Over-the-Counter versus Limit-Order Markets: The Role of Traders' Expertise

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Over-the-counter (OTC) markets attract substantial trading volume despite exhibiting frictions absent in centralized limit-order markets. We compare the efficiency of OTC and limit-order markets when traders' expertise is endogenous. We show that asymmetric access to counterparties in OTC markets yields increased rents from expertise acquisition for a few well-connected core traders. When the existence of gains to trade is uncertain, traders' higher expertise in OTC markets can improve allocative efficiency. In contrast, when expertise primarily causes adverse selection, competitive limit-order markets tend to dominate. Our model provides guidance for policy makers and empiricists evaluating the efficiency of market structures. (*JEL* D82, G23, L10)

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Many important asset classes, such as bonds, complex derivatives, and real estate, are primarily traded in over-the-counter (OTC) markets. Yet these markets are often regarded as inefficient and inferior to centralized limit-order markets.[1] From a policy perspective, the prevalence of OTC markets is even more troubling when viewed through the lens of standard models of OTC trading, which feature search frictions or incomplete networks. In these models, technology is typically the culprit; that is, if traders had immediate access to

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[1] For specific examples, see Financial Economists Roundtable (2010, 2015), Gensler (2011), Jackson and Miller (2013), or Schecter (2015).

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all potential counterparties, trade would be efficient.[2] However, technological limitations alone hardly can be the reason for the prevalence of OTC markets, as limit-order books have long been available and can be operated electronically at low cost.

In this paper, we compare the efficiency of OTC markets to that of centralized limit-order markets when traders' expertise is endogenous. In the context of our model, expertise acquisition refers to a trader's or institution's ex ante investments in specialized infrastructure yielding information relevant for valuing a given class of assets. We find that endogenizing traders' expertise yields important implications for the relative merits of these two market structures, and sheds light on the reasons for OTC markets' continued prevalence. To capture the above-discussed frictions, our model postulates that traders in the OTC market have asymmetric access to counterparties, implying that order flow is disproportionally directed to a small subset of well-connected core traders. In contrast, in the limit-order market, traders compete for incoming orders symmetrically. These differences in market structure have clear implications for ex ante expertise choices. Reduced competition in the OTC market yields increased rents to expertise acquisition for the subset of well-connected core traders receiving most of the order flow.[3] In contrast, stronger competition in the limit-order market reduces each individual trader's rents from expertise, especially when the number of competing traders is large. Moreover, the OTC market tends to avoid effort duplication. Whereas, in a limit-order market, multiple traders incur expertise acquisition costs to possibly gain the same information, information production in the OTC market is undertaken by the central counterparties, thereby reducing inefficient duplication.

OTC markets' increased incentives for expertise acquisition can be useful or harmful for allocative efficiency, depending on a specific transaction's economic context. In particular, when it is a priori uncertain whether transactions generate positive economic surplus, expertise is essential for gauging which transactions are efficiency enhancing. In this case, OTC markets may improve allocative efficiency by providing greater incentives for expertise acquisition to a subset of individuals or financial institutions. Expertise acquisition is, however, harmful when the surplus created by transactions tends to be known and the sole benefit of acquiring expertise is to gain information rents by adversely selecting other market participants. When this latter channel dominates, competitive limit-order markets may promote greater efficiency by reducing traders' incentives for socially wasteful expertise acquisition. Our analysis thus echoes concerns that market power in OTC

2 In our literature review, we also highlight exceptions to this common result.

3 The notion that traders in OTC markets have heterogeneous expertise is consistent with empirical evidence. See, for example, Green, Hollifield, and Schürhoff (2007) for municipal bonds, Hollifield, Neklyudov, and Spatt (2017) for securitized products, Jiang and Sun (2015) for corporate bonds, and Menkhoff et al. (2016) for foreign exchange instruments.

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markets can lead to inefficient rent seeking behavior, and highlights the merits of competitive markets in preventing this type of behavior. However, the implications of limited competition in OTC markets depend more generally on the nature of the information that tends to be produced for a given class of transactions. Correspondingly, our analysis points out important limitations of studies comparing trade efficiency across markets without accounting for the endogeneity of traders' information sets. In particular, we show that common empirical measures of trade efficiency such as bid-ask spreads and volume provide little information about efficiency when expertise is endogenous and necessary for ascertaining whether transactions generate positive economic surplus.

Our model compares OTC and limit-order markets in an environment reminiscent of Glosten and Milgrom (1985) and Glosten (1989) where an uninformed liquidity provider quotes ultimatum prices to several potentially informed traders. In Glosten and Milgrom (1985) and Glosten (1989), these traders arrive one at a time, in a random order, and each trader must choose whether to accept the terms of trade posted by the liquidity provider before the next trader arrives. In our model, we alter traders' arrival process to differentiate the market structures. In the centralized limit-order market, all traders arrive at the same time and the "liquidity provider" (i.e., an uninformed seller) quotes an ultimatum price.[4] The fact that multiple buyers simultaneously compete for the seller's quote affects their incentives to acquire information. In the OTC market, buyers instead arrive sequentially and the seller makes quotes bilaterally, that is, quotes are exclusive to the counterparty being contacted at the time. Whereas a first buyer can be contacted quickly, contacting subsequent buyers delays the realization of the surplus from trade. These delays in buyer arrival and, possibly, in the realization of the trade surplus cause efficiency losses (due to liquidity and immediacy concerns) absent from the centralized limit-order market. Like in Glosten (1989), the liquidity provider (i.e., seller) has market power, implying that his strategic pricing decisions may lead to inefficient rationing and thereby affect which market structure dominates.[5] In this setting, trade delays associated with OTC markets mechanically lower efficiency when prices and expertise are taken as given. However, as highlighted above, a key point of our paper is to analyze how these variables are affected by the market structure.

[4] This particular trading protocol for the limit-order market is also used by Jovanovic and Menkveld (2015), except when they allow for the presence of high-frequency middlemen.

[5] The notion that a few traders may benefit from market power even when trading is centralized through a limit-order book is consistent with empirical evidence by Sandås (2001) and Hollifield, Miller, and Sandås (2004), among others. The fact that traders do not act as price takers is also consistent with empirical evidence that a few large players account for a significant fraction of the trading volume of the assets currently traded in OTC markets. See, for example, Hendershott et al. (2019) and Li and Schürhoff (2019) for municipal bonds; Di Maggio, Kermani, and Song (2017) for corporate bonds; Atkeson, Eisfeldt, and Weill (2013), Begenau, Piazzesi, and Schneider (2015), and Siriwardane (forthcoming) for credit and interest-rate derivatives; and King, Osler, and Rime (2012) for foreign exchange instruments.

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Given the ambiguous role of expertise in determining the efficiency of trade, our model draws a nuanced picture of the relative merits of OTC and limit-order markets. While OTC markets provide greater incentives for expertise acquisition by a subset of core traders, this effect is desirable only when expertise primarily helps ascertain whether transactions generate positive economic surplus. In the context of secondary market transactions, expertise is, for example, required to accurately estimate an institution's shadow value of liquidity as well as a transaction's implications for taxes, risk sharing, asset-liability matching, and regulatory compliance. In the context of primary markets (e.g., VC funding, initial public offerings [IPOs], and follow-on offerings), investors' expertise may help determine whether a project or firm should be funded, that is, if capital injections generate positive surplus.[6] On the other hand, expertise acquisition is harmful when it primarily creates adverse-selection problems. For example, traders might spend resources to access earnings information just before it is publicly released, and this type of expertise acquisition harms efficiency by both taking up scarce resources (e.g., traders' human capital) and reducing market liquidity. These results suggest that the OTC market structure can have positive allocative effects in the context of transactions involving securities that are primarily traded for trader-specific hedging, liquidity, and inventory motives, and where expertise helps ascertain the existence of gains from trade between market participants. Examples of such securities may include safe bonds and customized derivatives. In contrast, the centralized limit-order market yields advantages in transactions in which traders would primarily use expertise to seek rents by adversely selecting other market participants. These concerns, in turn, may be particularly relevant in transactions involving stocks or standardized derivatives like corporate call options.

By focusing on how limited access to counterparties affects traders' expertise acquisition, our paper greatly differs from market microstructure papers where the costs and benefits of (de)centralized trading are determined by liquidity externalities (Admati and Pfleiderer 1988; Grossman and Miller 1988; Pagano 1989; Malamud and Rostek 2017; Babus and Parlatore 2018), the flexibility of discriminatory pricing (Biais, Foucault, and Salanié 1998; Viswanathan and Wang 2002), and counterparty risk (Duffie and Zhu 2011; Acharya and Bisin 2014).

Our paper is closer to the information-based market microstructure models of Seppi (1990), Grossman (1992), Biais (1993), and Zhu (2012). Seppi (1990) studies the existence of dynamic equilibria where a trader prefers to submit a large order to a dealer, outside of an exchange, rather than a sequence of small market orders to an exchange. Central to this result is the assumption

6 See, for example, Bond, Edmans, and Goldstein (2012) for a review of the literature on the real effects of financial markets and Binsbergen and Opp (forthcoming) for quantitative estimates of aggregate real surplus losses associated with informational inefficiencies.

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that the dealer knows the identity of his counterparties, which allows for the implementation of dynamic commitment strategies not possible in anonymous centralized markets. Grossman (1992) studies an upstairs (i.e., decentralized) market that features dealers who possess information about unexpressed demand unknown to the traders in the downstairs (i.e., centralized) market. Biais (1993) studies market structures that differ in terms of "transparency" when traders have private information about their inventories.[7] Like us, Zhu (2012) models decentralized trading as a sequence of ultimatum bargaining interactions with multiple counterparties. However, his focus is on the impact that repeated contacts have on the dynamics of trade, whereas in our model each potential counterparty can be only contacted once, implying that the "ringing phone curse" central in Zhu (2012) does not play a role. While Seppi (1990), Grossman (1992), Biais (1993), and Zhu (2012) all assume that some traders are exogenously endowed with private information, our paper shows how OTC and limit-order markets provide traders with different incentives to acquire private information, which in turn affects the efficiency of trade. In the spirit of the literature showing that security design can help alleviate trading inefficiencies associated with information acquisition at the origination stage (see, e.g., Dang, Gorton, and Holmström 2015; Yang forthcoming), our paper shows that trading *existing* securities in centralized limit-order markets also limits information acquisition, improving efficiency in asset classes where adverse selection may be a primary concern.

Our paper also relates to the literature on auctions with endogenous participation (e.g., McAfee and McMillan 1987; Levin and Smith 1994; Menezes and Monteiro 2000). This literature highlights the tension a seller might face when designing a trading mechanism: mechanisms that allow a seller to extract large rents ex post are associated with low participation rates ex ante. Instead of modeling buyers' decision to acquire expertise like in our paper, these papers model buyers' simultaneous decision to pay a participation cost in order to bid for an asset. Participation and information acquisition are then combined into a unique binary decision, which implies that all buyers who decide to participate are exogenously endowed with information about the value of the asset. This assumption differs from our model where a buyer's expertise is a continuous choice variable and buyers who decide not to acquire any expertise can still participate in the market, where their payoffs are affected by other buyers' expertise choices. Thus, buyers choose the level of expertise that maximizes their continuous payoff function (which always depends on other buyers' expertise levels and on relevant economic parameters, such as the distribution of asset values). In contrast, in these other papers, buyers solely compare the payoff from entering the market, net of the participation

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7 See also Pagano and Röell (1996), de Frutos and Manzano (2002), and Yin (2005), who study the impact of transparency on market liquidity in settings similar to that in Biais (1993), but allow for adverse selection, generalized risk aversion, and search costs, respectively.

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cost, to the payoff from not participating (which does not depend on other buyers' expertise levels or on any economic parameters). The differential implications of participation and expertise acquisition are also particularly evident in cases in which traders are likely to acquire information about an asset's common value component (rather than about gains from trade). For those cases, our analysis emphasizes that a limit-order market with many competing traders and low expertise levels dominates an OTC market with a small set of well-connected informed traders. Competition between a large set of traders is then beneficial for efficiency, because information acquisition is harmful.

Like in the literature mentioned above, Fishman (1988) and Bulow and Klemperer (2009) model prospective buyers who must pay a cost to enter the market and bid on an asset sold by a seller. Paying this cost is also associated with receiving an informative signal about the value of the asset, implying that all agents trying to buy the asset are informed. But, unlike the literature above, the decision to pay this cost is made sequentially by prospective buyers, and, thus, early bids inform subsequent buyers' decision to enter the market (see also Compte and Jehiel 2007; Roberts and Sweeting 2013). While this timeline is natural in the context of corporate takeovers, as argued by Fishman (1988), it is less so in the context of financial markets, where acquiring valuation expertise (by purchasing and analyzing data, hiring and training employees, etc.) requires significantly more time than the time available to respond to a quote. For this reason, our model instead assumes that any expertise acquisition occurs *prior* to the trading stage such that the "preemptive bidding" central in Fishman (1988) and Bulow and Klemperer (2009) does not play a role in determining buyers' decisions to acquire expertise.[8] In Bulow and Klemperer (2009), this preemptive bidding allows a market structure with sequential entry and bidding to socially dominate an auction with simultaneous entry and bidding. In contrast, our model highlights how the efficiency benefits of decentralized OTC trading greatly depend on the type of information expertise produces. Our model thus yields "cross-sectional" predictions that can shed light on why different asset classes tend to be traded in different types of markets.

The insight that the efficiency implications of decentralized markets vary starkly with the nature of expertise also distinguishes our paper from Kirilenko (2000) and Sherman (2005), who compare trading arrangements popular in foreign exchange markets and in IPO markets, respectively, but only for the case in which information is about the fundamental value of the asset and the market designer's objective is to maximize price informativeness.

[8] Preemptive bidding occurs when an early bidder offers a price that is high enough to deter any other prospective buyer from paying a fixed cost and entering the bidding process. See also Hirshleifer and Png (1989), Spatt (1989), and Daniel and Hirshleifer (2018).

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1. Model

In this section, we formally describe the environment we study in this paper.

1.1 Agents and assets

The owner of an asset considers selling it to one of $n \geq 2$ prospective buyers. Each agent i is risk neutral and values the asset as the sum of two components: $v_i = v + b_i$. The common value component v equally affects the utility of all traders, is distributed according to a continuous and differentiable cumulative distribution function (CDF) F_v, and has a mean value denoted by μ_v. This value component captures, for example, the fundamental cash flow of the asset. The private-value component b_i is normalized to zero for the seller and takes the value b for all buyers, where b has the continuous and differentiable CDF F_b and an unconditional mean value of μ_b. Thus, the variable b represents the gains from trade between the seller, on the one hand, and the buyers, on the other. This specification may, for example, capture cases in which buyers face common outside opportunities for investing their liquidity, common regulatory constraints and hedging motives, or common shocks to customer demand for a particular security.[9] From a modeling perspective this environment with common ex post valuations across buyers is appealing as it eliminates incentives for retrade between buyers, thus allowing us to better focus on the main channel of this paper. Yet we will show in Section 4 that our main insights carry over to the case in which the gains from trade b_i are uncorrelated across buyers, possibly capturing trader-specific liquidity and inventory concerns as well as buyers' idiosyncratic (rather than common) opportunities for retrade.

1.2 Information sets

All traders know the ex ante distributions of v and b_i. We will consider two distinct scenarios to cleanly differentiate the beneficial versus harmful effects of expertise acquisition by the seller's counterparties. In *Scenario 1*, buyers can obtain private information about the gains to trade, as captured by the realized value of b, prior to trade occurring. In *Scenario 2*, buyers can instead obtain private information about the asset's common value component, as captured by the realized value of v. Naturally, in practice, many important transactions feature the potential for both types of private information. Yet the objective of our qualitative analysis is to cleanly isolate the distinct effects that these different types of expertise have on the benefits of each market structure. We will discuss in Section 4 the implications of intermediate cases in which buyers can choose to acquire either types of private information.

[9] For example, a low value for b would obtain when buyers' future outside opportunities for using liquidity are particularly good, implying that their current excess liquidity is low and investing in the seller's asset is thereby relatively less beneficial. See also Section 5, where we further discuss empirical interpretations of the value components v and b_i.

