

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

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Various assets are traded in over-the-counter (OTC) markets which exhibit frictions absent in centralized limit-order markets. We analyze the relative merits of these two market structures in an environment where traders bringing liquidity-driven order flow to the market use price quotes to screen informed counterparties whose expertise is endogenous. In this environment, frictions present in OTC markets, such as time-consuming search, can promote higher efficiency for certain asset classes. In particular, OTC markets with predictable and exclusive trading encounters encourage expertise acquisition, which is beneficial in asset classes where expertise improves allocative efficiency, but harmful when it causes adverse selection. (JEL D82, G23, L10)

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1 Introduction

Many large asset classes are primarily traded in OTC markets, including real estate and bonds. Yet, despite their prevalence, OTC markets are commonly thought of as opaque and illiquid compared to centralized limit-order exchanges that serve as primary trading venues for other asset classes such as stocks. Many academics, commentators, and policy makers blamed OTC trading for exacerbating the recent financial crisis and suggested significant reforms, including centralizing trading.¹ Even for asset classes where centralized venues already exist, such as for currencies and bonds, investors often still decide to trade in the OTC market using “inferior” technologies (e.g., phone calls).² On the other hand, they prefer to trade other types of assets in centralized limit-order markets.

This paper shows how a small set of well-documented properties of limit-order and OTC markets can help explain cross-sectional variation in the relative appeal of these market structures. In particular, our stylized model provides an economic rationale for why bonds are mostly traded in OTC markets, whereas stocks and standardized derivatives such as corporate call options are mostly traded in limit-order markets.

In our model, opportunities to realize gains to trade are scarce and traders coming to the market with such opportunities have incentives to screen their counterparties, who may be privately informed.³ Asymmetric information is an important feature of our model capturing that traders in practice have heterogeneous expertise.⁴ In our parsimonious baseline model, a trader wishes to sell an asset to realize potentially uncertain gains to trade with candidate buyers. In the OTC market, the seller contacts buyers sequentially

¹For specific examples, see the Financial Economists Roundtable’s statements on “The Structure of Trading in Bond Markets” released in May 2015 and on “Reforming the OTC Derivatives Markets” released in June 2010, “Implementing the Dodd-Frank Act,” a speech given by U.S. CFTC’s chairman Gary Gensler in January 2011, “Comparing G-20 Reform of the Over-the-Counter Derivatives Markets,” a Congressional Report prepared by James K. Jackson and Rena S. Miller in February 2013, or “Canadian regulators push toward more transparency, oversight for huge fixed income market” by Barbara Shecter in the September 17, 2015 issue of the Financial Post.

²See Biais and Green (2007) for an historical perspective on the decentralization of bond trading.

³The fact that such traders do not act as price takers, but instead use pricing strategies to maximize their own profits is particularly relevant given evidence that a few large players accounts for a significant fraction of the trading volume of the assets currently traded in OTC markets. See, e.g., Li and Schürhoff (2014) and Hendershott et al. (2015) for municipal bonds, Di Maggio, Kermani, and Song (2016) for corporate bonds, Atkeson, Eisfeldt, and Weill (2013), Begenau, Piazzesi, and Schneider (2015), and Siriwardane (2016) for credit and interest-rate derivatives, and King, Osler, and Rime (2012) for foreign exchange instruments.

⁴See, e.g., Green, Hollifield, and Schürhoff (2007) for municipal bonds, Hollifield, Neklyudov, and Spatt (2014) for securitized products, Jiang and Sun (2015) for corporate bonds, and Menkhoff et al. (2016) for foreign exchange instruments.

and makes them offers. Whereas a first buyer can be contacted quickly, search is required to find a second buyer. This search delays the realization of trade surplus, which can be costly due to immediacy or liquidity concerns. In contrast, in the centralized limit-order market, no delay is necessary in reaching buyers: the seller posts a price and the buyers simultaneously decide whether to pick up this limit order.⁵

A key feature of our model is that information can be either about an asset's fundamental value (common to all traders), or about a trader's own idiosyncratic private-value component (independent across traders). When the market structure changes neither buyers' expertise acquisition nor the seller's pricing strategies, and trade delays lead to the destruction of social surplus, trading in the limit-order market by construction socially dominates OTC trading. However, our paper emphasizes that trading in OTC markets can incentivize traders to change their behaviors in socially beneficial ways.

In particular, search frictions in OTC markets that make it harder to reach some counterparties than others create predictability in trading encounters and guarantee a larger volume of offers to a subset of counterparties. Moreover, offers are exclusive, as counterparties in OTC markets are contacted sequentially and do not have to compete once they receive an offer. Predictable trading encounters in turn increase the incentives that this subset of traders has to invest in specialized infrastructure yielding private information about asset valuations. For some asset classes, allocative efficiency requires traders to acquire expertise, as doing so reduces the uncertainty about the existence of a surplus from trade. Acquiring information might then be interpreted as making costly investments in expertise and infrastructure that allow to quickly — in response to an offer — gauge an asset's impact on an investor's or firm's portfolio diversification, tax liabilities, and liquidity needs. For a dealer, it may also take the form of establishing relationships that provide superior access to information about clients' idiosyncratic willingness to pay, and thus, about the dealer's opportunities for re-trade (see also Vives 2014, for a related discussion). Our paper shows that if, for a given asset class, traders are likely to acquire this type of information, and thereby learn about the existence and magnitude of the gains to trade, then decentralized markets subject to search frictions can be more efficient than centralized markets.

⁵We also consider alternative centralized market structures in an Appendix. We show that our results extend to a second-price auction where the seller picks a reserve price or to a limit-order market where the seller can quote multiple prices sequentially.

The opposite is, however, true in asset classes where traders are likely to acquire information about an asset's common-value component. This type of information only improves traders' rent-seeking ability and impedes trade due to adverse selection. While the existing literature has highlighted that security design can help alleviate such inefficiencies associated with information acquisition at the origination stage (see, e.g., Dang, Gorton, and Holmström 2015, Yang 2015), we highlight that trading *existing* securities in centralized limit-order markets also limits information acquisition, improving efficiency in asset classes where adverse selection is a primary concern. Which market dominates thus depends on the extent to which traders' are likely to acquire information about private- or common-value components, which varies by asset class. Specifically, the OTC market structure can dominate for securities like bonds that are primarily traded for trader-specific liquidity and inventory motives, and where most of the potential uncertainty relates to private valuations. The centralized limit-order market, however, dominates for securities where most of the uncertainty and private information relate to fundamental valuations (often referred to as *information-sensitive securities*), such as for stocks or standardized derivatives like corporate call options.

Our results imply that search frictions in OTC markets can paradoxically increase efficiency by alleviating commitment problems for agents coming to the market with scarce opportunities to realize gains to trade. Search frictions commit these agents to not choosing trading strategies or mechanisms that leave specialized counterparties with little or no surplus *ex post*. This provides, in turn, some institutions with incentives to invest in socially valuable expertise *ex ante*. In that respect, our findings contrast with the unequivocal social losses associated with search frictions observed in standard models of OTC trading with symmetrically informed traders, like Duffie, Gârleanu, and Pedersen (2005).

Although our economic environment differs from theirs, how we model both market structures is 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 contrast, in our paper we alter traders' arrival process to differentiate the market structures in which traders operate. In our central-

ized limit-order market, all traders arrive at the same time and the “liquidity provider” (i.e., an uninformed seller) quotes them an ultimatum price. This particular trading protocol is also how Jovanovic and Menkveld (2015) model their limit-order market (except when they allow for the presence of high-frequency middlemen). The fact that multiple traders must simultaneously respond to the liquidity provider’s quote affects their incentives to acquire information, relative to the OTC market. In our OTC market, traders instead arrive sequentially and the liquidity provider quotes offers that are exclusive to the counterparty he is facing at the time. The delay in trader arrival and, possibly, in the realization of the trade surplus (due to search frictions and/or immediacy concerns) imposes a social cost, relative to the centralized limit-order market. Finally, we assume as in Glosten (1989) that the liquidity provider has market power — his temptation to inefficiently screen privately informed counterparties will affect which market structure dominates in our environment. 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 Christie and Schultz (1994), Sandås (2001), and Hollifield, Miller, and Sandås (2004). In addition, we know from Biais, Martimort, and Rochet (2000) and Vives (2011) that this inefficient screening behavior extends to environments with generalized trading mechanisms and imperfect competition.⁶

