the efficiency of the stock exchange, *Journal of Finance* 34, 171–187.

Harris, Lawrence E., 1990, *Liquidity, Trading Rules, and Electronic Trading Systems*, Salomon Brothers Center for the Study of Financial Institutions, Monograph series in Finance, New York University, New York.

Hendershott, Terrence, and Charles M. Jones, 2005a, Trade-through prohibitions and market quality, *Journal of Financial Markets* 8, 1–23.

Hendershott, Terrence, and Charles M. Jones, 2005b, Island goes dark: Transparency, fragmentation, and regulation, *Review of Financial Studies* 18, 743–793.

Hendershott, Terrence, and Haim Mendelson, 2000, Crossing networks and dealer markets: competition and performance, *Journal of Finance* 55, 2071–2115.

Mayhew, Stewart, 2002, Competition, market structure and bid-ask spreads in stock option markets, *Journal of Finance* 57, 931–958.

McCleskey, Scott, 2004, *Achieving Market Integration* (Elsevier Finance, London).

Mendelson, Haim, 1987, Consolidation, fragmentation, and market performance, *Journal of Financial and Quantitative Analysis* 22, 189–207.

Pagano, Marco, 1989, Trading volume and asset liquidity, *Quarterly Journal of Economics* 104, 255–274.

Parlour, Christine A., and Duane J. Seppi, 2003, Liquidity-based competition for order flow, *Review of Financial Studies* 16, 301–343.

Petersen, Mitchell A., 2005, Estimating standard errors in finance panel data sets: Comparing approaches, Working paper, Northwestern University.

Seppi, Duane J., 1997, Liquidity provision with limit orders and a strategic specialist, *Review of Financial Studies* 10, 103–150.

Securities and Exchange Commission Release No. 34-42459, Request for comment on issues relating to market fragmentation, 2000.

Securities and Exchange Commission, Release No. 34-51808, Regulation NMS, 2005.

Stoll, Hans R., 2006, Electronic trading in stock markets, *Journal of Economic Perspectives* 20, 153–174.

Viswanathan, S., and James J.D. Wang, 2002, Market architecture: Limit order books vs. dealership markets, *Journal of Financial Markets* 5, 127–168.