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In our model, expertise acquisition aims to capture low-frequency adjustments to a financial institution's technology and labor that require investments ex ante, before a particular quote for an asset is obtained. To emphasize this ex ante nature of traders' investments, we use the term "expertise acquisition" instead of "information acquisition," the latter of which might occur on short notice provided that expertise is already in place. For example, expertise might be acquired by a broker-dealer when hiring highly talented traders, investing in IT infrastructure and proprietary data, or establishing a large base of retail customers yielding information about retrade opportunities (e.g., because of retail clients' specific tax treatment or life-cycle hedging needs). Such expertise cannot be acquired quickly, after an offer is received, but rather has to be acquired ex ante to ensure that the institution can respond to a new quote on the spot. Thus, we specify the timeline for acquiring expertise as follows: before trading occurs, each buyer i must decide how much expertise $\pi_i \in [0,1]$ he acquires at a cost $c(\pi_i)$, and expertise π_i is then formally defined as the probability with which buyer i receives an informative signal s_i prior to trading. Under Scenario 1, a signal reveals the realized value of b to buyer i, whereas under Scenario 2, it instead reveals the realized value of v. Traders do not observe each others' investments in expertise (i.e., their choice of π_i), and do not observe whether other traders did, in fact, obtain an informative signal ex post.[10]

1.3 Market structures

While the number of prospective buyers n is a fundamental of the economy, how easily the seller can trade with them depends on the market structure. In the centralized limit-order market, the seller posts a limit-order price that is simultaneously available to all buyers (just like in Jovanovic and Menkveld 2015). If several buyers accept to pay the posted price, then one buyer is randomly chosen to participate in the trade.[11]

In contrast, in the decentralized OTC market, the various buyers have *asymmetric* prospects of receiving offers from the seller. Buyers are contacted sequentially, in a predictable order, and each offer is made exclusively to one buyer at a time. Buyers' position in the seller's network (i.e., as first, second, ..., nth buyer) is known in advance by all agents. This feature allows our model to capture the significant persistence and predictability of OTC interactions documented by Hagströmer and Menkveld (2016), Di Maggio, Kermani, and Song (2017), Hendershott et al. (2019), and Li and Schürhoff (2019), among others. In that sense, the first buyer may be viewed as a "core" counterparty who is well-known to the seller and can be contacted quickly,

10 Going forward, when interpreting the costs of expertise acquisition, it will be useful to bear in mind that we normalized the volume of assets for sale to one. Thus, the magnitude of expertise costs should be interpreted as measured *relative* to the volume of assets for sale.

11 We discuss the robustness of our theoretical results to alternative models of centralized trading in Section 4.

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whereas the second, third, etc., buyers are more "peripheral" and might be more difficult to locate and contact for the seller. While the order in which buyers are contacted is deterministic in our baseline model, we will analyze in Section 4 a case in which this order is imperfectly predictable.

In the OTC market, the seller first contacts buyer $i=1$ and quotes a price p_1. If this price is accepted, trade occurs at that price, but if it is rejected, the seller tries to contact buyer $i=2$. Contacting this second buyer quickly enough to realize gains to trade is possible only with probability ρ, which captures immediacy or liquidity concerns (Grossman and Miller 1988; Chacko, Jurek, and Stafford 2008; Nagel 2012) that may emanate while unsuccessfully trying to locate the next viable buyer (Ashcraft and Duffie 2007; Green, Hollifield, and Schürhoff 2007; Feldhütter 2012). More generally, the possibility that gains to trade may be lost in the process of searching for a buyer can "proxy for delays associated with reaching an awareness of trading opportunities, arranging financing and meeting suitable legal restrictions, negotiating trades, executing trades, and so on" as argued by Duffie (2012, p. 28). If realizing the gains to trade was still possible but buyer i rejected the seller's quote, then the seller tries to contact buyer $(i+1)$ (and again only succeeds with probability ρ, conditional on trying to contact buyer $(i+1)$), and so on. If trade fails with all n buyers, the seller is confined to keeping the asset and any potential surplus from trade is lost.

As is common in the literature (e.g., Glosten 1989; Jovanovic and Menkveld 2015; Glode and Opp 2016), the agent lacking private information (here the seller) is assumed to quote publicly observable ultimatum prices to potentially informed counterparties. This trading protocol eliminates, in either type of market, signaling concerns that are generally associated with multiple equilibria in trading games.[12] Moreover, assuming sequential and exclusive ultimatum offers in the OTC market simplifies the analysis of equilibrium bidding strategies and is consistent with the characterization of inter-dealer trading in financial markets by Viswanathan and Wang (2004, p. 3) as "very quick interactions." Ultimatum offers are also consistent with how Duffie (2012, p. 2) describes the negotiation process in OTC markets and the notion that a typical OTC dealer tries to maintain "a reputation for standing firm on its original quotes." These offers imply that the seller strategically quotes prices to maximize the private rents he can extract from his counterparties, potentially jeopardizing the realization of gains from trade. The seller's pricing behavior, in turn, also influences buyers' ex ante incentives for expertise acquisition.

1.4 Benchmark case: Symmetric information

Before proceeding to our main analysis of Scenarios 1 and 2, we briefly discuss a benchmark case in which all agents are symmetrically informed. Specifically, suppose that with probability $\bar{\pi}$ a public signal is released and informs all

12 Publicly observable prices ensure that price opacity is not a concern in OTC markets, allowing us to focus on the implications of the few key differences across market structures that this paper aims to highlight.

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agents about the realizations of v and b. Regardless of whether he is contacting the buyers simultaneously (i.e., in a limit-order market) or sequentially (i.e., in an OTC market), the seller maximizes his profit by quoting a price $p=v+b$ when the public signal reveals that $b \geq 0$. When no public signal is released and $\mu_b \geq 0$, the seller optimally quotes a price $p=\mu_v+\mu_b$. In all other cases, the seller optimally retains the asset. In both types of markets, the expected total surplus from trade is fully appropriated by the seller and is equal to

$$\tilde{\pi} \cdot [1-F_b(0)] \cdot \mathbb{E}[b|b \geq 0]+(1-\tilde{\pi}) \cdot \mu_b \cdot \mathbf{1}_{\{\mu_b \geq 0\}}. \quad (1)$$

Thus, if $c(\tilde{\pi})$ denotes the cost of generating this public signal, the marginal net effect of expertise acquisition on total surplus is simply given by

$$[1-F_b(0)] \cdot \mathbb{E}[b|b \geq 0]-\mu_b \cdot \mathbf{1}_{\{\mu_b \geq 0\}}-c'(\tilde{\pi}). \quad (2)$$

This expression highlights an important distinction between information about the gains to trade b, on the one hand, and information about the common value component v, on the other. Learning the realization of b is socially valuable, because it allows agents to condition trade on whether the surplus from trade is positive ($b \geq 0$), instead of solely relying on the ex ante mean μ_b (see also Scenario 1, studied in Section 2). In particular, when the ex ante mean of the gains to trade is not positive ($\mu_b \leq 0$), expertise acquisition is essential to generating any positive surplus from trade. On the other hand, learning the common value component v is not informative about the gains from trade and therefore does not improve allocative efficiency (see also Scenario 2, studied in Section 3).

2. Private Information about the Gains to Trade

In this section, we analyze the model under Scenario 1, where buyers' expertise yields signals about b, the magnitude of the gains to trade between the seller and the buyers. Analyzing a setting in which most of the private information relates to traders' private valuations might shed light on which market structure dominates for highly rated municipal and corporate bonds (where cash-flow uncertainty is typically low), or for certain types of risky securities, like currencies, for which it is relatively more difficult to obtain nonpublic information about cash flows.

2.1 Limit-order market

We first analyze the equilibrium outcomes for the centralized limit-order market, where the seller posts a price that can be accepted by any of the n prospective buyers. Using backward induction, we first characterize buyers' willingness to pay for the asset, given the information they have received. Second, we analyze the seller's optimal pricing decision, given buyers' conjectured expertise levels. Third, we analyze buyers' optimal ex ante expertise acquisition. Throughout, we focus on symmetric equilibria in

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the limit-order market, where all buyers optimally choose the same level of expertise $\pi_i = \pi$. We provide a formal equilibrium definition at the end of this subsection.

2.1.1 Buyers' willingness to pay. A buyer's willingness to pay for the asset is given by his expectation of v_i conditional on receiving the asset after agreeing to a posted limit-order quote. Under Scenario 1, traders do not obtain private information about the common value component v, and thus all traders evaluate v at its expected value μ_v. A buyer who received an informative signal knows the realization of b and simply assigns the value $(\mu_v + b)$ to the asset. In contrast, a buyer who did not receive a signal, a case we denote by $s = \emptyset$, must consider the possibility that he is being adversely selected by other potentially informed buyers.

Let $B(x, y, q)$ denote the binomial probability distribution function (PDF) of observing y successes out of x independent trials when the success probability of each trial is q. Given our focus on symmetric equilibria, we drop subscripts and denote by π the symmetric expertise level chosen by all buyers. Moreover, we use p to denote the limit-order price that the seller quotes.

A buyer's willingness to pay, after receiving a signal $s \in \{\emptyset, b\}$, then can be written as follows:

$$w(s) = \begin{cases} \mu_v + b, & \text{for } s = b, \\ \mu_v + \dfrac{\sum_{m=0}^{n-1} B(n-1, m, \pi)\left(\frac{F_b(p-\mu_v)}{1+\mathbf{1}_u(n-m-1)}\mathbb{E}[b|b<p-\mu_v] + \frac{(1-F_b(p-\mu_v))}{1+m+\mathbf{1}_u(n-m-1)}\mathbb{E}[b|b \geq p-\mu_v]\right)}{\sum_{m=0}^{n-1} B(n-1, m, \pi)\left(\frac{F_b(p-\mu_v)}{1+\mathbf{1}_u(n-m-1)} + \frac{(1-F_b(p-\mu_v))}{1+m+\mathbf{1}_u(n-m-1)}\right)}, & \text{for } s = \emptyset, \end{cases} \tag{3}$$

where $\mathbf{1}_u$ represents an indicator function that takes the value 1 if the buyer expects all other uninformed buyers to agree to the posted price p, and 0 otherwise. The first case in Equation (3) corresponds to the outcome that the buyer has received a signal revealing the value component b. In contrast, the second case in Equation (3) corresponds to the outcome that the buyer has not received a signal and thus has to account for the fact that he is more likely to receive the asset when informed buyers chose not to pick up the seller's limit order (i.e., when $\mu_v + b < p$ or, equivalently, $b < p - \mu_v$). The associated adverse-selection discount therefore depends on the distribution over the number of informed buyers in the market (i.e., $B(n-1, m, \pi)$, where m denotes the number of informed buyers) and on the associated probabilities with which the buyer obtains the asset given the likelihoods with which informed and uninformed buyers are willing to pay the posted price p (as captured by $(1 - F_b(p - \mu_v))$ and $\mathbf{1}_u$, respectively).

In our analysis below, we will repeatedly consider parameterizations where $b \sim N(\mu_b, \sigma_b)$, in which case the following closed-form solutions are available for the terms involving truncated expectations in Equation (3):

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$$\mathbb{E}[b|b<p-\mu_v]=\mu_b-\sigma_b^2\frac{f_b(p-\mu_v)}{F_b(p-\mu_v)}, \tag{4}$$

$$\mathbb{E}[b|b>p-\mu_v]=\mu_b+\sigma_b^2\frac{f_b(p-\mu_v)}{1-F_b(p-\mu_v)}. \tag{5}$$

It is also useful to define the probability with which a buyer rejects a price p conditional on being informed and conditional on being uninformed, respectively, as

$$F_{w|b}(p)=F_b(p-\mu_v), \tag{6}$$

$$F_{w|\emptyset}(p)=\mathbf{1}_{\{p>w(\emptyset)\}}, \tag{7}$$

where the strict inequality in the indicator function in Equation (7) presumes that a buyer agrees to pay a price quote equal to his willingness to pay.

2.1.2 Seller's pricing decision. As stated above, the seller does not observe each buyer's expertise or whether a buyer, in fact, obtained an informative signal ex post. Thus, the seller forms beliefs about buyers' symmetric expertise levels π and the corresponding distribution of informed and uninformed buyers in the market. In particular, when choosing a price p, the seller is concerned with the distribution of the *maximum* willingness to pay among buyers in the market, which we denote by $w_{\max}$. Anticipating an expertise level π, the probability with which a price p is rejected by all buyers in the market (i.e., $w_{\max}<p$) is given by

$$F_{w_{\max}}(p)=\pi^n F_{w|b}(p)+(1-\pi)^n F_{w|\emptyset}(p) \\ +(1-\pi^n-(1-\pi)^n)\min[F_{w|b}(p),F_{w|\emptyset}(p)]. \tag{8}$$

Equation (8) reflects three relevant cases: (1) only informed buyers are in the market, (2) only uninformed buyers are in the market, and (3) both informed and uninformed buyers are in the market.

The seller posts a price p that maximizes his expected payoff:

$$\Pi(p)=[1-F_{w_{\max}}(p)]\cdot p+F_{w_{\max}}(p)\cdot\mu_v. \tag{9}$$

With probability $[1-F_{w_{\max}}(p)]$, trade takes place and the seller collects the price p. With complementary probability $F_{w_{\max}}(p)$, the seller retains the asset, which he values at μ_v. While the distribution $F_{w_{\max}}(p)$ features a point mass at $w(\emptyset)$, it is continuous and differentiable for all $p\neq w(\emptyset)$. Thus, for $p\neq w(\emptyset)$, we can derive the *marginal* net benefit of increasing the price p as

$$\Pi'(p)=1-F_{w_{\max}}(p)-f_{w_{\max}}(p)\cdot(p-\mu_v). \tag{10}$$

This latter equation nicely illustrates the seller's trade-off between a higher price and a lower probability of trade. Marginally increasing the price yields

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higher revenues from included buyer types, $[1-F_{w_{\max}}(p)]$. Yet it also causes rationing of the marginal buyer types (satisfying $w(s)=p$) with whom there are gains from trade $(p-\mu_v)$ and who have the density value $f_{w_{\max}}(p)$.

The seller always optimally quotes a price $p \geq \mu_v$, as he values retaining the asset at μ_v. Moreover, it is worth noting that when the unconditional gains from trade are weakly negative ($\mu_b \leq 0$) and thus $w(\emptyset) \leq \mu_v$, the seller optimally chooses a price $p > w(\emptyset)$, implying that trade with uninformed buyers does not occur in equilibrium. This parameterization implies that the seller's optimal price satisfies the standard first-order condition $\Pi'(p)=0$, which simplifies to[13]

$$1-F_{w|b}(p)-f_{w|b}(p)\cdot(p-\mu_v)=0. \tag{13}$$

Equation (13) reveals that when the unconditional gains from trade are weakly negative ($\mu_b \leq 0$), the seller's optimal price quote is independent of the number of buyers n and their expertise levels π. This result is due to the fact that the seller only targets informed buyers in this case, and buyers' willingness to pay is symmetric conditional on obtaining information. Moreover, the price quote implied by the first-order condition (13) generically leads to rationing of buyer types with whom there would be positive gains from trade $(p-\mu_v)$. The seller is always strictly better off choosing a price quote higher than μ_v because $\Pi'(\mu_v) > 0$. Even though our main results do not require that $\mu_b \leq 0$, we will occasionally revisit this case to increase the analytical tractability of our analysis.