Our paper differs from other related market microstructure papers in the following ways. First, our model focuses on the role of informational problems, rather than liquidity externalities (Admati and Pfleiderer 1988, Grossman and Miller 1988, Pagano 1989, Malamud and Rostek 2014, Babus and Parlato 2016), 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), in determining the costs and benefits of (de)centralized trading. Second, unlike in Grossman (1992) where it is assumed that the upstairs (i.e., decentralized) market features dealers who possess information about unexpressed demand that is not available to the traders in the downstairs (i.e., centralized) market, our analysis compares the efficiency of decentralized and centralized markets when traders’ information is endogenous to the market structure. Third, our focus

⁶While investigating the costs and benefits of limit-order markets, Glosten (1994) shuts down the market power problem we study in this paper by assuming infinitely many liquidity suppliers. However, as we argue above, market power problems appear to be important considerations for many OTC settings.

on the social efficiency of trade distinguishes our paper from Kirilenko (2000) who studies the choice of a trading arrangement (one-shot batch auction vs. continuous dealer market) by an authority trying to maximize price discovery in the context of emerging foreign exchange markets (see also Sherman 2005, who focuses on IPO trading arrangements that maximize price discovery). Fourth, comparing limit-order markets to OTC markets and endogenizing expertise also differentiates this paper from Glode and Opp (2016), who show that trading through intermediation chains in OTC markets may improve the efficiency of trade in the presence of market power and asymmetric information.

The idea that decentralized markets allow traders to reach various potential counterparties in a sequential/exclusive manner while centralized markets allow traders to reach all potential counterparties in a simultaneous/competitive manner also relates our paper to Seppi (1990), Biais (1993), Bulow and Klemperer (2009) and Zhu (2012). Seppi (1990) studies the existence of dynamic equilibria where a trader prefers to submit a large order to a dealer rather than a sequence of small market orders to an exchange. Central to this result is the assumption that the dealer knows the identity of his counterparties, which allows for the implementation of dynamic commitments not possible in anonymous centralized markets. Biais (1993) also focuses on how markets differ in terms of “transparency.” Risk-averse traders are assumed to have private information about their inventories — thus, unlike in our model no information acquisition is needed and there cannot be asymmetric information about assets’ common value. Biais (1993) shows that the number of liquidity providers and their expected bids should be equal across markets where traders can observe competing quotes and markets where they cannot but bid-ask spreads are more volatile in transparent markets.⁷ In Bulow and Klemperer (2009), prospective buyers can enter the market and bid on the asset sold by an informed seller only if they pay a cost. Paying this cost is also associated with receiving an informative signal about the value of the asset, thus unlike in our model all agents trying to buy the asset are informed.⁸ The main result in Bulow and Klemperer (2009) differs greatly from ours: in their model sequential entry and

⁷See 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 allowing for adverse selection, generalized risk aversion, and search costs, respectively.

⁸See also Roberts and Sweeting (2013) who estimate, using data from U.S. timber auctions, an extension to the Bulow and Klemperer (2009) setting that endows prospective buyers with noisy signals about their private valuations prior to making the entry decision.

bidding always dominates simultaneous bidding through an auction, as it results in the first bidder offering a price that is high enough to deter any other prospective buyer from paying a deadweight cost and entering the bidding process. Our model instead shows that, if a seller sequentially searches for buyers who choose to invest in valuation expertise prior to transactions (e.g., by investing in infrastructure, human capital, and customer connections), which market structure dominates depends on fundamental asset characteristics such as the relative magnitude of common- vs. private-value uncertainty and the ease with which traders can find suitable buyers for a particular asset. Our novel “cross-sectional” predictions shed light on why different asset classes are traded in different market structures. 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. In our model, each potential counterparty can only be contacted once, hence, the “ringing phone curse” that is central in Zhu (2012) plays no role. Moreover, unlike in Seppi (1990), Biais (1993) and Zhu (2012) where traders’ information is exogenously given, our paper studies how traders’ incentives to acquire information depend on the market structure, and how this endogeneity of information affects social efficiency.

In the next section, we describe the economic environment we will study throughout the paper. Section 3 derives equilibrium trading outcomes in centralized limit-order markets and OTC markets when some traders have private information about their idiosyncratic valuation of the asset. Section 4 replicates the analysis, but for the case where traders’ private information relates to the common valuation of the asset. Comparing our results from Section 4 to those from Section 3 allows us to shed light on why some asset classes are better traded over the counter, and why other asset classes are better traded in limit-order markets. In Section 5, we discuss robustness and implementation issues, and Section 6 concludes. Unless stated otherwise, proofs of our results are relegated to the Appendix.

2 Model

The owner of an asset considers selling it to one of two prospective buyers.⁹ 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 matters to all traders and is distributed as $v \in \{\bar{v} - \sigma_v, \bar{v} + \sigma_v\}$ with equal probabilities. This component aims to capture the “fundamental” value of the asset. The private-value component b_i is assumed to be zero for the seller and takes a value $b_i \in \{\Delta - \sigma_b, \Delta + \sigma_b\}$ with equal and independent probabilities for each buyer i . This component aims to capture trader-specific liquidity and inventory concerns as well as their idiosyncratic opportunities for re-trade. In expectation, moving the asset from the seller to a buyer creates a social surplus of $E[b_i] = \Delta > 0$.

Each buyer i can become privately informed about the realization of v_i . In particular, ex ante, before trading takes place, buyer i can invest in expertise at a cost $\frac{c}{2}\pi_i^2$ in order to learn v_i with probability $\pi_i \in [0, 1]$. We will interpret π_i as trader i 's expertise and will discuss the determinants of expertise in practice in the context of both private or common-value uncertainty in later sections.

The seller only knows the ex-ante distributions of v and b_i before contacting buyers, which in most cases will eliminate signaling concerns that may allow multiple equilibria to emerge. Yet the seller has market power. In practice, opportunities to realize gains to trade tend to be scarce — for example, they may be caused by liquidity, or immediacy, shocks affecting a specific financial institution or client. In our model, a seller coming to the market with such a scarce opportunity to realize gains to trade (Δ on average) can quote prices to his counterparties.

While the number of prospective buyers is a fundamental of the economy, how informed they are and how easily the seller can access them depends on the market structure. In a centralized limit-order market, the seller posts a price that is simultaneously available to both buyers. If both buyers accept to pay the posted price, then one buyer is randomly chosen to participate in the trade. In an OTC market, the seller quotes a price exclusively to the first buyer. If this price is accepted, trade occurs at that price, but if it is

⁹Later in our analysis we discuss how our results are affected when the number of traders is increased. Our parsimonious baseline setting captures, however, the main economic insights of our paper and allows for a tractable analysis.

rejected, the seller tries to contact the second buyer. Contacting this second buyer quickly enough to realize gains to trade is possible only with probability ρ , which can capture search frictions that make locating a second buyer difficult (Ashcraft and Duffie 2007, Green, Hollifield, and Schürhoff 2007, Feldhütter 2012) as well as immediacy or liquidity concerns (Grossman and Miller 1988, Chacko, Jurek, and Stafford 2008, Nagel 2012). More generally, it 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 trade fails with both buyers, the seller is confined to keeping the asset and the surplus from trade is lost. Buyers’ position in the seller’s network (i.e., as either first or second buyer) is assumed to be known to all agents, which allows our model to capture the significant persistence and predictability of OTC interactions documented by Li and Schürhoff (2014), Hendershott et al. (2015), Di Maggio, Kermani, and Song (2016), and Hagströmer and Menkveld (2016).

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.” In the centralized market, these ultimatum price quotes can be interpreted as limit orders that all buyers can try to pick up or not (Jovanovic and Menkveld 2015). The common problem plaguing both market structures is that the seller may use his market power to screen his privately informed counterparties, at the cost of probabilistically destroying gains to trade, consistent with the empirical evidence of rent extraction by a few large traders in limit-order markets and of concentrated holding and trading of OTC securities cited in the introduction. While a binomial structure is imposed to keep our results tractable, the type of screening behavior we study in this paper is also present in more general settings where traders’ valuations are continuously distributed (see, e.g., Glode and Opp 2016, Glode, Opp, and Zhang 2016). We also discuss the robustness of our theoretical results to alternative models of centralized trading in Section 5.