2.1.3 Buyers' expertise acquisition. Finally, we analyze buyers' ex ante expertise acquisition decision. A buyer i who believes that all other buyers in the market will choose an expertise level π and that the seller will quote a price p expects to obtain the following surplus from choosing an expertise level π_i ex ante:

$$\begin{aligned} V_i(\pi_i)=&\pi_i\cdot[1-F_{w|b}(p)]\cdot(\mu_v+\mathbb{E}[b|b>p-\mu_v]-p)\left(F_{w|\emptyset}(p)\sum_{m=0}^{n-1}\frac{B(n-1,m,\pi)}{m+1}+\frac{1-F_{w|\emptyset}(p)}{n}\right)\\ &+(1-\pi_i)\cdot[1-F_{w|\emptyset}(p)]\cdot[w(\emptyset)-p]\sum_{m=0}^{n-1}B(n-1,m,\pi)\left(\frac{F_{w|b}(p)}{n-m}+\frac{1-F_{w|b}(p)}{n}\right)\\ &-c(\pi_i). \end{aligned} \tag{14}$$

[13] Conditional on choosing $p > w(\emptyset)$, the optimal price p must satisfy the standard marginal condition:

$$1-F_{w_{\max}}(p)-f_{w_{\max}}(p)\cdot(p-\mu_v)=0. \tag{11}$$

For all $p > w(\emptyset)$, we obtain the following simplified representations for the CDF and PDF: $F_{w_{\max}}(p)=(1-\pi)^n+(1-(1-\pi)^n)F_{w|b}(p)$ and $f_{w_{\max}}(p)=(1-(1-\pi)^n)f_{w|b}(p)$. As a result, we can rewrite the marginal condition as follows:

$$(1-(1-\pi)^n)[1-F_{w|b}(p)-f_{w|b}(p)\cdot(p-\mu_v)]=0. \tag{12}$$

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Correspondingly, the marginal net benefit of increasing π_i when $\pi_i \in (0,1)$ is given by

$$V_i'(\pi_i) = [1 - F_{w|b}(p)] \cdot (\mu_v + \mathbb{E}[b|b > p - \mu_v] - p) \left(F_{w|\emptyset}(p) \sum_{m=0}^{n-1} \frac{B(n-1,m,\pi)}{m+1} + \frac{1 - F_{w|\emptyset}(p)}{n} \right)$$
$$- (1 - F_{w|\emptyset}(p)) \cdot [w(\emptyset) - p] \sum_{m=0}^{n-1} B(n-1,m,\pi) \left(\frac{F_{w|b}(p)}{n-m} + \frac{1 - F_{w|b}(p)}{n} \right)$$
$$- c'(\pi_i). \tag{15}$$

A buyer's marginal net benefit of acquiring expertise is affected by the difference in expected payoffs conditional on being informed and uninformed, respectively, and the marginal cost of expertise acquisition. The expected payoff conditional on being informed is, in turn, determined by the product of the probability with which the buyer will wish to trade at the posted price, the probability of obtaining the asset when accepting the posted price, and the profit obtained conditional on acquiring the asset. Note that the marginal benefit of increasing π_i is independent of π_i, which implies that the only term in Equation (15) that depends on π_i is the marginal cost $c'(\pi_i)$. As shown above, whenever $\mu_b \leq 0$ the seller optimally targets informed buyers (i.e., $p > w(\emptyset)$), implying that Equation (15) further simplifies to

$$V_i'(\pi_i) = [1 - F_{w|b}(p)] \cdot (\mu_v + \mathbb{E}[b|b > p - \mu_v] - p) \cdot \sum_{m=0}^{n-1} \frac{B(n-1,m,\pi)}{m+1} - c'(\pi_i). \tag{16}$$

2.1.4 Equilibrium. We conclude this subsection with a formal equilibrium definition. A symmetric subgame-perfect Nash equilibrium in the limit-order market satisfies the following equilibrium conditions:

1. Given his beliefs that other buyers acquire expertise π and that the seller quotes the price p, each buyer i maximizes his expected surplus (14) by acquiring expertise $\pi_i = \pi$.
2. Given his beliefs that buyers acquire expertise π, the seller chooses p to maximize his expected payoff (9).
3. Given his beliefs that other buyers acquire expertise π and rationally respond to price quotes, each buyer optimally accepts price quotes based on his rational willingness to pay (3).

2.2 OTC market

We now proceed to analyzing the equilibrium outcomes in the OTC market. Again, we start our analysis by deriving each buyer's willingness to pay, followed by the seller's pricing decision and buyers' ex ante expertise choices.

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2.2.1 Buyers' willingness to pay. Consistent with our earlier notation, let $w_i(s_i)$ denote buyer i's willingness to pay conditional on his signal $s_i \in \{b, \emptyset\}$ and given that the previous $(i-1)$ buyers rejected the seller's price offers (thus, the index i also denotes a buyer's rank in the OTC market). As a first step, it is useful to keep track of the CDF of b conditional on having observed i rejections by buyers. These rejection events are used as signals by both the seller and the buyers that potentially obtain offers subsequently. Let $n_R = i$ indicate the event that the first i buyers have rejected the price offers p_1 through p_i. The conditional CDF of b is updated after each additional rejection according to the relation:

$$F_b(b|n_R = i) = \Pr[s_i = \emptyset | n_R = i] \cdot F_b(b|n_R = (i-1)) + \Pr[s_i = b | n_R = i] \cdot F_b(b|n_R = i \wedge s_i = b), \tag{17}$$

where the initial CDF is the unconditional CDF $F_b(b|n_R = 0) = F_b(b)$, and where we define the conditional probabilities that the ith buyer is uninformed and informed, respectively,

$$\Pr[s_i = \emptyset | n_R = i] = \frac{(1-\pi_i) \cdot \mathbf{1}_{\{w_i(\emptyset) < p_i\}}}{(1-\pi_i) \cdot \mathbf{1}_{\{w_i(\emptyset) < p_i\}} + \pi_i \cdot F_b(p_i - \mu_v | n_R = (i-1))}, \tag{18}$$

$$\Pr[s_i = b | n_R = i] = 1 - \Pr[s_i = \emptyset | n_R = i]. \tag{19}$$

Agents account for the fact that previously contacted buyers may have rejected the seller's offers while being either uninformed or informed. Correspondingly, the updated CDF is a probability-weighted average of these two potential events. Conditional on the ith buyer being uninformed, a rejection by this buyer does not cause any updating about the distribution of b, implying that the distribution is still $F_b(b|n_R = (i-1))$. In contrast, conditional on the ith buyer being informed, a rejection by this buyer implies that the distribution of b is truncated from above at $(p_i - \mu_v)$. Moreover, if the ith buyer obtained the lowest price offer to date, that is, if $p_i < \min[p_1, ..., p_{i-1}]$, this last rejection by buyer i also provides the most precise (strictest) truncation to date. In this case, conditional on buyer i being informed and rejecting the price p_i, the updated conditional CDF is given by

$$F_b(b|n_R = i \wedge s_i = b) = F_b(b|b < p_i - \mu_v) = \min\left[\frac{F_b(b)}{F_b(p_i - \mu_v)}, 1\right]. \tag{20}$$

Next, we derive buyer i's willingness to pay $w_i(s_i)$, which involves sequential updating for $w_i(\emptyset)$ analogously to the updating of the conditional CDF of b:

$$w_{i+1}(s_{i+1}) = \begin{cases} \mu_v + b, & \text{for } s_{i+1} = b, \\ \Pr[s_i = \emptyset | n_R = i] w_i(\emptyset) + \Pr[s_i = b | n_R = i] \mathbb{E}[\mu_v + b | n_R = i \wedge s_i = b], & \text{for } s_{i+1} = \emptyset. \end{cases} \tag{21}$$

This recursive representation for $w_i(\emptyset)$ has the initial condition that the first buyer's willingness to pay without receiving a signal is simply given by $w_1(\emptyset) =$

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$\mu_v + \mu_b$. Moreover, for $p_i < \min[p_1, ..., p_{i-1}]$, we obtain a simplified formula for the following term in Equation (21):

$$\mathbb{E}[\mu_v + b | n_R = i \wedge s_i = b] = \mu_v + \mathbb{E}[b | b < p_i - \mu_v]. \tag{22}$$

Finally, we can define the probability with which a buyer i rejects a price p_i conditional on being informed and uninformed, respectively, and given the $(i-1)$ previous rejections as follows:

$$F_{w_i|b}(p_i) = F_b(p_i - \mu_v | n_R = (i-1)), \tag{23}$$

$$F_{w_i|\emptyset}(p_i) = \mathbf{1}_{\{p_i > w_i(\emptyset)\}}. \tag{24}$$

Combining these CDFs, the seller assigns the following probability to the event that buyer i rejects a price offer p_i:

$$F_{w_i}(p_i) = \pi_i F_{w_i|b}(p_i) + (1-\pi_i) F_{w_i|\emptyset}(p_i). \tag{25}$$

2.2.2 Seller's pricing decision. Let $\mathbf{p} = (p_1, ..., p_n)'$ denote a vector of prices quoted by the seller to the n buyers. Going forward, we will use the notation $\Pi_i(\mathbf{p})$ to refer to the seller's expected payoff conditional on having reached the ith buyer, having charged the prices $p_1, ..., p_{i-1}$ to the first $(i-1)$ buyers, and anticipating to charge the prices p_i through p_n to the remaining buyers (if they are reached). After having received rejections from the first $(i-1)$ buyers and having successfully contacted buyer i, the seller chooses the price p_i to maximize the value:

$$\Pi_i(\mathbf{p}) = [1 - F_{w_i}(p_i)] \cdot p_i + F_{w_i}(p_i) \cdot [\rho \Pi_{i+1}(\mathbf{p}) + (1-\rho)\mu_v], \tag{26}$$

where for notational convenience we define the terminal value $\Pi_{n+1}(\mathbf{p}) \equiv \mu_v$, that is, the seller's continuation value after receiving n rejections is simply μ_v. The price-probability trade-off the seller faces when picking a price p_i shares similarities with the one applying in the limit-order market. Increasing the price quote improves the revenue conditional on trade occurring, but it also lowers the probability of trade, causing potentially inefficient retention. The sequential and exclusive nature of OTC trading, however, changes the seller's incentives to screen privately informed buyers with high price quotes. The trade-off is affected as the seller only faces one buyer at a time, and he accounts for the information revealed by previous rejections.

Again, the seller's problem is particularly tractable in cases in which the unconditional gains from trade are weakly negative ($\mu_b \leq 0$). In these cases, the seller always optimally chooses prices $p_i > \mu_v \geq w_i(\emptyset)$ that satisfy the first-order condition:

$$\frac{\partial \Pi_i(\mathbf{p})}{\partial p_i} = 1 - F_{w_i}(p_i) - f_{w_i}(p_i)(p_i - [\rho \Pi_{i+1}(\mathbf{p}) + (1-\rho)\mu_v]) + F_{w_i}(p_i)\rho \frac{\partial \Pi_{i+1}(\mathbf{p})}{\partial p_i} = 0, \tag{27}$$

where for all $p_i > w_i(\emptyset)$ we obtain

$$F_{w_i}(p_i) = \pi_i F_{w_i|b}(p_i) + (1-\pi_i), \tag{28}$$

$$f_{w_i}(p_i) = \pi_i f_{w_i|b}(p_i). \tag{29}$$

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2.2.3 Buyers' expertise acquisition. To derive buyers' optimal expertise acquisition problem, it is useful to note that for a buyer i, the most informative rejection among previous buyers' rejections comes from the informed buyer that was charged the lowest price to date, as this rejection creates the strictest truncation. Below, we use the notation "k most inf." to refer to the event that buyer k received the lowest price among all buyers up to buyer i that received an informative signal. Moreover, it is helpful to define the subsets of indices of buyers contacted before buyer i that are charged a price below and above the price charged to some buyer $k < i$, respectively, as

$$\Omega_i^-(k) = \{l \in \{1, ..., (i-1)\} \setminus k : p_l < p_k\}, \tag{30}$$

$$\Omega_i^+(k) = \{l \in \{1, ..., (i-1)\} \setminus k : p_l > p_k\}. \tag{31}$$

Finally, we also define the following ex ante probabilities that buyer i gets an offer from the seller:

$$\Pr[i \text{ gets offer}] = \Pr[i \text{ gets offer} \wedge \text{ none inf.}] + \sum_{k=1}^{i-1} \Pr[i \text{ gets offer} \wedge k \text{ most inf.}], \tag{32}$$

$$\Pr[i \text{ gets offer} \wedge \text{ none inf.}] = \rho^{i-1} \prod_{l=1}^{i-1} (1-\pi_l) F_{w_l|\emptyset}(p_l), \tag{33}$$

$$\Pr[i \text{ gets offer} \wedge k \text{ most inf.}] = \rho^{i-1} \left(\prod_{l \in \Omega_i^+(k)} F_{w_l}(p_l) \right) \cdot \pi_k F_{w_k|b}(p_k) \cdot \left(\prod_{j \in \Omega_i^-(k)} (1-\pi_j) F_{w_j|\emptyset}(p_j) \right), \tag{34}$$

where we use the fact that $F_{w_k|b}(p_k)$ represents the probability that buyer k rejects a price p_k if he is informed and is contacted after $(k-1)$ buyers have rejected the seller's previous quotes. Given these preliminary definitions, we can now generally represent buyer i's ex ante value function as

$$\begin{aligned} V_i(\pi_i) = \pi_i \cdot \Big[& \Pr[i \text{ gets offer} \wedge \text{ none inf.}] \cdot [1 - F_b(p_i - \mu_v)] \cdot (\mu_v + \mathbb{E}[b|b > p_i - \mu_v] - p_i) \\ & + \sum_{k=1}^{i-1} \Pr[i \text{ gets offer} \wedge k \text{ most inf.}] (1 - F_b(b|b < p_k - \mu_v)) (\mu_v + \mathbb{E}[b|p_i - \mu_v < b < p_k - \mu_v] - p_i) \Big] \\ & + (1-\pi_i) \cdot \Pr[i \text{ gets offer}] \cdot [1 - F_{w_i|\emptyset}(p_i)] \cdot [w_i(\emptyset) - p_i] \\ & - c(\pi_i). \end{aligned} \tag{35}$$

Equation (35) uses the fact that conditional on buyer k having been the informed buyer receiving the lowest price quote and having rejected this price, the

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conditional CDF of b is truncated from above by $(p_k - \mu_v)$. Buyer i's marginal net benefit of increasing the expertise level π_i when $\pi_i \in (0,1)$ is then given by

$$\begin{aligned}
V_i'(\pi_i) = &\Pr[i \text{ gets offer} \wedge \text{ none inf.}] \cdot [1 - F_b(p_i - \mu_v)] \cdot (\mu_v + \mathbb{E}[b|b > p_i - \mu_v] - p_i) \\
&+ \sum_{k=1}^{i-1} \Pr[i \text{ gets offer} \wedge k \text{ most inf.}](1 - F_b(b|b < p_k - \mu_v))(\mu_v + \mathbb{E}[b|p_i - \mu_v < b < p_k - \mu_v] - p_i) \\
&- \Pr[i \text{ gets offer}] \cdot [1 - F_{w_i|\emptyset}(p_i)] \cdot [w_i(\emptyset) - p_i] \\
&- c'(\pi_i).
\end{aligned} \tag{36}$$

Like in the case of the limit-order market, the marginal cost $c'(\pi_i)$ is the only term entering the marginal net benefit that directly depends on buyer i's own expertise choice π_i. In our analysis below, we will at times use the fact that under the assumption that the gains from trade are normally distributed, $b \sim N(\mu_b, \sigma_b)$, the double-truncated expectations entering Equation (35) are available in closed form (see Tallis 1961):

$$\mathbb{E}[b|p_i - \mu_v < b < p_k - \mu_v] = \mu_b + \sigma_b^2 \frac{f_b(p_i - \mu_v) - f_b(p_k - \mu_v)}{F_b(p_k - \mu_v) - F_b(p_i - \mu_v)}. \tag{37}$$

2.2.4 Equilibrium. Again, we conclude this subsection with an equilibrium definition. A subgame-perfect Nash equilibrium in the OTC market satisfies the following conditions:

1. Given his beliefs that other buyers acquire expertise $\pi_1, ..., \pi_{i-1}, \pi_{i+1}, ..., \pi_n$ and that the seller quotes prices $p_1, ..., p_n$, each buyer i maximizes his ex ante expected surplus (35) by acquiring expertise π_i.
2. Given his beliefs that buyers acquire expertise $\pi_1, ..., \pi_n$, the seller chooses prices $p_1, ..., p_n$ to maximize his expected payoffs at each trading encounter (26).
3. Given his beliefs that previously contacted buyers acquired expertise $\pi_1, ..., \pi_{i-1}$ and rationally responded to price quotes $p_1, ..., p_{i-1}$, buyer i optimally accepts price quotes according to his rational willingness to pay (21).

2.3 Comparing market structures

When introducing the model in the previous sections, we allowed for general continuous distributions F_b and F_v and expertise cost functions $c(\pi)$. This generality will allow us to highlight several channels influencing the relative merits of OTC and limit-order markets. Yet, to first isolate the forces we aim to emphasize in this paper, we start by analyzing a specification that yields analytical results for the key objects of interest in this paper. Thereafter, we will analyze model parameterizations that relax various assumptions, allowing us to explore additional channels.

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2.3.1 The main channel: Expertise acquisition. We begin the comparison of market structures with the following result.

Proposition 1. Consider the case in which $\mu_b=0$, $\rho=0$, and the expertise cost function is linear $c(\pi)=\alpha\pi$ with $\alpha\in(0,\bar{\alpha})$ to ensure that expertise acquisition is nonzero under at least one market structure (where $\bar{\alpha}$ is defined in Appendix A.1). Then the following results apply:

1. In the limit-order market, the probability that at least one buyer obtains an informative signal is weakly lower than it is in the OTC market.
2. The OTC market generates strictly greater total surplus and weakly greater surplus for the seller. For $n>\frac{\bar{\alpha}}{\alpha}$, the seller also obtains strictly greater surplus in the OTC market.

Proof. See Appendix A.1. ■

Proposition 1 provides sharp predictions for key objects of interest without imposing restrictions on the distributions F_b and F_v apart from the condition that the unconditional gains to trade are zero ($\mu_b=0$). This case serves as a useful benchmark that isolates the relevance of expertise acquisition: absent expertise, trade cannot yield any positive surplus as agents cannot determine whether gains from trade are positive or negative. Moreover, Proposition 1 considers the case in which technology frictions in the OTC market are most severe ($\rho=0$). The results thus clearly highlight how the imperfect "connectedness" of traders that is characteristic of OTC markets should not be interpreted as necessarily harming efficiency, contrary to the predictions and conclusions of much of the literature studying these markets (see, e.g., the canonical search-based model of OTC markets by Duffie, Gârleanu, and Pedersen 2005).

The benefits of OTC markets highlighted in Proposition 1 obtain for the following two reasons. First, by directing all the order flow initially to one central trader (buyer 1), that trader faces strictly greater incentives to acquire expertise than traders in the limit-order market who compete with each other for incoming orders.[14] Expertise acquisition, in turn, is essential to realizing gains to trade when the unconditional gains to trade are zero. Second, the OTC market avoids duplication of effort: whereas, in the limit-order market, multiple traders incur expertise acquisition costs to possibly gain the same information, information production in the OTC market is undertaken by one central counterparty. In sum, the OTC market yields effectively more information production, and a given level of information production is achieved in a more efficient way.

[14] Recall that the type of order flow we model is scarce in the sense that shocks creating potential gains from trade between agents do not affect infinite quantities; for instance, liquidity shocks hit only some traders and imply finite opportunities for surplus-creating trade.

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While the assumptions stated in Proposition 1 yield analytical tractability, they are by no means necessary to obtain our results. Below, we will show that similar results can obtain under model parameterizations with nonlinear cost functions, nonzero unconditional gains to trade, and $\rho > 0$. In addition, relaxing some of these assumptions will allow us to highlight new forces. However, in contrast to Proposition 1, these analyses will require us to specify the distribution for the gains to trade.

In particular, in the following analyses, we will repeatedly revisit a canonical setting in which the gains to trade b are normally distributed. The following proposition shows that this assumption, together with imposing a lower bound on the marginal cost of expertise, allows us to extend the results of Proposition 1 to cases in which the value of the parameter ρ is unrestricted.

Proposition 2. If $b \sim N(0, \sigma_b^2)$, and $c(\pi) = \alpha\pi$ with $\alpha \in [0.2\bar{\alpha}, \bar{\alpha})$ (where $\bar{\alpha}$ is provided in Appendix A.2), then the results stated in Proposition 1 obtain for any $\rho \in [0, 1]$.

Proof. See Appendix A.2. ■

As was the case with Proposition 1, the restrictions imposed by Proposition 2 ensure an analytically tractable analysis for a considerable range of parametric assumptions (in this case, for any $\rho \in [0, 1]$). Yet these restrictions are not necessary for the stated result. Rather, imposing a lower bound on the marginal cost yields tractability, as it implies that the OTC market features only expertise acquisition by the first buyer, which dramatically simplifies the analysis of this market structure. Interestingly, under the assumption of normality (for any σ_b) and for $\rho = 1$, enticing a second buyer to also acquire expertise in the OTC market (i.e., $\pi_2 > 0$) requires 80% lower expertise acquisition cost than it does to entice just the first buyer. This result explains why the lower bound on α is set to $0.2\overline{\alpha}$ and reveals the strongly asymmetric incentives for expertise acquisition in the OTC market, even when there are no frictions in reaching the second buyer (i.e., for $\rho = 1$). In contrast, the limit-order market gives traders symmetric access to incoming orders, thus providing identical incentives for expertise acquisition to all traders. Yet the resultant level of expertise is lower due to the above-discussed competition and duplication of effort channels.

2.3.2 Other channels. We now turn to various alternative model parameterizations to illustrate forces at play outside of the parameter regions considered in Propositions 1 and 2. To do so, we consider a flexible expertise cost function:

$$c(\pi) = \frac{\beta}{2}\left[(\pi + \gamma)^2 - \gamma^2\right], \tag{38}$$

which features convexity and satisfies the properties that $c(0) = 0$, $c'(0) = \beta\gamma$, and $c''(\pi) = \beta$. While the analyses that follow assume that b is normally

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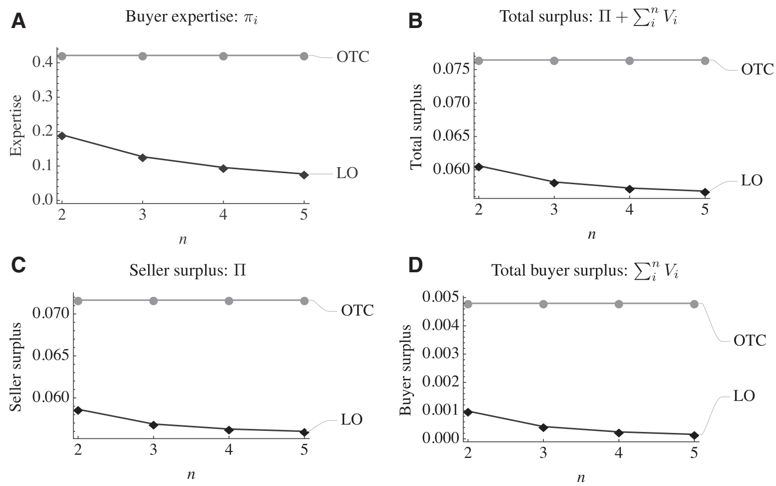

Figure 1
Varying the number of potential buyers
The graphs illustrate buyers' expertise acquisition (panel A), total surplus (panel B), seller surplus (panel C), and total buyer surplus (panel D) in the OTC market and in the limit-order market. The illustrated expertise level for the OTC market refers to buyer 1 only; all other buyers optimally choose $\pi_i = 0$ (for $i = 2, ..., n$). The expertise level shown for the limit-order market reflects buyers' symmetric level of expertise $\pi_i = \pi$. We set $b \sim N(0,1)$, $\rho = 0.95$, $\beta = 0.054$, and $\gamma = 2$.

distributed, we will not impose any restrictions on the distribution F_v. Whereas the prices quoted depend on the expected value of the common value component v, the outcomes we are interested in, in particular expertise acquisition and traders' surplus, do not depend on the distribution F_v, because agents have symmetric information about v in this part of our analysis (Scenario 1).

2.3.2.1 The number of counterparties. We start by considering the effects of the number of potential counterparties in the economy. The panels of Figure 1 separately illustrate buyers' expertise acquisition, total surplus, seller surplus, and total buyer surplus as functions of the number of buyers. In the limit-order market, expertise acquisition π monotonically declines with n. The more buyers are competing for the same volume of order flow (which is normalized to one) the lower the expected volume each buyer anticipates to obtain. Expecting a lower trade volume to which expertise can be applied, each buyer optimally scales down his expertise acquisition. In contrast, in the OTC market the first buyer is always contacted and his expertise acquisition is independent of the total number of buyers. In this parameterization, he is the only one acquiring expertise, just like in Propositions 1 and 2, even though the expertise cost function now features convexity, which increases the relative benefits of acquiring expertise in a dispersed manner. Overall, the results mirror those from Propositions 1 and 2 as both total surplus and seller surplus are higher in

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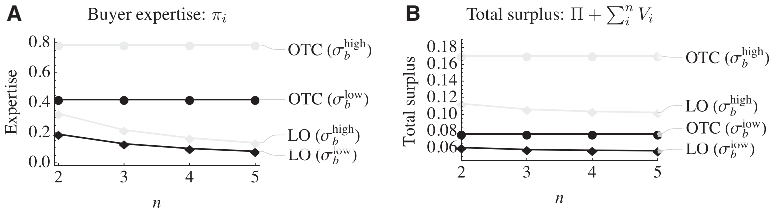

Figure 2
Varying the volatility of the gains to trade
The graphs illustrate buyers' expertise acquisition (panel A) and total surplus (panel B) in the OTC market and in the limit-order market. The illustrated expertise level for the OTC market refers to buyer 1 only; all other buyers optimally choose $\pi_i = 0$ (for $i = 2,...,n$). The expertise level shown for the limit-order market reflects buyers' symmetric level of expertise $\pi_i = \pi$. The parameterization labeled σ_b^{low} is identical to the one in Figure 1. The parameterization labeled σ_b^{high} only differs from this baseline parameterization in that it increases σ_b to a value of 1.15.

the OTC market. Figure 1 also shows that these gaps widen as the number of potential counterparties increases.

2.3.2.2 Volatility of the gains to trade. Next, in Figure 2, we examine how increasing the volatility of the gains to trade affects equilibrium outcomes. To do so, we maintain the parameter values underlying Figure 1, except that we vary the value for σ_b. Increasing σ_b while keeping expertise costs fixed makes it more attractive to acquire expertise. As a result, expertise acquisition increases under both market structures. Yet the gap in total surplus between OTC and limit-order markets widens as the benefits of expertise acquisition increase with higher values of σ_b, rendering the above-discussed differential incentives for expertise acquisition provided by both market structures more consequential.

2.3.2.3 Positive expected gains to trade. We now consider environments in which the expected gains to trade are positive to illustrate three effects. First, we discuss how the presence of unconditional gains to trade affects expertise acquisition. Second, we show the existence of equilibria where multiple buyers acquire expertise in the OTC market. Third, and finally, we discuss the implications of the presence of unconditional gains to trade μ_b that are large relative to the volatility σ_b.

Whereas the seller was targeting informed buyers in the parameterizations above for which the expected gains from trade were zero or negative, he may now find it optimal to quote prices that are also accepted by uninformed buyers. But, for now, Figure 3 illustrates the effects of an increase in the unconditional gains to trade that is not large enough to cause the seller to switch from targeting informed buyers to targeting uninformed buyers. Apart from this increase in μ_b, Figure 3 is based on the same parameterization used in Figure 1.

Under both market structures, buyers acquire more expertise under the parameterization where μ_b is positive. Given the symmetry of the Normal

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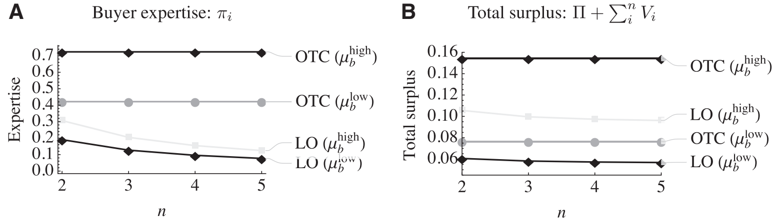

Figure 3
Varying the expected gains from trade
The graphs illustrate buyers' expertise acquisition (panel A) and total surplus (panel B) in the OTC market and in the limit-order market. The illustrated expertise level for the OTC market refers to buyer 1 only; all other buyers optimally choose $\pi_i = 0$ (for $i = 2, ..., n$). The expertise level shown for the limit-order market reflects buyers' symmetric level of expertise $\pi_i = \pi$. The parameterization labeled μ_b^{low} is identical to the one in Figure 1. The parameterization labeled μ_b^{high} only differs from this baseline parameterization in that it increases μ_b to a value of 0.10.

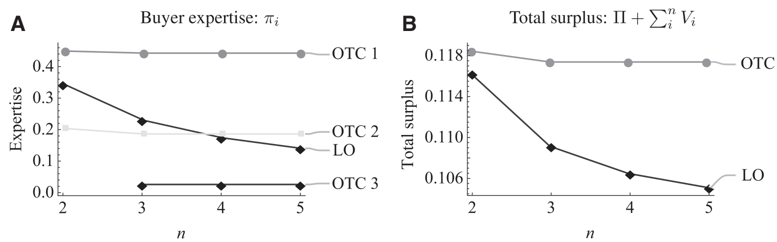

Figure 4
Expertise acquisition by multiple buyers in the OTC market
The graphs illustrate buyers' expertise acquisition (panel A) and total surplus (panel B) in the OTC market and in the limit-order market. The illustrated expertise levels for the OTC market labeled "OTC 1," "OTC 2," and "OTC 3" apply to buyers 1, 2, and 3, respectively; all other buyers optimally choose $\pi_i = 0$. The expertise level shown for the limit-order market reflects buyers' symmetric level of expertise $\pi_i = \pi$. The parameterization is identical to the one of Figure 1, except that we set $\mu_b = 0.1$, $\rho = 1$, and $\beta = 0.052$.

distribution, shifting the mean of b above zero implies that the probability of positive gains from trade ($b > 0$) becomes greater than 50%. Even though the seller optimally increases his price quote as μ_b goes up, this increase is less than one-for-one. As a result, *ceteris paribus*, buyers expect to receive more surplus. Moreover, as the quoted prices are attractive to only informed buyers observing sufficiently high realizations of b—uninformed buyers are still rationed—buyers have to acquire expertise to access this higher surplus. As the expertise gap between both market structures widens with the increase in μ_b so does the gap in total surplus, as illustrated by Figure 3B.

Given the positive effect of increasing μ_b on expertise acquisition, an environment with $\mu_b > 0$ is well suited to illustrate equilibria where multiple buyers acquire expertise in the OTC market. Figure 4 illustrates a parameterization where up to three buyers acquire expertise in the OTC

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market. To strengthen the incentives for expertise acquisition in the OTC market, Figure 4 considers the increased value for μ_b as the graphs in Figure 3 labeled μ_b^{high} and also increases the value of the parameter ρ and decreases the cost parameter β. In the illustrated equilibrium, the second and third buyers acquire expertise, but they acquire less than the first buyer does. Given the presence of additional informed buyers, the seller quotes a more aggressive price to the first buyer, causing that buyer to acquire less expertise. The presence of two additional informed buyers effectively puts competitive pressure on the first buyer. As total information production declines, relative to the case in which only the first buyer acquires expertise, so does total surplus. Yet the OTC market is still less competitive than the limit-order market and thus still dominates in terms of information production and total surplus.

To conclude this section, we discuss the model's implications when the average of the gains to trade is large relative to the volatility. This analysis will highlight a key point of our paper (which we further develop in the next section): whereas OTC markets provide stronger incentives for expertise acquisition, the efficiency implications of this channel depend on the economic context. In particular, it is straightforward to see why large increases in the unconditional gains to trade can cause expertise acquisition to become socially harmful. As μ_b is increased, the ex ante probability that there are positive gains to trade ($b > 0$) starts approaching one. Thus, for sufficiently large values of μ_b, the uncertainty about whether trade creates positive surplus becomes so small that spending positive amounts of resources to eliminate this uncertainty reduces total surplus. Nonetheless, expertise acquisition may remain privately optimal for buyers seeking information rents. Even worse so, this expertise then leads to trade breakdowns induced by asymmetric information. Competition in the limit-order market reduces expertise acquisition, which is now beneficial.

Following the approach used in the previous propositions, we consider a tractable benchmark setting in which b is normally distributed to prove the following analytical results:

Proposition 3. Consider the case in which $b \sim N(\mu_b, \sigma_b)$ with $\frac{\mu_b}{\sigma_b} > 0.58$, $\rho = 0$, the expertise cost function is linear $c(\pi) = \alpha\pi$ with $\alpha \in (0, \bar{\alpha})$, and $n > n^*$ (where $\bar{\alpha}$ and n^* are provided in closed form in Appendix A.3). Then the following results apply:

1. In the limit-order market, buyers do not acquire expertise and they obtain zero surplus. Total surplus and seller surplus are equal to μ_b.
2. In the OTC market, buyer 1 acquires expertise and obtains strictly positive surplus. Total surplus and seller surplus are lower than they would be in the limit-order market.

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Proof. See Appendix A.3. ■

If there are sufficiently many potential counterparties, expertise acquisition vanishes completely in the limit-order market, but not in the OTC market. If the unconditional gains to trade are high enough, this type of uninformed trade leads to greater total surplus and seller surplus. The notion that expertise acquisition is not socially beneficial when gains to trade are known to be positive ex ante is also a central feature of settings with pure common value uncertainty, a case we study in the next section.

3. Private Information about the Common Value Component

In this section, we analyze market outcomes under Scenario 2, that is, the case in which buyers can obtain signals on the realization of the common value component v. An empirical counterpart for this type of information might be, for example, earnings information that is obtained by some trader shortly before it is released publicly. For this scenario, we assume that the unconditional gains from trade are positive ($\mu_b > 0$), which is now necessary for trade to occur and generate surplus in equilibrium.

3.1 Limit-order market

3.1.1 Buyers' willingness to pay. The analysis of buyers' willingness to pay under this scenario is analogous to the one under Scenario 1 (see Section 2). In particular, all equations characterizing buyers' willingness to pay also apply here, once adjusted according to the following mapping: $F_b \to F_v$, $\mu_b \to \mu_v$, $\mu_v \to \mu_b$.