In our analysis, we focus on two distinct cases that cleanly isolate our model’s cross-sectional predictions

on how the preferred market structure varies depending on the nature of uncertainty for a given asset class: first, we consider the case where σ_b is large and $\sigma_v = 0$, and second, the case where σ_v is large and $\sigma_b = 0$. Focusing on these two cases allows us to highlight how uncertainty in private valuations b_i and in the common value v differently impact the efficiency of each market structure. We then compare across market structures the social utilitarian welfare (i.e., the expected surplus from trade, net of expertise acquisition costs). We discuss in Section 5 how ex ante order flow agreements may help ensure that the market structure with the higher utilitarian welfare for a given case is indeed the one where trade occurs in equilibrium.

Before going further, we briefly discuss which market structure dominates in a particular benchmark case where $\sigma_v \rightarrow 0$ and $\sigma_b \rightarrow 0$, that is, where asymmetric information is absent. In this case, both buyers are always willing to pay at least $\bar{v} - \sigma_v + \Delta - \sigma_b$ for the asset. However, the seller can also quote prices higher than $p = \bar{v} - \sigma_v + \Delta - \sigma_b$, but the upside of collecting these prices is at most $\sigma_v + \sigma_b$, which is too small to justify the discrete drops in the probability of acceptance and in the surplus from trade. The seller thus finds it optimal to quote a price $p = \bar{v} - \sigma_v + \Delta - \sigma_b$ that is accepted with probability 1, regardless of whether he is contacting the two buyers simultaneously (i.e., in a centralized limit-order market) or sequentially (i.e., in an OTC market). The expected social surplus generated by trade is then Δ in both types of markets.

3 Private-Value Uncertainty

In this section, we study the case where σ_v is small (i.e., $\sigma_v = 0$) and equilibrium trading outcomes are therefore driven by the mean and the volatility of buyers' private valuations (i.e., Δ and σ_b). Moreover, we assume that the uncertainty in private valuations is large enough to ensure that trade does not always create a positive social surplus, that is, $\sigma_b \geq \Delta$. Analyzing a setting where most of the uncertainty and private information relate to traders' private valuations sheds light on which market structure dominates for highly rated municipal and corporate bonds.

3.1 Limit-Order Trading Game

We first analyze trade in a centralized limit-order market where the seller posts a price that can be accepted by any of the two prospective buyers. If both buyers are willing to pay the posted price, then one of them is randomly chosen to participate in the trade. At this trading stage, the buyers' expertise as characterized by the probabilities of being informed, π_1 and π_2 , is taken as given. In Subsection 3.3, we analyze how expertise is chosen ex ante, before trade occurs. In the case of private-value uncertainty, expertise can be thought of as a dealer's human capital, his firm's IT infrastructure, and his access to information about the portfolio positions and trading needs of his firm's clients, all of which help a dealer quickly determine whether his firm is currently willing to acquire an asset at a quoted price.

The highest price that has a positive probability of being accepted by a buyer is $p = \bar{v} + \Delta + \sigma_b$. This price is accepted only if at least one of the buyers is informed and values the asset at $v_i = \bar{v} + \Delta + \sigma_b$. Throughout, we will refer to a price quote that matches the willingness to pay of the highest buyer type as the *high price*. The seller may alternatively post a price $p = \bar{v} + \Delta$, which is low enough to also be accepted by buyers who do not have private information about their valuation. Going forward, we will refer to a price quote equal to the willingness to pay of an uninformed buyer type as the *medium price*. In this section, we consider the case where there is no common-value uncertainty (i.e., $\sigma_v = 0$), implying that an uninformed buyer is not worried about being adversely selected by the other buyer.¹⁰ Finally, the seller may consider posting a *low price* $p = \bar{v} + \Delta - \sigma_b$, which is accepted by all buyers, but posting this price is dominated by keeping the asset, which in expectation is worth \bar{v} to him. Keeping the asset is, in turn, dominated by posting either the high or the medium price. The lemma that follows summarizes the equilibrium trading outcome that arises in this centralized market.

Lemma 1 *In a centralized limit-order market with uncertain private values, the seller posts the medium price $p = \bar{v} + \Delta$ in equilibrium whenever:*

$$\frac{\Delta}{\sigma_b} \geq \frac{1}{2} \left(\frac{2\pi_1 + 2\pi_2 - \pi_1\pi_2}{2 - \pi_1 - \pi_2} \right), \quad (1)$$

¹⁰In contrast, when we later look at cases where $\sigma_v > 0$, adverse selection will affect trading behavior.

and the social surplus from trade in this case is: $(1 - \frac{1}{4}\pi_1\pi_2) \Delta + \frac{1}{4}(\pi_1 + \pi_2 + \pi_1\pi_2) \sigma_b$. Otherwise, the seller posts the high price $p = \bar{v} + \Delta + \sigma_b$ and the social surplus from trade is: $\frac{1}{2}(\pi_1 + \pi_2 - \frac{1}{2}\pi_1\pi_2) (\Delta + \sigma_b)$.

The seller has to make a price concession relative to the highest feasible price if he wishes to ensure that uninformed traders are also willing to buy the asset. However, such a price concession leaves surplus for any informed buyer with a high private-value realization. When the expected surplus from trade (Δ) is large, the seller is willing to make this price concession, but when the uncertainty in the surplus from trade (σ_b) is large, the price concession needed is too high and the seller prefers to post a high price, targeting informed buyers with high private values only. An “aggressive” trading strategy of quoting the high price eliminates the rents going to informed buyers, but it also destroys the surplus from trade with a higher probability.

From a social standpoint, the surplus from trade is greater if the seller posts the medium price $p = \bar{v} + \Delta$ rather than the high price $p = \bar{v} + \Delta + \sigma_b$ whenever:

$$\begin{aligned} \left(1 - \frac{1}{4}\pi_1\pi_2\right) \Delta + \frac{1}{4}(\pi_1 + \pi_2 + \pi_1\pi_2) \sigma_b &> \frac{1}{2} \left(\pi_1 + \pi_2 - \frac{1}{2}\pi_1\pi_2\right) (\Delta + \sigma_b) \\ \Leftrightarrow \frac{\Delta}{\sigma_b} &> \frac{1}{2} \left(\frac{\pi_1 + \pi_2 - 2\pi_1\pi_2}{2 - \pi_1 - \pi_2}\right). \end{aligned} \quad (2)$$

Hence, in the region where $\frac{1}{2} \left(\frac{\pi_1 + \pi_2 - 2\pi_1\pi_2}{2 - \pi_1 - \pi_2}\right) < \frac{\Delta}{\sigma_b} < \frac{1}{2} \left(\frac{2\pi_1 + 2\pi_2 - \pi_1\pi_2}{2 - \pi_1 - \pi_2}\right)$, the seller posts a socially inefficient, high price. This region always exists when both $\pi_i \in (0, 1)$.

3.2 OTC Trading Game

We now consider how trade occurs in an OTC market where the seller first quotes a price to the first buyer, and if his offer is rejected, tries to contact the second buyer. If the first buyer rejects and trade is delayed, the surplus from trade disappears with probability $(1 - \rho)$ (or equivalently, the second buyer cannot be found quickly enough). Hence, only with probability ρ can the seller successfully contact the second buyer and quote him an ultimatum price, just like he did with the first buyer. If trade fails with both buyers, the seller is confined to keeping the asset and any surplus from trade is lost. To capture the significant persistence

and predictability of OTC trading interactions documented by Li and Schürhoff (2014), Hendershott et al. (2015), Di Maggio, Kermani, and Song (2016) and Hagströmer and Menkveld (2016), we assume that the order with which the seller contacts the two buyers is known to all agents. The first buyer may be viewed as a counterparty that is well-known to the seller and can be contacted quickly, whereas the second credible buyer is more peripheral and first has to be identified by the seller. As above, we take buyers' expertise, as characterized by the probabilities π_1 and π_2 , as given when analyzing this trading game, and will analyze ex ante expertise acquisition in Subsection 3.3.

Since in this section we analyze the case without common-value uncertainty ($\sigma_v = 0$), a rejection by the first buyer is only informative about the private valuation of the first buyer. Thus, neither the seller nor the second buyer learn anything about the second buyer's willingness to pay from such a rejection. After a rejection, the seller reaches the second buyer with probability ρ and quotes a price. As earlier, the highest price that can be accepted by the second buyer is $p = \bar{v} + \Delta + \sigma_b$, but it is only accepted if the second buyer is informed and has a high valuation for the asset. The seller may instead quote the medium price $p = \bar{v} + \Delta$, which is low enough to also be accepted by a second buyer who did not receive a signal about his private valuation. Finally, the seller may quote the low price $p = \bar{v} + \Delta - \sigma_b$, which is always accepted by the second buyer. With probability $(1 - \rho)$, the surplus from trade disappears before the seller can quote a price to the second buyer. In this case, the seller retains the asset, which is worth \bar{v} to him.