3.1.2 Seller's pricing decision. When choosing a price p the seller is concerned with the distribution of the maximum willingness to pay among all buyers present in the market, $F_{w_{\max}}$, and this distribution is again analogous to the one derived in Section 2 (subject to the above-described mapping). The seller posts a limit-order quote p to maximize his expected payoff:

$$\Pi(p) = [1 - F_{w_{\max}}(p)]p + [F_{w_{\max}}(p) - (1-\pi)^n F_{w|\emptyset}(p)] \cdot \mathbb{E}[v | v < p - \mu_b]) \\ + (1-\pi)^n F_{w|\emptyset}(p)\mu_v. \tag{39}$$

Now the seller is concerned about being adversely selected, as buyers may obtain private information about the common value component v that affects the seller's utility from retaining the asset. In Equation (39), we separate the probability of a rejection, $F_{w_{\max}}(p)$, into the probabilities of two disjoint events: (1) at least one informed buyer is in the market and p is rejected by all buyers and (2) not a single informed buyer is in the market and p is rejected by all buyers. In the former case, the rejection is informative about v, in particular the conditional expected value of v is $\mathbb{E}[v|v < p - \mu_b]$ after a rejection. In the latter case, the rejection is uninformative about v, implying that the conditional expected value

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of the common value component remains equal to the unconditional expected value μ_v.

3.1.3 Buyers' expertise acquisition. The analysis of buyers' expertise acquisition is again analogous to the one in Section 2, subject to the above-mentioned mapping.

3.2 OTC market

For the OTC market, the analysis for buyers' willingness to pay and their expertise acquisition is also analogous to the one in Section 2, subject to the mapping described in Section 3.1. Yet the seller's pricing decision differs, as the seller now accounts for adverse selection on the common value component v.

3.2.1 Seller's pricing decision. After receiving $(i-1)$ rejections from the first $(i-1)$ buyers, the seller chooses to quote a price p_i to buyer i in order to maximize:

$$\Pi_i(\mathbf{p}) = [1-F_{w_i}(p_i)]\cdot p_i + F_{w_i}(p_i)\cdot(\rho\Pi_{i+1}(\mathbf{p})+(1-\rho)\mathbb{E}[v|n_R=i]), \qquad (40)$$

where we define the terminal value as follows:

$$\Pi_{n+1}(\mathbf{p}) \equiv \mathbb{E}[v|n_R=n]. \qquad (41)$$

Note that conditional on receiving i rejections, the seller has the same conditional expectation about the common value component v as the $(i+1)$th buyer if that buyer has not received a signal. Thus, we obtain the following equivalence:

$$\mathbb{E}[v|n_R=i] = w_{i+1}(\emptyset) - \mu_b, \qquad (42)$$

where $w_{i+1}(\emptyset)$ follows from Equation (21), subject to the mapping described in Section 3.1.

3.3 Comparing market structures

Like in Section 2.3, we begin by considering a specific set of conditions that yield analytical tractability and allow us to focus on our main channel: endogenous expertise. We summarize these conditions and the associated results in the following proposition.

Proposition 4. Consider the case in which $\mu_b > 0$, $v \sim N(\mu_v, \sigma_v)$, $\rho = 0$, the expertise cost function is linear $c(\pi) = \alpha\pi$ with $\alpha \in (0, \bar{\alpha})$, and $n > n^*$ (where $\bar{\alpha}$ and n^* are provided in closed form in Appendix A.4). Then the following results apply:

1. In the limit-order market, buyers do not acquire expertise and they obtain zero surplus. Total surplus and seller surplus are equal to μ_b, which is the first-best level of total surplus.

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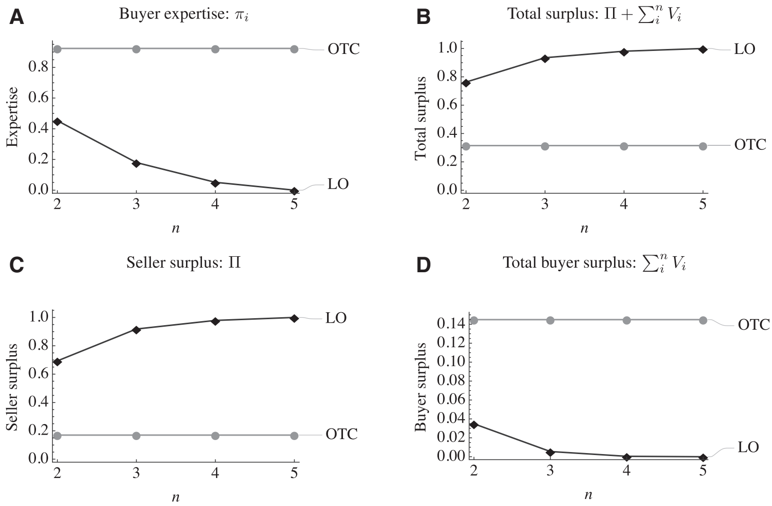

Figure 5
Common value uncertainty. The graphs illustrate buyers' expertise acquisition (panel A), total surplus (panel B), seller surplus (panel C), and total buyer surplus (panel D) in the OTC market and in the limit-order market. The illustrated expertise level for the OTC market refers to buyer 1 only; all other buyers optimally choose $\pi_i = 0$ (for $i = 2, ..., n$). The expertise level shown for the limit-order market reflects buyers' symmetric level of expertise $\pi_i = \pi$. We set $v \sim N(0,1)$, $\mu_b = 1$, $\rho = 0$, $\beta = 0.34$, and $\gamma = 0.25$.

2. In the OTC market, the first buyer acquires expertise and obtains strictly positive surplus. Total surplus is below the first-best level and the seller receives lower surplus than he would in the limit-order market.

Proof. See Appendix A.4. ■

When the number of potential buyers n is sufficiently large, the first-best level of total surplus is achieved in the limit-order market. As the number of competing traders increases, incentives for expertise acquisition decline, eventually eliminating expertise acquisition completely. Once traders do not acquire expertise, information asymmetries vanish, and trade is fully efficient.

In contrast, the OTC market insulates some traders from competition and thus encourages them to acquire expertise. This is a recurring theme throughout the paper. Yet, in an environment in which expertise is not needed to inform optimal allocations, because the gains to trade are now known to be positive, this expertise is harmful for two reasons. First, it causes asymmetric information that leads to inefficient trade breakdowns. Second, costly expertise acquisition leads to a waste of resources solely spent on seeking private rents.[15]

Figure 5 illustrates these forces graphically. The considered parameterization again relies on the same cost function (38) as the previous illustrations in Section

[15] See also Hirshleifer (1971), Glode, Green, and Lowery (2012), and Dang, Gorton, and Holmström (2015).

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2.3. Panel A illustrates how expertise acquisition declines in the limit-order market as the number of buyers n is increased. For $n \geq 5$ buyer competition in the limit-order market is sufficient to completely eliminate expertise acquisition, mirroring the results of Proposition 4. As a result, both total surplus and seller surplus rise with n, reaching first-best levels for $n \geq 5$. In contrast, the lower level of competition in the OTC market maintains expertise acquisition incentives for the first buyer, leading to inefficient trade and inefficient expertise acquisition throughout. Excessive expertise acquisition is truly the culprit here, as the OTC market also would be fully efficient if none of the buyers were to acquire expertise. However, buyer 1 clearly prefers the OTC market; his surplus is greater than the surplus of all buyers combined in the limit-order market (see panel D of Figure 5).

In sum, the relative efficiency of OTC and limit-order markets starkly differs in this context, relative to the one obtained under Scenario 1 (in Section 2). Remarkably, these contrasting results apply despite the fact that the two scenarios look very similar when compared based on measures of pricing (e.g., bid-ask spreads), trade volume, and even expertise (assuming one does not control for the type of expertise). This insight highlights relevant challenges for empirical studies relying on such measures to evaluate the relative efficiency of various market structures. We will discuss this issue and related empirical implications in Section 5.

4. Robustness and Extensions

In this section, we consider several extensions of our model to discuss the robustness of our main results.

4.1 Imperfectly predictable OTC networks

Our analysis thus far has emphasized asymmetric connectedness of traders as a key feature of OTC markets. To capture this characteristic, our baseline model considered a clear hierarchy of OTC counterparties in terms of their access to order flow. Yet such a clear ranking is not necessary for our main results. Rather, a sufficient degree of predictability is needed to support the expertise channel we highlight in this paper.

To illustrate this point, we revisit the conditions laid out in Proposition 1, which yield analytical tractability. In our baseline model, the first buyer was contacted first with probability one, implying a marginal benefit of expertise equal to $\bar{\alpha} > 0$ (the formula for $\bar{\alpha}$ is provided in the proof of Proposition 1). The first buyer weighed this marginal benefit $\bar{\alpha}$ against the marginal cost of expertise acquisition α. Suppose now that contrary to our baseline setting, all buyers $i = 1, ..., n$ have a strictly positive probability ϕ_i of being contacted first. Proposition 1 considers the case of $\rho = 0$, so our analysis is greatly simplified because it is not necessary to specify buyers' probabilities of being contacted second, third, etc.

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In this extension with imperfect predictability, each buyer compares a marginal benefit of $\phi_i \bar{\alpha}$ to the marginal cost of expertise acquisition α. As long as the probabilities differ sufficiently, in particular if $\phi_1 > \frac{\alpha}{\bar{\alpha}}$ and $\phi_i < \frac{\alpha}{\bar{\alpha}}$ (for $i = 2, ..., n$), the exact same expertise choices apply as under Proposition 1. However, total surplus is still lower than under the baseline case of $\phi_1 = 1$, as the seller can interact with the informed buyer only with a probability $\phi_1 < 1$ rather than with probability 1. Yet, as long as ϕ_1 is not too low, total surplus and seller surplus are still higher in the OTC market than in the limit-order market. Consider the following example (derivations are provided in Appendix B.1):

Example 1. Suppose that $b \sim N(0,1)$, $\rho = 0$, $\alpha = 0.09$, and $n = 10$. Using a result from the proof of Proposition 2 we obtain $\bar{\alpha} \approx 0.13$. If $\phi_1 > \frac{\alpha}{\bar{\alpha}} \approx 0.69$, then seller surplus, buyer surplus, and total surplus are higher in the OTC market than in the limit-order market.

This example illustrates that if the first buyer has a sufficiently high probability of being contacted first (here 69% of the time), the OTC market is still preferred by all agents (for buyers $i \geq 2$ weakly preferred). In contrast, without any predictability, the OTC market generates lower surpluses for all traders. Consider the extreme case in which all buyers have a symmetric probability of being contacted, that is, $\phi_i = 1/n$. In this case, buyers choose not to acquire any expertise in the OTC market for $n > \frac{\bar{\alpha}}{\alpha}$. As a result, total surplus in the OTC market is zero, whereas seller surplus and total surplus are strictly positive in the limit-order market.

In sum, the asymmetric connectedness of traders in the OTC market is a key feature of the channel we highlight in this paper, although the order in which buyers are contacted does not have to be deterministic as assumed in our baseline model.

4.2 Two-dimensional expertise acquisition

In our baseline model, we analyzed two distinct scenarios that helped us cleanly differentiate the beneficial versus harmful effects of expertise acquisition. Under Scenario 1, buyers were able to acquire private information about the gains to trade b. Under Scenario 2, buyers instead acquired private information about the common value component v. In practice, there may be many relevant examples where traders can potentially acquire both types of private information, a possibility that we now discuss in detail.

If each buyer could choose to either acquire expertise about b or about v, the benefits of either types of signals would be similar, as suggested by the resemblance of the objectives buyers maximize when choosing expertise under Scenarios 1 and 2. Taking the seller's price as given, a buyer profits from expertise because it increases the probability that he will be able to buy the asset when his willingness to pay $w(s_i)$ is greater than the price p quoted by the seller. Whether the willingness to pay exceeds the price (i.e., $w(s_i) > p$)

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because of a good signal about the common value component ($s_i = v$) or a good signal about the gains from trade ($s_i = b$) does not matter to the buyer, as long as the probability of receiving the asset conditional on agreeing to the price is the same.

Appendix B.2 shows that, in the limit-order market, this probability primarily depends on how many competing buyers have received the same type of signal as buyer i and less so on how many of them have received the other type of signal. While a buyer who observed a good signal $s_i = b$ must compete for the asset with all other buyers informed about b, he only competes with buyers informed about v when v is large enough, that is, with probability $[1 - F_{w|v}(p)]$. Thus, like in our baseline model, a buyer's incentives to acquire a specific type of expertise is dampened by the fact that many other buyers are expected to acquire the same type of expertise.

Moreover, with two-dimensional expertise acquisition, a buyer informed about b is facing adverse selection from buyers informed about v, and vice versa. Thus, informed buyers must adjust their willingness to pay in ways similar to how the uninformed buyers did in our baseline model. In addition, expertise choices naturally depend on the relative costs of acquiring private information about the value components b and v; as the cost of obtaining private information on a given value component becomes large, the model with two-dimensional expertise acquisition becomes observationally equivalent to either Scenario 1 or Scenario 2.

Finally, in this extended setting a seller's pricing decision again depends on the overall price-acceptance probability trade-off, which accounts for buyers' equilibrium acquisition and adverse selection on the common value component v.

Overall, while a setting with two-dimensional expertise choice is less tractable, it still features economic trade-offs very similar to those highlighted in our baseline analysis. To provide additional guidance for empirical studies, we will discuss in Section 5 potential empirical approaches to identify classes of transactions where each type of expertise is more likely to be of primary relevance.

4.3 Alternative trading environments

To focus on the role of traders' endogenous expertise choices, we modeled trading interactions in close resemblance to the canonical framework of Glosten and Milgrom (1985). In both the OTC and the limit-order market, an uninformed liquidity provider was assumed to quote ultimatum prices to potentially informed traders. In this section, we highlight how the key insights developed in our environment would extend to many well-known trading mechanisms that could potentially be featured in centralized markets. In particular, if the seller could use auctions (see, e.g., Myerson 1981) in a centralized venue to extract maximum rents from buyers at the trading stage, buyers would also have particularly low incentives to acquire expertise ex ante, echoing our

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results for the centralized limit-order market in our model. In fact, because informed buyers receive perfectly correlated signals under Scenarios 1 and 2, it is straightforward to design mechanisms that allow the seller to extract all rents, *taking buyers' expertise as given*. Yet these mechanisms would also yield the worst possible levels of allocative efficiency and seller surplus (i.e., zero surplus) once we account for the endogeneity of expertise choices.

To fix ideas, consider our environment under Scenario 1 with $\mu_b \leq 0$, such that expertise can be socially valuable. Using the revelation principle, a seller could set up a mechanism that asks buyers to report their signals s_i and specifies transfers as follows: (1) any buyer who reports to have received an informative signal that is below the maximum signal reported by any other buyer has to pay a large fine; (2) any of the buyers who submits the highest report receives the asset with equal probability, in exchange for a payment equal to the associated valuation; and (3) any buyer who reports not to have received a signal does not receive the asset and does not make any payments. Under this mechanism, buyers that receive an informative signal would not have incentives to underreport, as underreporting entails a positive probability of being caught and paying a large fine. In addition, these buyers would be indifferent between truthfully revealing their signal $s_i = b$, pooling with uninformed buyers, and not participating in the mechanism (all of which yield zero surplus). Under this mechanism, all available surplus would be extracted by the seller, holding expertise fixed (see also Cremer and McLean 1988, for related mechanisms when traders' signals are imperfectly correlated). However, this centralized mechanism would also eliminate buyers' incentives to acquire expertise ex ante. In turn, facing uninformed buyers, the seller's surplus and total surplus would be zero. This result contrasts with our results for bilateral OTC trading, which generally yields a positive surplus for the seller and at least some buyer(s).

Similarly, consider the environment we analyzed under Scenario 2, where expertise is harmful and $\mu_b > 0$. Here, a mechanism that allows the seller to extract all rents at the trading stage would also eliminate buyers' incentives for expertise acquisition, yet now this effect would improve allocative efficiency. Again, this result mirrors the conclusions we obtained from analyzing the centralized limit-order market in our model. In particular, Proposition 4 highlighted that under Scenario 2, the centralized limit-order market is attractive as it eliminates all incentives for expertise acquisition for large enough n, thereby achieving the maximum possible surplus for the seller.

Another potential variation to our trading environment would be to consider the case in which potentially informed buyers can quote offers to the seller (rather than the uninformed seller making the take-it-or-leave-it offer). In this case, buyers' offers would generally introduce signaling concerns and the associated equilibrium multiplicity typical in signaling games, a feature that would lead to less sharp predictions. Yet, under reasonable restrictions on beliefs, increased competition among buyers for order flow would still have the tendency to reduce each individual buyer's ability to extract information

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rents, thereby weakening incentives for expertise acquisition. That is, the central channel highlighted in our analysis that increased competition for order flow in the limit-order market reduces individual traders' information rents and incentives for expertise acquisition would still operate.