When choosing a price to quote to the second buyer, the seller picks the price that maximizes his expected payoff. We denote the seller's maximum expected payoff from trade conditional on the first buyer rejecting his price quote as $\bar{v} + \rho W^*(\pi_2)$. The seller thus chooses whether to quote $p = \bar{v} + \Delta + \sigma_b$, $p = \bar{v} + \Delta$, or $p = \bar{v} + \Delta - \sigma_b$ to the first buyer knowing that he can still collect $\bar{v} + \rho W^*(\pi_2)$ in expectation if his first price quote is rejected. For the same reasons as in the centralized limit-order market, we can eliminate strategies that involve quoting the low price $p = \bar{v} + \Delta - \sigma_b$ to any of the buyers.

Lemma 2 *In an OTC market with uncertain private values and where $\pi_1 \geq \pi_2$, the seller quotes the medium*

price $p = \bar{v} + \Delta$ to both buyers in equilibrium whenever:

$$\frac{\Delta}{\sigma_b} \geq \frac{1}{2} \left(\frac{1}{1 - \rho + \frac{\rho\pi_2}{2}} \right) \left(\frac{\pi_1}{1 - \pi_1} \right), \quad (3)$$

and the social surplus from trade in this case is: $\left[1 - \frac{\pi_1}{2} + \frac{\rho\pi_1}{2} \left(1 - \frac{\pi_2}{2} \right) \right] \Delta + \frac{\pi_1}{2} \left(1 + \frac{\rho\pi_2}{2} \right) \sigma_b$. The seller, however, quotes the high price $p = \bar{v} + \Delta + \sigma_b$ to the first buyer and the medium price $p = \bar{v} + \Delta$ to the second buyer (if contacted) whenever:

$$\frac{1}{2} \left(\frac{\pi_2}{1 - \pi_2} \right) \leq \frac{\Delta}{\sigma_b} < \frac{1}{2} \left(\frac{1}{1 - \rho + \frac{\rho\pi_2}{2}} \right) \left(\frac{\pi_1}{1 - \pi_1} \right), \quad (4)$$

and the social surplus from trade is then: $\left[\frac{\pi_1}{2} + \rho \left(1 - \frac{\pi_1}{2} \right) \left(1 - \frac{\pi_2}{2} \right) \right] \Delta + \left[\frac{\pi_1}{2} + \rho \left(1 - \frac{\pi_1}{2} \right) \frac{\pi_2}{2} \right] \sigma_b$. Finally, the seller quotes the high price $p = \bar{v} + \Delta + \sigma_b$ to both buyers whenever:

$$\frac{\Delta}{\sigma_b} < \frac{1}{2} \left(\frac{\pi_2}{1 - \pi_2} \right), \quad (5)$$

and the social surplus from trade is then: $\left[\frac{\pi_1}{2} + \rho \left(1 - \frac{\pi_1}{2} \right) \frac{\pi_2}{2} \right] (\Delta + \sigma_b)$.

The larger the continuation value $\rho W^*(\pi_2) > 0$ is, the smaller is the potential downside of quoting a high price to the first buyer. Hence, whenever $\pi_1 \geq \pi_2$, which will be the relevant case once we endogenize traders' expertise, a strategy of quoting the medium price $p = \bar{v} + \Delta$ to the first buyer and the high price $p = \bar{v} + \Delta + \sigma_b$ to the second buyer will never be optimal.

As in the centralized limit-order market, the seller has to make a price concession to encourage uninformed traders to buy the asset. When picking a price, the seller faces a trade-off between the probability of a sale and the payoff collected conditional on a sale. The sequential and exclusive nature of OTC trading changes the seller's incentives to screen privately informed buyers, relative to the centralized market.

While our main focus is on the analysis of the model where expertise is endogenous (see Subsection 3.3), the trading game already reveals that technological frictions present in OTC markets do not necessarily reduce social surplus once we account for agents' privately optimal trading behavior. In fact, the trading

game in the OTC market can become *more* efficient as we decrease the probability ρ with which the seller can contact the second buyer before gains to trade are lost. An OTC market subject to greater search frictions (i.e., a market with a lower ρ) may better incentivize a trader with market power to quote prices that yield higher trade volume and higher social surplus, even when compared to a centralized limit-order market. The seller quotes less aggressive prices to the first buyer if there is a high probability that the surplus from trading with the second buyer will vanish before that buyer can be contacted. Since price quotes are less aggressive, trade volume with the first buyer is higher, and as a result, expected social surplus can be larger, even if the second buyer cannot be contacted at all (i.e., $\rho = 0$).

This social benefit of search frictions when expertise is exogenous already 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 the first buyer depends on the payoff he expects to collect if trade fails. This strategic response by the seller is 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.¹¹ As a result, these models associate unequivocal social losses to search frictions.¹² Moreover, our analysis in the next subsection and in Section 4 will reveal how, once we endogenize expertise, the relative allocative efficiency of OTC and limit-order markets will systematically differ based on the nature of uncertainty that dominates for a given asset class (private- vs. common-value uncertainty).

3.3 Endogenous Expertise and the Relative Efficiency of Markets

Given the results above, we can now analyze buyers' optimal expertise acquisition decisions in both market structures and compare social welfare.

In both market structures, we can rule out equilibria where π_1 and π_2 are so high that the seller optimally quotes a high price with probability one. Expecting high price quotes with probability one, buyers would

¹¹See, however, Duffie, Malamud, and Manso (2014) who study an environment with search frictions where pairs of asymmetrically informed traders participate in double auctions. Yet, their paper does not compare the relative merits of limit-order markets and OTC markets, which is the objective of our paper.

¹²See also Lester et al. (2015) who show that increasing competition can worsen the efficiency of trade in an environment where information is exogenous and relates to an asset's common value and where markets are relatively competitive already.

be better off not acquiring expertise, as they always receive zero surplus in the trading game. Yet, absent expertise acquisition ($\pi_i = 0$), buyers always reject a high price quote, rendering such a pricing strategy suboptimal for the seller. Moreover, we can rule out equilibria where buyers do not acquire expertise, since the marginal cost of acquiring expertise is zero at $\pi_i = 0$, but the marginal benefit of expertise is strictly positive when the seller does not quote a high price with probability one. In summary, the only equilibria that are sustainable are those where the seller either mixes between a high and a medium price, or where he quotes a medium price with probability one. The following proposition characterizes equilibrium expertise acquisition and pricing in both market structures.

Proposition 1 *In the limit-order market, the seller quotes the medium price $p = \bar{v} + \Delta$ with probability $m \in (0, 1]$ and the high price $p = \bar{v} + \sigma_b + \Delta$ with complementary probability $(1 - m)$. Buyers' optimal expertise is given by:*

$$\pi_1 = \pi_2 = \pi^*(m) \equiv \frac{\sigma_b}{\left(\frac{4c}{m} - \frac{\sigma_b}{2}\right)}, \quad (6)$$

where $m = 1$ if

$$\frac{\Delta}{\sigma_b} > \left(1 - \frac{\pi^*(1)}{4}\right) \left(\frac{\pi^*(1)}{1 - \pi^*(1)}\right), \quad (7)$$

and otherwise, $m \in (0, 1)$ solves:

$$\frac{\Delta}{\sigma_b} = \left(1 - \frac{\pi^*(m)}{4}\right) \left(\frac{\pi^*(m)}{1 - \pi^*(m)}\right). \quad (8)$$

In the OTC market, when facing the first buyer, the seller quotes the medium price $p = \bar{v} + \Delta$ with probability $m \in (0, 1]$ and the high price $p = \bar{v} + \sigma_b + \Delta$ with probability $(1 - m)$. Conditional on receiving a rejection from the first buyer and finding the second buyer, the seller quotes a medium price $p = \bar{v} + \Delta$ with probability one. Buyers' optimal expertise is given by:

$$\pi_1 = \pi_1^*(m) \equiv \frac{m\sigma_b}{2c}, \quad (9)$$

$$\pi_2 = \pi_2^*(m) \equiv \left[1 - m + \left(m - \frac{1}{2} \right) \pi_1^*(m) \right] \frac{\rho\sigma_b}{2c}, \quad (10)$$

where $m = 1$ if

$$\frac{\Delta}{\sigma_b} > \frac{1}{2 - \rho(2 - \pi_2^*(1))} \left(\frac{\pi_1^*(1)}{1 - \pi_1^*(1)} \right), \quad (11)$$

and otherwise, $m \in (0, 1)$ solves:

$$\frac{\Delta}{\sigma_b} = \frac{1}{2 - \rho(2 - \pi_2^*(m))} \left(\frac{\pi_1^*(m)}{1 - \pi_1^*(m)} \right). \quad (12)$$

Using the results of Proposition 1, we now perform comparative statics to shed light on the determinants of social efficiency under the two market structures. To highlight the importance of expertise acquisition for social efficiency, it is instructive to consider assets, as characterized by the parameters c , Δ , and σ_b , where the seller quotes the medium price with probability one in both market structures. The conditions for this equilibrium outcome are satisfied in both market structures when expertise acquisition is sufficiently costly, that is, for high enough values of the cost parameter c .