More broadly, these results reiterate our main insight that limited access to counterparties in OTC markets increases incentives for expertise acquisition by alleviating commitment problems; OTC frictions allow the seller to credibly promise not to choose trading strategies or mechanisms that leave specialized counterparties with little to no surplus ex post, thereby providing a subset of traders with incentives to invest in expertise ex ante.

4.4 Uncorrelated private values

In our baseline model laid out in Section 1, we specified the gains to trade between the seller, on the one hand, and all buyers, on the other, as equal to the common stochastic parameter b. This specification captured situations where buyers face common outside opportunities for investing their liquidity, common regulatory constraints and hedging motives, or common shocks to customer demand for a particular security. In this section, we highlight that key insights developed for this case carry over to cases in which the gains to trade are uncorrelated across buyers, that is, when the value components b_i are uncorrelated.[16] Modeling gains to trade that are uncorrelated across buyers allows to capture trader-specific liquidity and inventory concerns, as well as buyers' idiosyncratic (rather than common) opportunities for retrade.

To economize on space, we relegate the formal presentation and analysis for this extension to Appendix B.3 and discuss the economic intuition and illustrations here in the main text. Figure 6 follows the familiar format of previous figures, plotting equilibrium expertise choices, total surplus, seller surplus, and total buyer surplus. In the presence of uncorrelated value components b_i, the duplication of effort channel does not operate, as buyers acquire information on distinct variables. Yet the competition channel highlighted throughout this paper operates here in just the same fashion: as the number of potential buyers n is increased, each buyer's incentives for expertise acquisition decline. Yet, because expertise is needed to inform traders about their private valuations and associated gains to trade, total surplus and seller surplus decline as n is increased. Moreover, the OTC market yields higher total surplus and seller surplus throughout.

To summarize, the economic insight that we aim to highlight in this paper—that asymmetric connectedness in the OTC market helps incentivize expertise acquisition that may be needed for allocative efficiency—also operates in

[16] In fact, in previous versions of this paper, we focused on this type of specification. Yet we found that, from a modeling perspective, the setup with uncorrelated private values is less tractable for two reasons. First, this setup does not yield the clean analytical comparisons of market structures based on agents' surplus as derived in Propositions 1 through 3. Second, a setting with uncorrelated private values raises the issue of potential retrade that is less tractable with an increasing number of buyers, distracting from the main focus of our paper.

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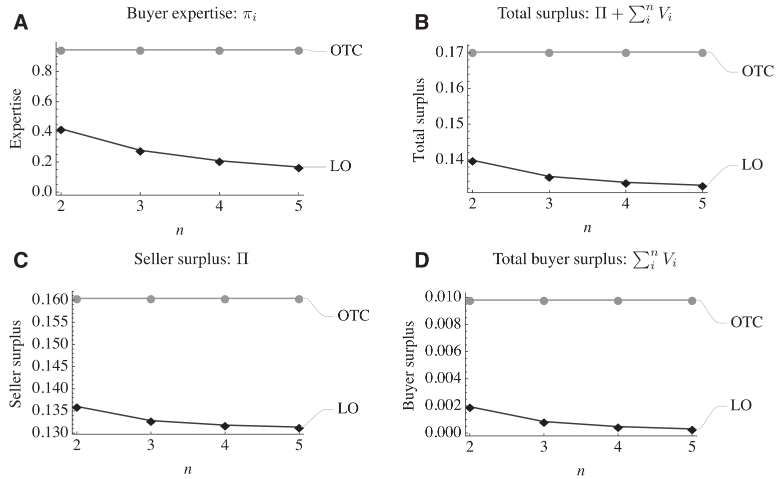

Figure 6
Uncorrelated private value components b_i
The graphs illustrate buyers' expertise acquisition (panel A), total surplus (panel B), seller surplus (panel C), and total buyer surplus (panel D) in the OTC market and in the limit-order market. The illustrated expertise level for the OTC market refers to buyer 1 only; all other buyers optimally choose $\pi_i = 0$ (for $i = 2, ..., n$). The expertise level shown for the limit-order market reflects buyers' symmetric level of expertise $\pi_i = \pi$. We set $b_i \sim N(0,1)$ for all i, $\rho = 0$, $\beta = 0.022$, and $\gamma = 5$.

environments in which the potential gains to trade are uncorrelated among buyers.

4.5 Multiple sellers

In our model, we have analyzed an environment with only one seller. The incentives to screen counterparties with price quotes would, however, still apply in settings with multiple sellers. Screening can arise as long as each seller faces a somewhat inelastic "residual" demand curve, that is, a seller faces a trade-off between the price he collects when a sale occurs and the probability of a sale occurring. In our environment, this property would be satisfied as long as the total supply of assets by all sellers was smaller than the total capacity to absorb it by all buyers. Furthermore, we know from Biais, Martimort, and Rochet (2000) and Vives (2011) that inefficient screening may also occur in richer environments with risk-averse traders, inventory risk, and liquidity providers that compete in mechanisms. Finally, the roles of buyers and sellers could be reversed in our model without affecting our main insights.

4.6 Implementation

While our results indicated an alignment of the seller's ranking of market structures (based on his surplus) and the ranking based on total surplus, some buyers were generally worse off under the more efficient market structure. To ensure that all traders are better off under the market structure that yields higher

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total surplus, the model could be extended by a market-design game similar to the network-formation game considered in Glode and Opp (2016). Such a game would precede the trading games discussed in previous sections, and characterize order-flow agreements that traders commit to before information is obtained and trading occurs. A key component of these order-flow agreements would be ex ante transfers that incentivize traders to commit to sending specified volumes of orders, in a probabilistic sense, to specific counterparties. Even if quotes were not publicly observable, commitment to these types of agreements could possibly be sustained in repeated game settings, where variants of the folk theorem with imperfect public information apply (see Fudenberg, Levine, and Maskin 1994). In financial markets, such agreements with payments for order flow are very common. Battalio, Corwin, and Jennings (2016) report that U.S. brokers systematically sell all of their retail marketable orders to market makers (wholesalers). In general, transfers may occur via explicit agreements involving cash payments, or they may be implicit arrangements promising profitable IPO allocations or subsidies on other services (see, e.g., Blume 1993; Chordia and Subrahmanyam 1995; Reuter 2006; Nimalendran, Ritter, and Zhang 2007).

5. Empirical Predictions and Policy Implications

In this section, we discuss how our results can assist the interpretation and design of empirical analyses studying the efficiency of market structures. In addition, we highlight associated policy implications.

5.1 Interpretation and measurement

As a first step, we outline possible approaches to obtaining empirical measures for the two value components that feature prominently in our theory. A trader's valuation of an asset can conceptually be split into a component that is common to all traders and another one that represents gains to trade. Our model provides sharply contrasting implications for the preferred market structure, depending on whether traders tend to acquire expertise on the former or the latter component. Empirically testing whether our paper's prescriptions regarding the more efficient market structure already tend to hold in practice, under the existing regulatory regime, requires good measures of how the relative incentives to acquire each type of expertise vary over time and in the cross-section.

Interpreting the common value component v in our model is relatively straightforward. Typically, new information about an existing security's uncertain cash flows and level of systematic risk should lead *all* traders to update their valuations. Correspondingly, examples of costly expertise acquisition on the common value component include hiring financial analysts to parse through a firm's accounting data, building models that better predict future exchange rates, or collecting data about local real estate conditions. To the extent that these actions are mainly aimed at taking advantage of counterparties

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through informed speculation on existing securities, they match the model's description of the type of expertise acquisition that leads to adverse selection, thereby lowering the efficiency of trade. This channel is likely to be of first-order relevance when expertise yields information that would in any case be publicly released in the near future. Similarly, when the existence of gains to trade is already known to agents, expertise by construction primarily yields private information supporting rent-seeking motives. The key prediction and policy implication of our analysis is that classes of transactions that satisfy these characteristics are more efficiently performed in limit-order markets. For example, existing securities such as stocks and standardized derivatives like corporate call options might primarily attract expertise acquisition for rent-seeking motives and thus would be more efficiently traded in limit-order markets.

On the other hand, the value component b_i in our model represents the amount of surplus that is created through trade between the seller and each buyer, that is, it captures the potential economic reasons trade can be beneficial in the first place.[17] Correspondingly, in practice, information on factors that cause *a subset* of traders to become more efficient holders of an asset than others is also essential to ensuring that trade indeed yields a positive surplus. Relevant examples of costly expertise acquisition yielding this type of information include developing relationships with brokers to assess the overall demand for a particular municipal bond among in-state residents, or adjusting valuation models that assess the opportunity costs for bank-holding companies of purchasing a derivative security given a new set of regulatory rules. Similarly, expertise acquisition might yield information specific to one particular agent or institution: a bank-holding company might need to improve its data infrastructure to better assess and hedge its company-wide inventory and liquidity risks, and a wealthy investor might need to pay for advice from tax accountants and financial planners to optimize the composition of his portfolio, given tax, life-cycle, and diversification concerns. In the context of primary markets, an underwriter investment bank might generously remunerate employees that help determine the net benefit from taking various private firms public, which might be positive or negative depending on factors such as benefits of control, moral hazard problems, external financing constraints, and owners' preferences for liquidity and diversification.

The related main implication of our model, both from a normative and a positive perspective, is that OTC markets are better suited for classes of transactions where the existence of gains to trade is a priori largely uncertain. In terms of asset classes, securities primarily traded for hedging, liquidity, and inventory motives such as municipal bonds and complex derivatives might often involve transactions that fit this description well. For these types of

[17] Moreover, in standard environments (including ours) differences in traders' ex post valuations are needed for trade to even occur (Milgrom and Stokey 1982).

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securities most of the value of expertise lies in knowing which types of institutions or agents are the efficient holders or counterparties. For example, expert knowledge is required to fully understand the risk exposures implied by a complex derivative as well as the types of assets or positions that are natural hedges for these exposures. In the time dimension, the relative benefits of acquiring information about the surplus from trade is also likely to increase with heterogeneity in investors' tax treatment and institutions' regulatory constraints, with the volatility of dealers' inventories, and with the sensitivity of banks' profits to capital and liquidity conditions. In sum, quantifying the amount of uncertainty in the existence of gains to trade between prospective buyers and sellers is a challenging, yet important step for empirically investigating the forces at play in our model.

5.2 Differential predictions

The dependence of the preferred market structure on the characteristics of classes of transactions allows us to differentiate our analysis from alternative theories. Many market design papers, such as Milgrom and Weber (1982) or Bulow and Klemperer (2009), argue for the benefits of a specific trade mechanism (e.g., English auction or sequential bidding), without yielding "cross-sectional" predictions that shed light on why different asset classes tend to be traded in different types of markets (see also the papers cited in the introduction). In contrast, our model suggests empirical relationships between the types of transactions mentioned above, the presence of adverse-selection problems, and the level of trade centralization.

Another prediction of our model that could be tested in the data relates to how trading is expected to occur in OTC markets. The main reason OTC markets can improve the efficiency of trade in our environment is that they provide to a subset of well-connected core traders stronger incentives to acquire expertise. Contrary to the standard intuition in models of asymmetric information, the uninformed trader in our model can be better off transacting with a well-informed counterparty than with an uninformed one, provided that the counterparty's information pertains to the presence of gains to trade. Although papers such as Hagströmer and Menkveld (2016), Di Maggio, Kermani, and Song (2017), Hendershott et al. (2019), and Li and Schürhoff (2019) have already documented that a small number of OTC dealers tend to be contacted much more frequently than others, our model predicts that the level of expertise acquired by these central OTC dealers should be larger than that of peripheral dealers. If data about traders' expertise investments per se is not available, using estimates of dealer information derived from transaction data, in the spirit of Di Maggio et al. (forthcoming), could help test this prediction. Further, our model predicts that the benefits of first contacting these core counterparties should increase in times when the existence of gains to trade is particularly uncertain, such as in crisis periods, when market participants' relative liquidity needs might exhibit more dispersion.

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The efficiency benefits of asymmetric access to OTC counterparties found in our model also contrasts with the predictions of many models where search frictions unambiguously lower the efficiency of trade. In our model, the seller's pricing strategy when trading with a buyer depends on the ease with which additional counterparties can be reached. More severe frictions in reaching additional counterparties imply more cautious and generous pricing behavior, which in turn increases well-connected traders' incentives for expertise acquisition. These strategic responses by both the seller and the buyer are absent from search-based models like Duffie, Gârleanu, and Pedersen (2005), where traders are symmetrically informed and the surplus from trade is split according to Nash bargaining. As a result, documenting how a shock to trader connections affects information acquisition and pricing in OTC markets should shed light on the empirical validity of our channels.

Our theory also differs from the narrative that OTC markets are particularly prevalent in asset classes where trade volume is naturally low and where the costs of operating a limit-order book would be prohibitively high. Two challenges to this narrative do not apply to our theory: first, an ample number of examples of securities feature large volumes of OTC trade. Second, adding securities to an existing electronic limit-order market entails very low costs. In contrast, information about the existence of surplus from trade is unlikely to be available without costly expertise acquisition (see the various examples discussed above). In this context, it is also useful to keep in mind that the volume of assets for sale is normalized to one in our model (see footnote 10). Intuitively, if buyers expect a low volume of liquidity-driven order flow, acquiring expertise about a given asset is less advantageous, as this expertise can be applied to a smaller dollar amount of trade. Given the normalization, the costs of acquiring expertise *per unit of expected volume* should be relatively higher in circumstances (e.g., asset classes or time periods) where expected order flow is low. Our model predicts that when expertise costs are high relative to the expected volume of order flow, trade needs to be strongly concentrated to ensure that at least one well-connected dealer has incentives to acquire expertise.

5.3 Policy implications

Our results also highlight relevant limitations of policy-oriented studies that aim to compare trade efficiency across markets without accounting for the endogeneity of traders' information sets and the nature of expertise. In particular, our analysis shows that common measures, such as bid-ask spreads and transaction volume, provide little information about efficiency when expertise is endogenous and needed to assess the gains to trade. Consider a parameterization of our model in line with Scenario 1 where the gains to trade are largely uncertain, and where their expected value μ_b is positive but close to zero. A market structure that completely discourages expertise acquisition

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(e.g., a limit-order market) would feature maximal trade volume at the low uninformed "ask" price, yet the realized surplus from trade would be close to zero (i.e., equal to μ_b). This market structure would feature substantial *excess volume* in the sense that a large fraction of transactions would destroy surplus. For example, if the gains to trade were symmetrically distributed with a mean close to zero, then approximately 50% of transactions would actually destroy surplus and should be avoided. In contrast, a market structure that encourages expertise acquisition (e.g., an OTC market) would feature higher ask prices and much lower trade volume. Yet the surplus from trade would be significantly larger, as transactions destroying surplus would be avoided. From a policy perspective, these insights are potentially of first-order relevance when drawing conclusions based on existing empirical evidence across markets. In particular, our model's predictions for the OTC market are fully consistent with empirical studies documenting higher spreads, lower volume, and greater rents for a small set of dealers in these markets (see, e.g., Biais and Green 2007). Yet our analysis highlights that, in classes of transactions where expertise is needed to inform agents about the presence of gains from trade, these empirical observations do not lend themselves to the conclusion that limit-order markets would yield higher levels of allocative efficiency.

6. Conclusion

In this paper, we compared the relative merits of centralized limit-order markets and decentralized OTC markets in an environment in which traders' expertise is endogenous. Relative to the limit-order market, the OTC market is less competitive and yields increased rents and incentives for expertise acquisition for a subset of well-connected core traders. We find that the efficiency implications of these differential expertise incentives strongly depend on the nature of expertise agents can acquire.

When expertise yields information that helps agents determine whether a transaction generates positive economic surplus, heightened incentives for expertise acquisition can be essential for allocative efficiency. In contrast, when expertise merely provides an informational advantage about an asset's value (rather than about the value added from transacting) it introduces adverse selection and impedes the efficiency of trade. In turn, given that OTC and limit-order markets provide starkly different incentives for expertise acquisition, our model yields sharp predictions for the prevalence and efficiency of these two market structures across different classes of transactions. Moreover, our analysis highlights that common empirical measures, such as bid-ask spreads or transaction volume, provide little information about the relative efficiency of markets when expertise is endogenous and needed to determine the gains from a transaction. These results have potentially important implications for

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ongoing debates about regulatory reforms that aim to curtail OTC trading in favor of trading in centralized markets.

Appendix A. Proofs Omitted from the Main Text

A.1 Proof of Proposition 1

Proof. Condition (13) does not depend on the number of buyers n. Moreover, under the assumptions stated in the proposition, the pricing decision in the OTC market is the same as the one in the limit-order market for $n=1$. Thus, in both the limit-order market and in the OTC market, the price p optimally quoted by the seller when $\pi>0$ satisfies the first-order condition:

$$\frac{f_b(p-\mu_v)(p-\mu_v)}{1-F_b(p-\mu_v)}=1. \tag{A1}$$

Moreover, a price satisfying condition (A1) is also weakly optimal for $\pi=0$ (for $\pi=0$ and $\mu_b=0$, charging any price $p\geq\mu_v$ yields the seller a payoff equal to μ_v). From condition (A1), we obtain that $p>\mu_v\geq w(\emptyset)$, which implies that $F_{w|\emptyset}(p)=1$. If buyer i believes that all other buyers choose an expertise level of π in the limit-order market, then he expects the following constant marginal net benefit of increasing his expertise π_i:

$$V_i'(\pi_i)=[1-F_{w|b}(p)]\cdot(\mu_v+\mathbb{E}[b|b>p-\mu_v]-p)\sum_{m=0}^{n-1}\frac{B(n-1,m,\pi)}{m+1}-\alpha. \tag{A2}$$

Thus, buyer i only finds it optimal to choose a $\pi_i\in(0,1)$ if the expertise level of all other buyers π implies a zero marginal net benefit, that is, if π solves the following equality:

$$\sum_{m=0}^{n-1}\frac{B(n-1,m,\pi)}{m+1}=\frac{\alpha}{\overline{\alpha}}, \tag{A3}$$

where we define

$$\overline{\alpha}\equiv[1-F_{w|b}(p)]\cdot(\mu_v+\mathbb{E}[b|b>p-\mu_v]-p), \tag{A4}$$

and where the parameter restriction $\alpha\leq\overline{\alpha}$ ensures that there is a positive amount of expertise acquisition under at least one of the two market structures. In particular, $\overline{\alpha}$ represents the marginal benefit of the first buyer in the OTC market:

$$V_1'(\pi_1)=\overline{\alpha}-\alpha, \tag{A5}$$

and thus the first buyer sets $\pi_1=1$, which is strictly optimal for the buyer for $\alpha<\overline{\alpha}$ and weakly optimal for $\alpha=\overline{\alpha}$ (but strictly dominates socially). Expected payoffs in the OTC market are given by

$$V_1=[1-F_{w|b}(p)]\cdot(\mu_v+\mathbb{E}[b|b>p-\mu_v]-p)-\alpha, \tag{A6}$$

$$\Pi=[1-F_{w|b}(p)]\cdot(p-\mu_v)+\mu_v, \tag{A7}$$

$$\Pi+V_1=[1-F_{w|b}(p)]\cdot\mathbb{E}[b|b>p-\mu_v]+\mu_v-\alpha. \tag{A8}$$

In the limit-order market, the expected payoffs are given by

$$V_i=\pi[1-F_{w|b}(p)]\cdot(\mu_v+\mathbb{E}[b|b>p-\mu_v]-p)\sum_{m=0}^{n-1}\frac{B(n-1,m,\pi)}{m+1}-\pi\alpha, \tag{A9}$$

$$\Pi=[1-(1-\pi)^n][1-F_{w|b}(p)]\cdot(p-\mu_v)+\mu_v, \tag{A10}$$

$$\Pi+\sum_i^n V_i=[1-(1-\pi)^n][1-F_{w|b}(p)]\cdot\mathbb{E}[b|b>p-\mu_v]+\mu_v-n\pi\alpha. \tag{A11}$$

Two cases can obtain in the limit-order market, which we now detail.

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Case 1 ($n \leq \frac{\bar{\alpha}}{\alpha}$): In the limit-order market, buyers optimally acquire expertise $\pi = 1$. The expected payoffs are then given by

$$V_i = [1 - F_{w|b}(p)] \cdot (\mu_v + \mathbb{E}[b|b > p - \mu_v] - p) \sum_{m=0}^{n-1} \frac{B(n-1, m, \pi)}{m+1} - \alpha, \tag{A12}$$

$$\Pi = [1 - F_{w|b}(p)] \cdot (p - \mu_v) + \mu_v, \tag{A13}$$

$$\Pi + \sum_i^n V_i = [1 - F_{w|b}(p)] \cdot \mathbb{E}[b|b > p - \mu_v] + \mu_v - n\alpha, \tag{A14}$$

which immediately reveals that the total payoff $\Pi + \sum_i^n V_i$ in the limit-order market is lower than the one in the OTC market. The difference is equal to $(n-1)\alpha$. The seller's surplus is identical in both markets.

Case 2 ($n > \frac{\bar{\alpha}}{\alpha}$): Buyers in the limit-order market optimally set $\pi < 1$. Because $V_i(\pi_i)$ is linear in π_i, the expected payoffs are then given by

$$V_i = 0, \tag{A15}$$

$$\Pi = [1 - (1-\pi)^n][1 - F_{w|b}(p)] \cdot (p - \mu_v) + \mu_v, \tag{A16}$$

$$\Pi + \sum_i^n V_i = \Pi. \tag{A17}$$

Relative to the OTC market, both the seller surplus and the total buyer surplus are lower in the limit-order market. Thus, total surplus is also lower in the limit-order market. ■

A.2 Proof of Proposition 2

Proof. *Pricing.* Suppose that in equilibrium, the seller believes that only the first buyer acquires expertise $\pi_1 = 1$, and that all other buyers do not acquire expertise (i.e., $\pi_i = 0$ for $i = 2, 3, ..., n$). As a result, the seller's continuation values are $\Pi_i = \mu_v$, for $i = 2, 3, ..., n$ and the price the seller optimally quotes to the first buyer satisfies the marginal condition:

$$\frac{f_b(p_1 - \mu_v) \cdot (p_1 - \mu_v)}{1 - F_b(p_1 - \mu_v)} = 1. \tag{A18}$$

Given the belief that $\pi_i = 0$ for all $i \geq 2$, any price $p_2 > w_2(\emptyset)$ is optimal, as such a price is rejected with probability one (note that $w_2(\emptyset) < \mu_v$, and μ_v is the seller's reservation price for the asset). However, suppose the seller specifically quotes an optimal price $p_2 > w_2(\emptyset)$ that is also optimal when $\pi_2 > 0$ with $\pi_2 \searrow 0$. This price p_2 must solve the zero marginal profit condition (for $\mu_b = 0$ the seller optimally targets the informed types):

$$1 - F_b(p_2 - \mu_v | b < p_1 - \mu_v) - f_b(p_2 - \mu_v | b < p_1 - \mu_v) \cdot (p_2 - \mu_v) = 0. \tag{A19}$$

or equivalently:

$$\frac{f_b(p_2 - \mu_v) \cdot (p_2 - \mu_v)}{F_b(p_1 - \mu_v) - F_b(p_2 - \mu_v)} = 1. \tag{A20}$$

The assumption that $b \sim N(0, \sigma_b)$ implies the following solutions to Equations (A18) and (A20):

$$p_1 \approx \mu_v + \sigma_b \cdot 0.75, \tag{A21}$$

$$p_2 \approx \mu_v + \sigma_b \cdot 0.37. \tag{A22}$$

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Incentives to acquire expertise. Because $\mu_b = 0$, the marginal benefit of expertise for the first buyer is given by

$$\begin{aligned}\overline{\alpha} &= [1-F_b(p_1-\mu_v)]\cdot(\mu_v+\mathbb{E}[b|b>p_1-\mu_v]-p_1)\\ &= [1-F_b(p_1-\mu_v)]\cdot\left(\mu_v+\sigma_b^2\frac{f_b(p_1-\mu_v)}{1-F_b(p_1-\mu_v)}-p_1\right)\\ &= \sigma_b^2 f_b(p_1-\mu_v)-[1-F_b(p_1-\mu_v)](p_1-\mu_v)\\ &\approx 0.13\cdot\sigma_b. \end{aligned} \tag{A23}$$

For $\rho = 1$, and given the belief that $\pi_1 = 1$, the marginal benefit of expertise for the second buyer is

$$\begin{aligned}\overline{\alpha}_2 &= F_b(p_1-\mu_v)\int_{p_2-\mu_v}^{p_1-\mu_v}\frac{f_b(b)}{F_b(p_1-\mu_v)}(\mu_v+b-p_2)db\\ &= [F_b(p_1-\mu_v)-F_b(p_2-\mu_v)](\mu_v+\mathbb{E}[b|p_2-\mu_v<b<p_1-\mu_v]-p_2)\\ &= [F_b(p_1-\mu_v)-F_b(p_2-\mu_v)]\left(\mu_v+\sigma_b^2\frac{f_b(p_2-\mu_v)-f_b(p_1-\mu_v)}{F_b(p_1-\mu_v)-F_b(p_2-\mu_v)}-p_2\right)\\ &= \sigma_b^2[f_b(p_2-\mu_v)-f_b(p_1-\mu_v)]-[F_b(p_1-\mu_v)-F_b(p_2-\mu_v)](p_2-\mu_v)\\ &\approx 0.025\cdot\sigma_b\\ &\approx 0.194\cdot\overline{\alpha}. \end{aligned} \tag{A24}$$

Thus, for $\alpha > 0.194\cdot\bar{\alpha}$, the second buyer's marginal benefit of acquiring expertise is negative net of cost, implying that $\pi_2 = 0$. Given the seller's beliefs, the price p_2 solving Equation (A20) is also an optimal price quoted to buyers $i \geq 3$. Given that buyers $i \geq 3$ believe that only buyer 1 acquires a positive amount of expertise and that they will be quoted the price $p_i = p_2$ (for $i \geq 3$), each one of them expects a marginal benefit of expertise equal to $\overline{\alpha}_2$, sustaining the Nash equilibrium with $\pi_i = 0$ for all $i \geq 2$. ■

A.3 Proof of Proposition 3

Proof. *No expertise acquisition in limit-order market for $n > n^*$.* Suppose that for $n > n^*$ the seller believes that all buyers indeed choose $\pi_j = 0$, and that buyer i also believes that all other buyers choose $\pi_j = 0$. Using Equation (15), we know that buyer i's marginal net benefit of increasing expertise is given by

$$V_i'(\pi_i) = \frac{[1-F_{w|b}(p)]\cdot(\mu_v+\mathbb{E}[b|b>p-\mu_v]-p)}{n}-\alpha, \tag{A25}$$

where we use $F_{w|\emptyset}(p) = 0$, because the seller optimally sets $p = \mu_v + \mu_b = w(\emptyset)$ given his beliefs that only uninformed buyers are in the market. Moreover, note that

$$F_{w|b}(p) = F_{w|b}(\mu_v+\mu_b) = F_b(\mu_v+\mu_b-\mu_v) = 0.5. \tag{A26}$$

Thus, the marginal net benefit of increasing π_i is negative whenever

$$n > n^* \equiv \frac{\mathbb{E}[b|b>\mu_b]-\mu_b}{2\alpha} = \frac{\sigma_b^2\frac{f_b(\mu_b)}{1-F_b(\mu_b)}}{2\alpha} = \frac{\sigma_b}{\alpha}\frac{1}{\sqrt{2\text{pi}}}, \tag{A27}$$

where "pi" refers to Archimedes' constant, implying that buyer i optimally does not deviate from $\pi_i = 0$. By symmetry, none of the buyers i have an incentive to acquire expertise, supporting the conjectured equilibrium.

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Positive expertise acquisition in the OTC market for all n. An equilibrium with expertise acquisition $\pi_1 = 1$ exists in the OTC market as long as the marginal cost of expertise is bounded from above by buyer 1's marginal benefit of expertise, $\bar{\alpha}$:

$$\alpha < \bar{\alpha} \equiv [1 - F_b(p_1 - \mu_v)] \cdot (\mu_v + \mathbb{E}[b|b > p_1 - \mu_v] - p_1), \tag{A28}$$

where p_1 solves Equation (13), as the seller believes that $\pi_1 = 1$, implying that it is always optimal to target the informed buyer types, and because under the given assumptions (in particular, $\rho = 0$), the seller's marginal pricing trade-off in the OTC market is equivalent to the one in the limit-order market.

Comparing expected payoffs across market structures. In the OTC market, the expected payoffs are given by

$$V_1 = [1 - F_b(p_1 - \mu_v)] \cdot (\mu_v + \mathbb{E}[b|b > p_1 - \mu_v] - p_1) - \alpha, \tag{A29}$$

$$\Pi = [1 - F_b(p_1 - \mu_v)] \cdot p_1 + F_b(p_1 - \mu_v) \cdot \mu_v, \tag{A30}$$

$$\Pi + V_1 = \mu_v + [1 - F_b(p_1 - \mu_v)] \cdot \mathbb{E}[b|b > p_1 - \mu_v] - \alpha, \tag{A31}$$

where for the normal distribution we obtain

$$\mathbb{E}[b|b > p_1 - \mu_v] = \mu_b + \sigma_b^2 \frac{f_b(p_1 - \mu_v)}{1 - F_b(p_1 - \mu_v)}, \tag{A32}$$

and thus

$$\Pi + V_1 = \mu_v + [1 - F_b(p_1 - \mu_v)] \cdot \left(\mu_b + \sigma_b^2 \frac{f_b(p_1 - \mu_v)}{1 - F_b(p_1 - \mu_v)} \right) - \alpha, \tag{A33}$$

$$\Pi + V_1 = \mu_v + [1 - F_b(p_1 - \mu_v] \cdot \mu_b + \sigma_b^2 f_b(p_1 - \mu_v)) - \alpha. \tag{A34}$$

As a result, the limit-order market dominates in terms of total surplus when

$$[1 - F_b(p_1 - \mu_v) \cdot \mu_b + \sigma_b^2 f_b(p_1 - \mu_v)] - \alpha < \mu_b, \tag{A35}$$

that is,

$$\sigma_b^2 f_b(p_1 - \mu_v) - F_b(p_1 - \mu_v)\mu_b - \alpha < 0. \tag{A36}$$

Using the fact that p_1 solves Equation (13), it can be verified numerically that under normality we obtain

$$\sigma_b^2 f_b(p_1 - \mu_v) < F_b(p_1 - \mu_v)\mu_b \quad \Leftrightarrow \quad \frac{\mu_b}{\sigma_b} > 0.58, \tag{A37}$$

which accounts for the fact that the objects p_1, f_b, and F_b are all functions of σ_b and μ_b. Thus, for $\frac{\mu_b}{\sigma_b} > 0.58$ and for $\alpha \in (0, \bar{\alpha})$, total surplus is greater in the limit-order market than it is in the OTC market. ■

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A.4 Proof of Proposition 4

Proof. *No expertise acquisition in limit-order market for $n > n^*$.* Suppose that there indeed exists an n^* such that for $n > n^*$ the seller believes in equilibrium that all buyers choose $\pi_j = 0$, and each buyer i believes that all other buyers $j \neq i$ choose $\pi_j = 0$. We verify if any individual buyer i would have an incentive to deviate to $\pi_i > 0$. Using Equation (15), we know that buyer i's marginal net benefit of increasing expertise is given by

$$V_i'(\pi_i) = \frac{(1 - F_{w|v}(p)) \cdot (\mu_b + \mathbb{E}[v|v > p - \mu_b] - p)}{n} - \alpha, \tag{A38}$$

where we use $F_{w|\emptyset}(p) = 0$, because the seller optimally sets $p = w(\emptyset) = \mu_v + \mu_b$ when expecting only uninformed buyers in the market. Moreover, note that

$$F_{w|v}(p) = F_v(\mu_v) = 0.5. \tag{A39}$$

Thus, the marginal benefit of increasing π_i is negative whenever

$$n > n^* \equiv \frac{\mathbb{E}[v|v > \mu_v] - \mu_v}{2\alpha} = \frac{\sigma_v^2 \frac{f_v(\mu_v)}{1 - F_v(\mu_v)}}{2\alpha} = \frac{\sigma_v}{\alpha\sqrt{2\text{pi}}}, \tag{A40}$$

implying that buyer i optimally does not deviate from $\pi_i = 0$. By symmetry, none of the other buyers have an incentive to acquire expertise, supporting the conjectured equilibrium.