In Figures 1 and 2, we plot the social surplus from trade, net of expertise acquisition costs, and the privately optimal expertise acquisition as a function of the uncertainty in private valuations σ_b , for different parameterizations of ρ . We normalize $\Delta = 1$ and set $c = 15$. The plots illustrate how the trading venue that maximizes social surplus varies with asset characteristics and with the social cost of trade delays in OTC markets. Panel (a) of Figure 1 shows that, when trade delays are not too costly (e.g., $\rho = 0.8$), an OTC market socially dominates a centralized limit-order market. Yet, the OTC market can also become inferior

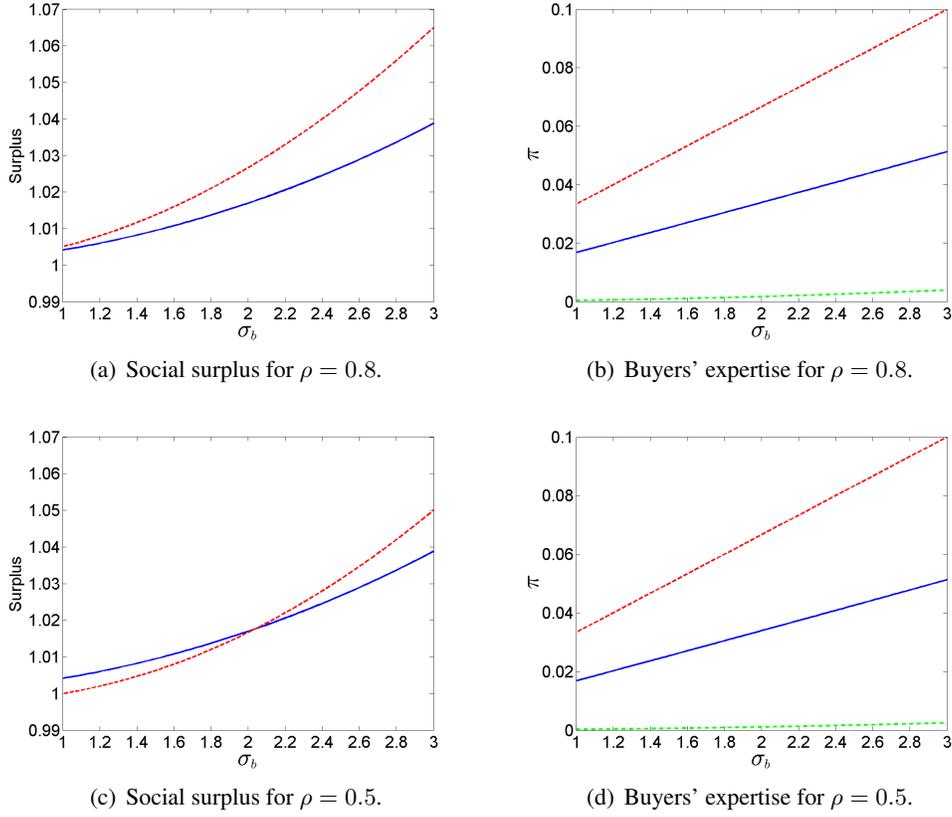


Figure 1: Surplus from trade and expertise acquisition with uncertain private values. In these figures, we set $\Delta = 1$, $\sigma_v = 0$, and $c = 15$, and plot the social surplus from trade, net of the costs of expertise acquisition, and the buyers' expertise levels π_i as functions of the uncertainty in private valuations σ_b . In Panels (a) and (c), the dashed line represents the surplus in the OTC market, whereas the solid line represents the surplus in the limit-order market. In Panels (b) and (d), the dashed line represents the first buyer's expertise π_1 , and the dotted line represents the second buyer's expertise π_2 in the OTC market, whereas the solid line represents the buyers' symmetric expertise in the limit-order market.

to the limit-order market when trade delays become costlier. This result is evidenced by Panel (c) of Figure 1, which compare the social surplus when $\rho = 0.5$.

In the OTC market, the first buyer is quoted a price with probability one, and he is guaranteed to obtain the asset if he decides to pay this quote. As mentioned above, the plots illustrate parameterizations where the seller optimally quotes the medium price with probability one. Thus, the first buyer obtains a trading profit whenever he assigns a high value to the asset (that is, when $b_1 = \sigma_b$), and he benefits from expertise

acquisition in that it helps him avoid purchasing the asset when his private value is lower than the seller's (that is, when $b_1 = -\sigma_b$). The first buyer's higher ranking in terms of the likelihood of being contacted and the exclusivity of offers made in the OTC market give the first buyer assurance that, ex ante, expertise is worth acquiring. In contrast, the second buyer only receives a price quote if (i) the first buyer rejected the seller's offer and (ii) the second buyer is reached before gains to trade have vanished. Expecting that order flow comes his way with a smaller probability, the second (more distant) buyer thus acquires much less expertise than the first buyer does.

In contrast, in the limit-order market buyers have symmetric access to orders and are competing for these orders. As a result, a buyer may not obtain the asset even when willing to trade at the posted price. Lacking preferential access to orders, the first buyer optimally reduces his expertise acquisition, relative to the OTC market. In contrast, the second buyer acquires more expertise in the limit-order market, since he has improved access to orders, relative to the OTC market.

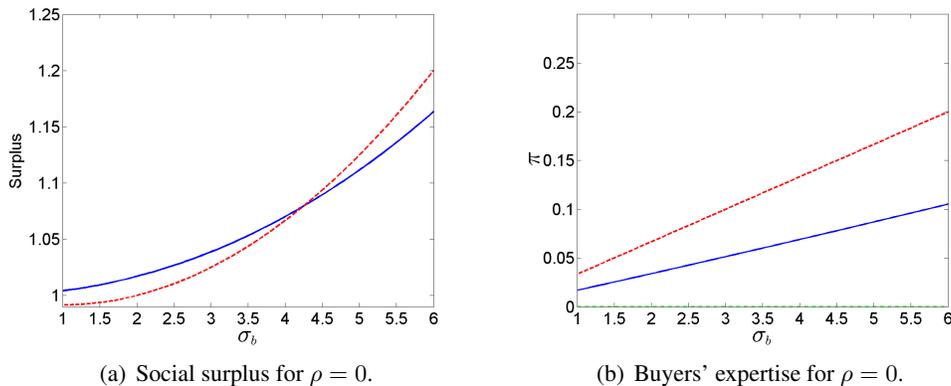


Figure 2: Surplus from trade and expertise acquisition with uncertain private values. In these figures, we set $\rho = 0$, $\Delta = 1$, $\sigma_v = 0$, and $c = 15$ and plot the social surplus from trade, net of the expertise acquisition costs, and the buyers' expertise levels π_i as functions of the uncertainty in private valuations σ_b . In Panel (a), the dash line represents the surplus in the OTC market while the solid line represents the surplus in the centralized market. In Panel (b), the dash line represents the first buyer's expertise π_1 and the dotted line represents the second buyer's expertise π_2 in the OTC market, while the solid line represents the buyers' symmetric expertise in the centralized market.

Interestingly, the OTC market with its asymmetric expertise levels can lead to higher social efficiency even though (i) the cost of expertise acquisition is a convex function, and (ii) buyers' efforts to acquire

information are not duplicating — their expertise yields information on distinct private values b_1 and b_2 . In particular, the panels plotting social surplus reveal that the OTC market becomes relatively more efficient as private-value uncertainty σ_b increases. For sufficiently large σ_b , the OTC market dominates even when $\rho = 0$, that is, when frictions in the OTC market are so severe that the second buyer never can be reached (see Panel (a) of Figure 2).