Positive expertise acquisition in the OTC market for all n. An equilibrium with expertise acquisition $\pi_1 = 1$ exists in the OTC market as long as the marginal cost of expertise is bounded from above by buyer 1's marginal benefit of expertise, $\bar{\alpha}$:

$$\alpha < \bar{\alpha} \equiv [1 - F_v(p_1 - \mu_b)] \cdot (\mu_b + \mathbb{E}[v|v > p_1 - \mu_b] - p_1), \tag{A41}$$

where p_1 is the price optimally quoted by the seller. Given the belief that buyer 1 optimally acquires expertise $\pi_1 = 1$, the seller optimally targets the informed buyer types, that is, p_1 solves the marginal condition:

$$\frac{f_v(p_1 - \mu_b)}{1 - F_v(p_1 - \mu_b)} \cdot (p_1 - \mu_b) = 1. \tag{A42}$$

Comparing expected payoffs across market structures. In the OTC market, we obtain the following expected payoffs:

$$V_1 = [1 - F_v(p_1 - \mu_b)] \cdot (\mu_b + \mathbb{E}[v|v > p_1 - \mu_b] - p_1) - \alpha \cdot 1, \tag{A43}$$

$$\Pi = [1 - F_v(p_1 - \mu_b)] \cdot p_1 + F_v(p_1 - \mu_b) \cdot \mathbb{E}[v|v \leq p_1 - \mu_b], \tag{A44}$$

$$\begin{aligned} \Pi + V_1 = {} & [1 - F_v(p_1 - \mu_b)] \cdot (\mu_b + \mathbb{E}[v|v > p_1 - \mu_b]), \\ & + F_v(p_1 - \mu_b) \cdot \mathbb{E}[v|v \leq p_1 - \mu_b] - \alpha, \end{aligned} \tag{A45}$$

where for $v \sim N(\mu_v, \sigma_v)$ the truncated expectations are given by

$$\mathbb{E}[v|v > p_1 - \mu_b] = \mu_v + \sigma_v^2 \frac{f_v(p_1 - \mu_b)}{1 - F_v(p_1 - \mu_b)}, \tag{A46}$$

$$\mathbb{E}[v|v \leq p_1 - \mu_b] = \mu_v - \sigma_v^2 \frac{f_v(p_1 - \mu_b)}{F_v(p_1 - \mu_b)}, \tag{A47}$$

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such that we obtain

$$\begin{aligned}\Pi+V_1=\mu_v+[1-F_v(p_1-\mu_b)]\cdot\left(\mu_b+\sigma_v^2\frac{f_v(p_1-\mu_b)}{1-F_v(p_1-\mu_b)}\right)\\-F_v(p_1-\mu_b)\sigma_v^2\frac{f_v(p_1-\mu_b)}{F_v(p_1-\mu_b)}-\alpha\\=\mu_v+[1-F_v(p_1-\mu_b)]\mu_b-\alpha.\end{aligned} \quad \text{(A48)}$$

In contrast, in the limit-order market, for $n>n^*$ we obtain

$$\Pi+\sum_i^n V_i=\Pi=\mu_v+\mu_b. \quad \text{(A49)}$$

Thus, seller surplus and total surplus are strictly higher in the limit-order market. ■

Appendix B. Extensions

B.1 Imperfectly Predictable OTC Networks

In this appendix, we verify the two constraints that are sufficient for the result in Example 1 to hold. First, the conditions $\phi_1>\frac{\alpha}{\bar{\alpha}}\approx 0.69$ and $\phi_i<\frac{\alpha}{\bar{\alpha}}$ (for $i\geq 2$) ensure that the first buyer acquires expertise $\pi_1=1$ and that all other buyers set $\pi_i=0$. Second, from the proof of Proposition 1 we know that for $n>\frac{\bar{\alpha}}{\alpha}\approx 1.45$ (which is satisfied for $n=10$) the seller surplus in the limit-order market is a factor $[1-(1-\pi^{\text{LO}})^n]$ times the seller surplus in the OTC market with $\phi_1=1$. For $\phi_1>[1-(1-\pi^{\text{LO}})^n]$, the OTC market generates more surplus for the seller, which also ensures that total surplus is greater (because in the limit-order market only the seller receives a positive surplus, such that total surplus equals seller surplus). In the limit-order market, we obtain $\pi^{\text{LO}}\approx 0.09$ such that $[1-(1-\pi^{\text{LO}})^{10}]\approx 0.60$, implying that the second condition is also satisfied (i.e., $\phi_1>0.69\Rightarrow\phi_1>0.60$).

B.2 Two-Dimensional Expertise Acquisition

Using notation analogous to that from the baseline model, we can extend our model to shed light on a buyer's incentives to choose among two types of expertise. The probability of buyer i being informed is still denoted π_i but we now assume that, conditional on receiving a signal, the probability of being informed about the gains to trade, $s_i=b$, is λ_i whereas the probability of being informed about the common value, $s_i=v$, is $(1-\lambda_i)$. In the limit-order market, buyer i's choices of λ_i and π_i maximize:

$$\begin{aligned}V_i(\pi_i\lambda_i,\pi_i(1-\lambda_i))=&\pi_i\lambda_i\cdot[1-F_{w|b}(p)]\cdot\mathbb{E}[w(b)-p|w(b)\geq p]\cdot\Pr[i\text{ gets asset}|s_i=b\wedge w(b)\geq p]\\&+\pi_i(1-\lambda_i)\cdot[1-F_{w|v}(p)]\cdot\mathbb{E}[w(v)-p|w(v)\geq p]\cdot\Pr[i\text{ gets asset}|s_i=v\wedge w(v)\geq p]\\&+(1-\pi_i)\cdot[1-F_{w|\emptyset}(p)]\cdot[w(\emptyset)-p]\cdot\Pr[i\text{ gets asset}|s_i=\emptyset]\\&-c(\pi_i\lambda_i,\pi_i(1-\lambda_i)).\end{aligned} \quad \text{(B1)}$$

As pointed out in Section 3, the buyer's incentives to acquire expertise on the value component v are similar to his incentives to acquire expertise on the value component b. Taking the seller's price as given, a buyer profits from expertise because it increases the probability that he will be able to buy the asset when his willingness to pay $w(s_i)$ is greater than the price quote p. Whether $w(s_i)>p$ obtains due to a good signal about the common value component $s_i=v$ or a good signal about the gains from trade $s_i=b$ does not matter to the buyer, as long as the probability of receiving the asset conditional on agreeing to the price quote is the same. We can derive the probabilities of

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receiving the asset conditional on receiving a signal of each type and agreeing to the limit-order price p as

$$\Pr[i \text{ gets asset}|s_i = b \wedge w(b) \geq p]$$
$$= \sum_{m=0}^{n-1} \sum_{m'=0}^{m} B(n-1,m,\pi)B(m,m',\lambda)$$
$$\cdot \left[\frac{F_{w|v}(p)}{1+m'+(n-m-1)(1-F_{w|\emptyset}(p))} + \frac{1-F_{w|v}(p)}{1+m+(n-m-1)(1-F_{w|\emptyset}(p))} \right], \quad \text{(B2)}$$

$$\Pr[i \text{ gets asset}|s_i = v \wedge w(v) \geq p]$$
$$= \sum_{m=0}^{n-1} \sum_{m'=0}^{m} B(n-1,m,\pi)B(m,m',1-\lambda)$$
$$\cdot \left[\frac{F_{w|b}(p)}{1+m'+(n-m-1)(1-F_{w|\emptyset}(p))} + \frac{1-F_{w|b}(p)}{1+m+(n-m-1)(1-F_{w|\emptyset}(p))} \right], \quad \text{(B3)}$$

where π and λ characterize the symmetric expertise choices of all other buyers. In the OTC market with $\rho=0$ the first buyer's objective is identical to the one provided in (B1), except that the probability of receiving the asset conditional on accepting the price is always one. In the limit-order market, the probabilities (B2) and (B3) depend more on how many competing buyers have received the same type of signal as buyer i than on how many of them have received the other type of signal; while a buyer who observed a good signal $s_i = b$ must compete for the asset with all other buyers informed about b, he only competes with buyers informed about v when v is large enough, that is, with probability $[1-F_{w|v}(p)]$. Moreover, with two-dimensional expertise acquisition, a buyer informed about b is facing adverse selection from buyers informed about v, and vice versa. Clearly, if from buyer i's viewpoint, the two types of value components feature the same expertise costs and the same distributions (for v and b and for other agents expertise choices π and λ), then the benefits of acquiring expertise of either type are also symmetric for buyer i.

B.3 Uncorrelated Private Values

In this appendix, we analyze equilibrium outcomes when buyers' private values are uncorrelated, that is, $v_i = v + b_i$ where each $b_i \sim F_b$ independently, and buyers' expertise yields signals about their own b_i. As with correlated private values (see Section 2), expertise acquisition can have positive effects on allocative efficiency in this case as it informs traders about the existence of gains from trade. The analysis below underlies the discussions and illustrations in Section 4.4.

B.3.1 Limit-Order Market.

B.3.1.1 Buyers' willingness to pay A buyer who receives a signal $s_i = b_i$ has the willingness to pay $w_i(b_i) = \mu_v + b_i$. In contrast, a buyer who receives a signal $s_i = \emptyset$ is willing to pay $w_i(\emptyset) = \mu_v + \mu_b$ for the asset. It is again useful to define the probability with which a buyer rejects a price p conditional on being informed and conditional on being uninformed, respectively,

$$F_{w_i|b_i}(p) = F_b(p-\mu_v), \quad \text{(B4)}$$

$$F_{w_i|\emptyset}(p) = \mathbf{1}_{\{p > \mu_v + \mu_b\}}. \quad \text{(B5)}$$

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B.3.1.2 Seller's pricing decision. When choosing a price p the seller is again concerned with the distribution of the maximum willingness to pay among all buyers in the market. We can write the distribution of the maximum willingness to pay among buyers as follows:

$$F_{w_{\max}}(p)=\sum_{m=1}^{n-1} B(n,m,\pi)\min[F_{w_i|b_i}(p)^m, F_{w_i|\emptyset}(p)]$$

$$+B(n,0,\pi)F_{w_i|\emptyset}(p)+B(n,n,\pi)F_{w_i|b_i}(p)^n. \quad \text{(B6)}$$

The seller then quotes a price p to maximize his expected payoff:

$$\Pi(p)=[1-F_{w_{\max}}(p)]\cdot p+F_{w_{\max}}(p)\cdot\mu_v. \quad \text{(B7)}$$

For all $p\neq w_i(\emptyset)$, the marginal net benefit of increasing the price is given by

$$\Pi'(p)=1-F_{w_{\max}}(p)-f_{w_{\max}}(p)\cdot(p-\mu_v), \quad \text{(B8)}$$

where for $p>w_i(\emptyset)$ we obtain

$$F_{w_{\max}}(p)=\sum_{m=1}^{n} B(n,m,\pi)F_{w_i|b_i}(p)^m+B(n,0,\pi), \quad \text{(B9)}$$

$$f_{w_{\max}}(p)=\sum_{m=1}^{n} B(n,m,\pi)mF_{w_i|b_i}(p)^{m-1}f_{w_i|b_i}(p). \quad \text{(B10)}$$

Again, for $\mu_b\leq 0$, the seller will optimally quote a price $p>w_i(\emptyset)$, such that the first-order condition $\Pi'(p)=0$ holds.

B.3.1.3 Buyers' expertise acquisition. A buyer i believing that all other buyers will choose an expertise level π and that the seller will quote a price p expects the following profit from choosing an expertise level π_i ex ante:

$$V(\pi_i)=\pi_i\cdot[1-F_{w_i|b_i}(p)]\cdot(\mu_v+\mathbb{E}[b_i|b_i>p-\mu_v]-p)\cdot\Pr[\text{get asset}|\text{accept } p]$$

$$+(1-\pi_i)\cdot[1-F_{w_i|\emptyset}(p)]\cdot[w_i(\emptyset)-p]\cdot\Pr[\text{get asset}|\text{accept } p]$$

$$-c(\pi_i), \quad \text{(B11)}$$

where

$$\Pr[\text{get asset}|\text{accept } p]=F_{w_i|\emptyset}(p)\sum_{m=0}^{n-1}B(n-1,m,\pi)\sum_{k=0}^{m}\frac{B(m,k,(1-F_{w_i|b_i}(p)))}{k+1}$$

$$+[1-F_{w_i|\emptyset}(p)]\sum_{m=0}^{n-1}B(n-1,m,\pi)\sum_{k=0}^{m}\frac{B(m,k,(1-F_{w_i|b_i}(p)))}{k+(n-1-m)+1}. \quad \text{(B12)}$$

The marginal net benefit of increasing π_i when $\pi_i\in(0,1)$ is given by

$$V'(\pi_i)=[1-F_{w_i|b_i}(p)]\cdot(\mu_v+\mathbb{E}[b_i|b_i>p-\mu_v]-p)\cdot\Pr[\text{get asset}|\text{accept } p]$$

$$-[1-F_{w_i|\emptyset}(p)]\cdot[w_i(\emptyset)-p]\cdot\Pr[\text{get asset}|\text{accept } p]$$

$$-c'(\pi_i). \quad \text{(B13)}$$

Whenever $\mu_b\leq 0$ we know that the seller targets informed buyers by setting $p>w_i(\emptyset)$, implying that $F_{w_i|\emptyset}(p)=1$, and thus, we obtain the simple marginal net benefit function:

$$V'(\pi_i)=[1-F_{w_i|b_i}(p)]\cdot(\mu_v+\mathbb{E}[b_i|b_i>p-\mu_v]-p)\cdot\Pr[\text{get asset}|\text{accept } p]-c'(\pi_i), \quad \text{(B14)}$$

where

$$\Pr[\text{get asset}|\text{accept } p]=\sum_{m=0}^{n-1}B(n-1,m,\pi)\sum_{k=0}^{m}\frac{B(m,k,(1-F_{w_i|b_i}(p)))}{k+1}. \quad \text{(B15)}$$

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B.3.2 OTC Market.

B.3.2.1 Buyers' willingness to pay. Buyers' willingness to pay is identical to the one in the limit-order market, because buyers' signals are informative only about their own private value components. We obtain the following probability with which buyer i rejects a price quote p_i:

$$F_{w_i}(p_i) = \pi_i F_{w_i|b_i}(p_i) + (1-\pi_i) F_{w_i|\emptyset}(p_i). \tag{B16}$$

B.3.2.2 Seller's pricing decision. Let $\mathbf{p}_i^n$ denote the vector of prices $(p_i, p_{i+1}, ..., p_n)'$. When facing buyer i, the seller chooses the price quote p_i to maximize the expected payoff:

$$\Pi_i(\mathbf{p}_i^n) = [1 - F_{w_i}(p_i)] \cdot p_i + F_{w_i}(p_i) \cdot [\rho \Pi_{i+1}(\mathbf{p}_{i+1}^n) + (1-\rho)\mu_v]. \tag{B17}$$

For all $p_i > w_i(\emptyset)$, we get

$$F_{w_i}(w_i) = \pi_i F_{w_i|b_i}(w_i) + (1-\pi_i), \tag{B18}$$

$$f_{w_i}(w_i) = \pi_i f_{w_i|b_i}(w_i). \tag{B19}$$

If $\mu_b \leq 0$ the seller always chooses $p_i > \mu_v$, implying that in equilibrium uninformed buyers do not trade. In this case, the following first-order condition is satisfied by the seller's optimal price quote:

$$\frac{\partial \Pi_i(\mathbf{p}_i^n)}{\partial p_i} = 1 - F_{w_i}(p_i) - f_{w_i}(p_i)[p_i - (\rho \Pi_{i+1}(\mathbf{p}_{i+1}^n) + (1-\rho)\mu_v)] = 0. \tag{B20}$$

B.3.2.3 Buyers' expertise acquisition. Buyer i's expected value from choosing an expertise level π_i is given by

$$\begin{aligned} V_i(\pi_i) = \Pr[i \text{ gets offer}] \cdot \big[\pi_i \cdot [1 - F_{w_i|b_i}(p_i)] \cdot (\mu_v + \mathbb{E}[b_i | b_i > p_i - \mu_v] - p_i) \\ + (1-\pi_i) \cdot [1 - F_{w_i|\emptyset}(p_i)][w_i(\emptyset) - p_i]\big] - c(\pi_i), \end{aligned} \tag{B21}$$

where:

$$\Pr[i \text{ gets offer}] = \rho^{i-1} \prod_{k=1}^{i-1} [(1-\pi_k) F_{w_k|\emptyset}(p_k) + \pi_k F_{w_k|b_k}(p_k)]. \tag{B22}$$

The marginal net benefit of increasing π_i is given by

$$\begin{aligned} V_i'(\pi_i) = \Pr[i \text{ gets offer}] \cdot \big[[1 - F_{w_i|b_i}(p_i)] \cdot (\mu_v + \mathbb{E}[b_i | b_i > p_i - \mu_v] - p_i) \\ - [1 - F_{w_i|\emptyset}(p_i)][w_i(\emptyset) - p_i]\big] - c'(\pi_i). \end{aligned} \tag{B23}$$

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