There are two main forces contributing to this result. First, the OTC market provides greater incentives for expertise acquisition in that the probability that at least one of the two buyers is informed is higher in this market than in the limit-order market. Lacking predictable trading interactions, that is, asymmetric probabilities with which different traders receive access to orders, the limit-order market reduces incentives to acquire expertise *ex ante*. This effect of symmetric competition can be easily understood by considering the limit, where a large number of buyers compete for a few scarce limit orders. Then, each individual buyer's *ex ante* probability of obtaining access to a price quote approaches zero, implying that private incentives for *ex ante* expertise acquisition also go to zero. In contrast, in the OTC market some buyers have a predictably higher probability of receiving an exclusive offer, implying that expertise acquisition does not go to zero as the number of potential buyers increases. In equilibrium, those traders that have acquired more expertise are also those that are more likely to receive offers. Expertise acquisition is, in turn, more socially desirable the larger private-value uncertainty σ_b is.

Second, conditional on expertise, the social surplus in the limit-order market suffers from the fact that the asset is not necessarily allocated to an informed high buyer type, even if such a type accepts the price quoted by the seller. The equilibrium price quoted by the seller attracts both uninformed and informed buyers, implying that a high type gets the asset only with probability $1/2$ if the other buyer is uninformed. In contrast, in the OTC market only the first buyer has a significant probability of being informed (the second buyer acquires almost no expertise), but the first buyer *always* gets the asset when he learns that his private value is high.

Regarding this second effect, one might wonder if the efficiency of the limit-order market could be improved if the seller separated buyer types by posting two price quotes sequentially — first, a high price

that is only accepted by the high type, and then a medium price that is accepted by uninformed buyers. As shown in Appendix C, this is indeed possible, for a given level of buyer expertise. However, since such a trading strategy leaves zero surplus for informed buyers, buyers have no incentives to acquire expertise in the first place. More generally, any trading strategy that allows the seller to separate buyer types and extract all their rents ex post cannot be an equilibrium with expertise acquisition. Yet, expertise acquisition is socially desirable, in particular the higher σ_b is.

In summary, traders’ *symmetric* access to orders in the limit-order market implies that either asset allocations do not efficiently incorporate available information (with one round of trade), or expertise acquisition is inefficiently low (with two rounds of trade). In contrast, the *asymmetric* access to orders in the OTC market — which naturally arises when some counterparties are “harder to find” — alleviates these problems. Yet, as we will show in the next section, a limit-order market with low expertise acquisition can actually be a more efficient trading venue for asset classes where common-value uncertainty dominates.

4 Common-Value Uncertainty

In this section, we analyze the case where traders face common-value uncertainty ($\sigma_v > 0$) instead of private-value uncertainty ($\sigma_b = 0$). Throughout, we assume that $\sigma_v \geq \Delta$, such that the seller is again better off keeping the asset than quoting a price equal to the lowest buyer type’s valuation ($\bar{v} + \Delta - \sigma_v$). Common-value uncertainty is likely a dominant source of uncertainty for securities like stocks, which are generically more sensitive to information about fundamental asset values than debt claims (DeMarzo and Duffie 1999, Dang, Gorton, and Holmström 2015, Yang 2015). As we did in the previous section, we first characterize the trading games in the limit-order market and in the OTC market conditional on given levels of expertise, and then analyze the full equilibrium with ex ante expertise acquisition.

4.1 Limit-Order Trading Game

First, consider the trading game in the limit-order market. The buyers are again probabilistically informed (with probabilities π_1 and π_2), but this time the information pertains to the common value of the asset. The

price quote that matches the willingness to pay of the highest buyer type is $p = \bar{v} + \Delta + \sigma_v$. This price is accepted only if at least one of the two buyers is informed that $v = \bar{v} + \sigma_v$. In line with the earlier analysis, we will refer to this price as the *high price*.

The seller may instead post a price that is low enough to also be accepted by buyers who did not receive information. An uninformed buyer needs to protect himself against the potential private information of competing buyers. There is adverse selection among buyers, as any uninformed buyer recognizes that one he accepts a price quote he is sure to get the asset if the other buyer knows that $v = \bar{v} - \sigma_v$, but he gets the asset only with probability $1/2$ if the other buyer knows that $v = \bar{v} + \sigma_v$. As we show in the proof of the lemma below, the highest price an uninformed buyer i is willing to pay for the asset in the limit-order market, given his adverse selection concerns regarding buyer j 's private information, is:

$$p = \bar{v} - \left(\frac{\pi_j}{2 + \pi_j} \right) \sigma_v + \Delta. \quad (13)$$

Finally, the seller may consider posting the *low price* $p = \bar{v} + \Delta - \sigma_v$, which would be accepted by all buyer types. Yet, posting this price is dominated by keeping the asset and keeping the asset is, in turn, dominated by posting the high price $p = \bar{v} + \Delta + \sigma_v$.

Lemma 3 *In the limit-order market with uncertain common values where buyer expertise satisfies $\pi_1 \geq \pi_2$, the seller posts a medium price:*

$$p = \bar{v} - \left(\frac{\pi_1}{2 + \pi_1} \right) \sigma_v + \Delta \quad (14)$$

in equilibrium whenever:

$$\frac{\Delta}{\sigma_v} \geq \left(\frac{1 + \pi_2}{2 + \pi_1} \right) \left(\frac{2\pi_1}{2 - \pi_1 - \pi_2} \right), \quad (15)$$

and the social surplus from trade in this case is: $(1 - \frac{\pi_1\pi_2}{2}) \Delta$. Otherwise, the seller posts the high price $p = \bar{v} + \Delta + \sigma_v$ and the social surplus from trade is: $\frac{1}{2} (\pi_1 + \pi_2 - \pi_1\pi_2) \Delta$.

From a social standpoint, trade efficiency improves if the seller posts the medium price rather than the high price, as doing so maximizes expected trade volume and gains to trade. Hence, in the region where condition (15) is violated, the seller posts a socially inefficient, high price.

4.2 OTC Trading Game

Next, we analyze the trading game in the OTC market. To keep the analysis parsimonious and comparable to the analysis in Section 3, we make sure that price opacity is not a concern. That is, we assume that the seller's offer to the first buyer is disclosed to the second buyer, in case that second buyer is reached.¹³

In the common-value environment, a rejection by the first buyer can contain useful information affecting the trading behaviors of the seller and the second buyer. Below in Lemma 4 we characterize the conditions under which the seller quotes a medium, efficient price $p = \bar{v} + \Delta$ to the first buyer in equilibrium (note that this medium price is now different than in the limit-order market). This price is only rejected by an informed buyer who knows that $v = \bar{v} - \sigma_v$. Hence, both the seller and the second buyer know that the asset is then worth $v_2 = \bar{v} + \Delta - \sigma_v$ to the second buyer while it is only worth $v = \bar{v} - \sigma_v$ to the seller. The seller then quotes the low price $p = \bar{v} + \Delta - \sigma_v$ to the second buyer, which is accepted with probability one.

Lemma 4 *In an OTC market with uncertain common values, the seller quotes a medium price $p = \bar{v} + \Delta$ to the first buyer and the low price $p = \bar{v} + \Delta - \sigma_v$ to the second buyer whenever:*

$$\frac{\Delta}{\sigma_v} \geq \max \left\{ \frac{\pi_1 + 2\pi_1\rho - 2\rho}{2(1 - \pi_1)(1 - \rho)}, \frac{\pi_1^2 - 2\pi_1(\pi_2\rho + 1) + 2\pi_2\rho}{(\pi_1 - 2)(2\pi_1(\rho - 1) + (\pi_2 - 2)\rho + 2)} \right\}. \quad (16)$$

The social surplus from trade is then: $[1 - \frac{\pi_1}{2}(1 - \rho)] \Delta$. Otherwise, the seller's optimal quotes include the high price $p = \bar{v} + \Delta + \sigma_v$ being quoted to the first buyer, as detailed in Appendix A.

Lemma 4 focuses on presenting the conditions under which the seller quotes a medium price to the first buyer in equilibrium. We will show in the next subsection that a pure strategy equilibrium with a high price

¹³Similar results would obtain if the price quoted to the first buyer was unobservable and we focused on equilibria where the second buyer's beliefs about how trade occurred with the first buyer are unaffected by the price the seller quotes to the second buyer (i.e., the second buyer's off-equilibrium beliefs about the value of the asset are constrained to be the same as his equilibrium beliefs).

quote does not exist once expertise is chosen endogenously. The “conservative” strategy of quoting the medium price quote to the first buyer maximizes social surplus in that it yields higher social surplus than under any strategy where the seller quotes the first buyer a high price, a strategy which can at most create a social surplus of $[\frac{\pi_1}{2} + (1 - \frac{\pi_1}{2})\rho] \Delta$. When the seller quotes the high price to the first buyer, trade occurs only with probability $\frac{\pi_1}{2}$ with the first buyer, and even if the second buyer always accepts the price quoted by the seller, the surplus is strictly lower, due to the social cost of delay. Moreover, as in the limit-order market, there is no equilibrium where the seller quotes the low price $p = \bar{v} + \Delta - \sigma_v$ to the first buyer, since doing so is dominated by the strategy of keeping the asset, which is in turn dominated by posting the high price $p = \bar{v} + \Delta + \sigma_v$.

4.3 Endogenous Expertise and the Relative Efficiency of Markets

We now analyze buyers’ optimal acquisition of expertise in both market structures and compare social welfare. Since we are analyzing a common-value environment, expertise acquisition is now impeding trade due to adverse selection. That is, although expertise acquisition improves a trader’s rent-seeking ability, it is socially harmful (see also Hirshleifer (1971) and Glode, Green, and Lowery (2012)). The existing literature has highlighted that security design can help alleviate such inefficiencies associated with information acquisition (Dang, Gorton, and Holmström 2015, Yang 2015). One of our contributions is to highlight that for *existing* securities that are traded in secondary markets, the choice between trading in OTC vs. limit-order markets also has important ramifications for the inefficiencies caused by adverse selection.

The following proposition details equilibrium expertise acquisition and trading behavior in both market structures.

Proposition 2 *In the limit-order market, the seller quotes a medium price $p = \bar{v} - \left(\frac{\pi_1}{2+\pi_1}\right) \sigma_v + \Delta$ with probability $m \in (0, 1]$ and the high price $p = \bar{v} + \sigma_v + \Delta$ with complementary probability $(1 - m)$. Buyers’ optimal expertise is given by:*

$$\pi_1 = \pi_2 = \pi^*(m) \equiv \frac{m\sigma_v + \sqrt{16c^2 + (m\sigma_v)^2}}{4c} - 1, \quad (17)$$

where $m = 1$ if:

$$\frac{\Delta}{\sigma_v} > \left(\frac{1 + \pi^*(1)}{2 + \pi^*(1)} \right) \left(\frac{\pi^*(1)}{1 - \pi^*(1)} \right), \quad (18)$$

and otherwise, $m \in (0, 1)$ solves:

$$\frac{\Delta}{\sigma_v} = \left(\frac{1 + \pi^*(m)}{2 + \pi^*(m)} \right) \left(\frac{\pi^*(m)}{1 - \pi^*(m)} \right). \quad (19)$$

In the OTC market, when facing the first buyer the seller quotes a medium price $p = \bar{v} + \Delta$ with probability $m_1 \in (0, 1]$ and the high price $p = \bar{v} + \sigma_v + \Delta$ with complementary probability $(1 - m_1)$. If the medium price was quoted and the first buyer rejected it, conditional on finding the second buyer the seller quotes the low price $p = \bar{v} - \sigma_v + \Delta$ with probability one. If the high price was quoted and the first buyer rejected it, conditional on finding the second buyer the seller quotes a medium price $p = \bar{v} - \frac{\pi_1}{2 - \pi_1} \sigma_v + \Delta$ with probability $m_2 \in (0, 1]$ and the low price $p = \bar{v} - \sigma_v + \Delta$ with complementary probability $(1 - m_2)$. Buyers' optimal expertise satisfies:

$$\pi_1 = \pi_1^*(m_1) = \frac{m_1 \sigma_v}{2c}, \quad (20)$$

$$\pi_2 = \pi_2^*(m_1, m_2) = \frac{2\rho\sigma_v}{c} (1 - m_1) m_2 \left(1 - \frac{\pi_1^*(m_1)}{2} \right) \frac{1 - \pi_1^*(m_1)}{(2 - \pi_1^*(m_1))^2}, \quad (21)$$

where $m_1 = 1$ if

$$\frac{\Delta}{\sigma_v} > \frac{\pi_1^*(1)^2 - 2\pi_1^*(1)(\pi_2^*(1)\rho + 1) + 2\pi_2^*(1)\rho}{(\pi_1^*(1) - 2)(2\pi_1^*(1)(\rho - 1) + (\pi_2^*(m_1, m_2) - 2)\rho + 2)}, \quad (22)$$

and otherwise, $m_1 \in (0, 1)$ solves:

$$\frac{\Delta}{\sigma_v} = \frac{\pi_1^*(m_1)^2 - 2\pi_1^*(m_1)(\pi_2^*(m_1)\rho + 1) + 2\pi_2^*(m_1)\rho}{(\pi_1^*(m_1) - 2)(2\pi_1^*(m_1)(\rho - 1) + (\pi_2^*(m_1, m_2) - 2)\rho + 2)}, \quad (23)$$

and where $m_2 = 1$ if

$$\frac{\Delta}{\sigma_v} < \frac{2(1 - \pi_1^*(m_1))[(2 - \pi_1^*(m_1))/\pi_2^*(m_1, 1) - 1]}{2 - \pi_1^*(m_1)}, \quad (24)$$

and otherwise, $m_2 \in (0, 1)$ solves:

$$\frac{\Delta}{\sigma_v} = \frac{2(1 - \pi_1^*(m_1))[(2 - \pi_1^*(m_1))/\pi_2^*(m_1, m_2) - 1]}{2 - \pi_1^*(m_1)}. \quad (25)$$

Again, equilibria where the seller quotes the high price with probability one do not exist. Expecting high price quotes with probability one, buyers would not have incentives to acquire expertise, as they would always receive zero surplus in the trading game. Yet, absent expertise acquisition, high price quotes are always rejected, rendering such a pricing strategy suboptimal for the seller.

Below, we use the results from Proposition 2 to perform comparative statics that illustrate the determinants of social efficiency under the two market structures. To facilitate a comparison with the results under private-value uncertainty presented in Subsection 3.3, we again consider assets, as characterized by the parameters c , Δ , and σ_b , where the seller quotes a medium price with probability one in both market structures. Such equilibria always obtain when expertise acquisition is sufficiently costly.

Figure 3 compares the social surplus and the buyers' expertise acquisition in the two market structures as a function of σ_v . In all our parameterizations, the centralized limit-order market is more efficient. A key reason for this result is the fact that, in the presence of common-value uncertainty, information generates an adverse selection problem that reduces the efficiency of trade. Unlike with private-value uncertainty, this information is not required to allocate the asset to its efficient holder. Thus, now the trading venue that provides *lower* incentives for expertise acquisition becomes the one that socially dominates. Since competition between buyers in the limit-order market lowers ex ante incentives for expertise acquisition, relative to the OTC market, the limit-order market yields greater volume and greater surplus from trade. Moreover, as we increase σ_v buyers face higher private incentives to acquire socially costly expertise, and the gap between the social efficiency of limit-order and OTC markets widens.

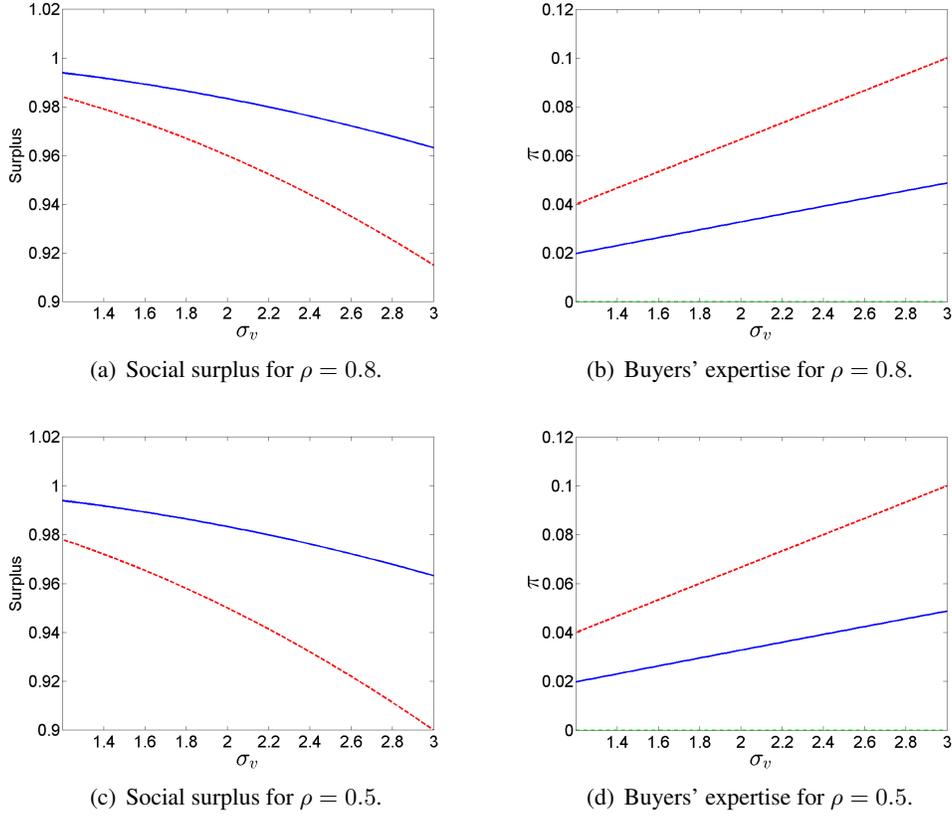


Figure 3: Social surplus and expertise acquisition with uncertain common values. In these figures, we set $\Delta = 1$, $\sigma_b = 0$, and $c = 15$, and plot the social surplus from trade, net of expertise acquisition costs, and the buyers' expertise levels π_i as functions of the uncertainty in common valuations σ_v . In Panels (a) and (c), the dashed line represents the surplus in the OTC market while the solid line represents the surplus in the limit-order market. In Panels (b) and (d), the dashed line represents the first buyer's expertise π_1 and the dotted line represents the second buyer's expertise π_2 in the OTC market, while the solid line represents the buyers' symmetric expertise in the limit-order market.

Comparing these results to Figure 1 highlights that whether common- or private-value uncertainty dominates for a given asset class has important implications for the relative efficiency of OTC and limit-order markets. Since the limit-order market weakens incentives for expertise acquisition, OTC markets tend to socially dominate when information is socially valuable (see Figure 1). Figure 3, however, shows that when information has no social value and instead merely introduces adverse selection, the limit-order market can be used to lower socially wasteful expertise acquisition. More broadly, our results suggest that factors out-

side of our model that are also known to affect the social value of expertise acquisition, such as the presence of feedback effects between trading and the real economy (Bond, Edmans, and Goldstein 2012), should be taken into consideration before imposing regulations that ban or limit OTC trading.

5 Discussion

5.1 Robustness

Our baseline model considered a setting with one seller and two buyers. As already mentioned in Subsection 3.3, if we extended our model to consider more than two prospective buyers the results developed above would only be strengthened. Holding buyer expertise fixed, the seller's incentives to quote high prices in the limit-order market would be increased as the number of prospective buyers goes to infinity (i.e., in a very "thick" market). Such aggressive screening behavior would not cause allocative inefficiencies as with probability one there would be at least one buyer who is informed and has a high private valuation. However, this limiting result reverses completely once we endogenize buyers' expertise levels. With many competing buyers, each buyer's benefit from acquiring expertise in a limit-order market would decrease. Thus, in asset classes where *private*-value uncertainty dominates, OTC markets would still offer social benefits relative to limit-order markets by providing greater incentives for expertise acquisition by buyers. An OTC market with search frictions effectively commits the seller to contacting certain, easier-to-reach traders first and to quote them less aggressive prices, which increases these traders' incentives to specialize and acquire expertise in the first place.

In addition, the incentives to screen counterparties with price quotes would still generally 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. Moreover, the roles of buyers and sellers could be reversed in our model without affecting our main results.

Note that we could also go beyond our Glosten and Milgrom-type setup for the limit-order market and allow for dynamic pricing strategies. As mentioned in Subsection 3.3, we analyze two periods of trading in the limit-order market in Appendix C. The ability to quote two prices sequentially strengthens the seller's incentives to post an aggressive price in the first period of limit-order trading, and allows extracting more rents from buyers. Yet, doing so again limits buyers' incentives to acquire expertise *ex ante*, supporting our key findings for the limit-order market discussed above.

Additionally, we show in Appendix C that the payoff functions derived for the baseline model would remain unchanged if centralized trading occurred through a second-price auction with a reserve price instead of through a limit-order market. Moreover, if the seller could use optimal auctions (Myerson 1981) in a centralized venue to extract maximum rents from buyers at the trading stage, buyers would again have particularly low *ex ante* incentives to acquire expertise, which impedes allocative efficiency in asset classes with significant private-value uncertainty.

Our results thus suggest more generally that search frictions in OTC markets can increase efficiency by alleviating commitment problems of market participants with access to scarce welfare-enhancing trading opportunities — search frictions allow these agents to credibly promise not to choose trading strategies or mechanisms that leave specialized counterparties with little or no surplus *ex post*, thereby providing some institutions with incentives to invest in socially valuable expertise *ex ante*.

5.2 Implementation

So far, we have shown that depending on the characteristics of an asset class either centralized limit-order markets or decentralized OTC markets can yield higher efficiency. One obvious way to implement the superior market structure is through regulatory enforcement. Alternatively, a market-design game similar to the network-formation game considered in Glode and Opp (2016) can be used to ensure that the market

structure with the highest total ex ante surplus is indeed the one where trade occurs in equilibrium. Such a game precedes the trading games discussed in previous sections, and characterizes order-flow agreements that traders commit to before information is obtained and trading occurs. A key component of these order-flow agreements are ex ante transfers that incentivize traders to commit to sending specified volumes of orders, in a probabilistic sense, to specific counterparties. While we consider a parsimonious environment with at most two trading rounds in this paper, commitment to these types of agreements can be sustained more generally 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).

6 Conclusion

In this paper, we compare the social efficiency of centralized limit-order markets and decentralized OTC markets in an environment with asymmetric information and endogenous expertise. In our model, agents bringing liquidity-driven order-flow to the market screen other traders with price quotes. We show that search frictions characteristic of OTC markets are not necessarily inefficient, as they tend to positively affect allocative efficiency and expertise acquisition in asset classes with significant private-value uncertainty. In contrast, elevated expertise-acquisition incentives in OTC markets are counter-productive in asset classes with significant common-value uncertainty. We find that which market structure dominates for a given asset class is thus strongly affected by the extent to which traders' private information relates to common or private valuations. Our stylized model thus provides an economic rationale for why bonds are mostly traded in OTC markets, whereas stocks and standardized derivatives such as corporate call options are mostly traded in limit-order markets.

Appendix

A Proofs of Lemmas

Proof of Lemma 1: The high price $p = \bar{v} + \Delta + \sigma_b$ is accepted only if at least one of the buyers is informed and values the asset at $v_i = \bar{v} + \Delta + \sigma_b$, which occurs with probability:

$$\frac{3}{4}\pi_1\pi_2 + \frac{1}{2}\pi_1(1 - \pi_2) + \frac{1}{2}\pi_2(1 - \pi_1) = \frac{1}{2}\left(\pi_1 + \pi_2 - \frac{1}{2}\pi_1\pi_2\right). \quad (\text{A1})$$

By posting this price, the seller collects an expected payoff of:

$$\begin{aligned} & \frac{1}{2}\left(\pi_1 + \pi_2 - \frac{1}{2}\pi_1\pi_2\right)(\bar{v} + \Delta + \sigma_b) + \left[1 - \frac{1}{2}\left(\pi_1 + \pi_2 - \frac{1}{2}\pi_1\pi_2\right)\right]\bar{v} \\ &= \bar{v} + \frac{1}{2}\left(\pi_1 + \pi_2 - \frac{1}{2}\pi_1\pi_2\right)(\Delta + \sigma_b). \end{aligned} \quad (\text{A2})$$

The seller may also consider posting a medium price $p = \bar{v} + \Delta$, which is low enough to also be accepted by buyers who do not have private information about their v_i . An informed buyer accepts to pay this price only when he knows that his own $v_i = \bar{v} + \Delta + \sigma_b$. By posting a price $p = \bar{v} + \Delta$, the seller thus collects an expected payoff of:

$$\left(1 - \frac{1}{4}\pi_1\pi_2\right)(\bar{v} + \Delta) + \frac{1}{4}\pi_1\pi_2\bar{v} = \bar{v} + \left(1 - \frac{1}{4}\pi_1\pi_2\right)\Delta. \quad (\text{A3})$$

Finally, the seller may consider posting a low price $p = \bar{v} + \Delta - \sigma_b$, which is accepted by all buyers, but posting this price is dominated by keeping the asset which in expectation is worth \bar{v} to him. Keeping the asset is, in turn, dominated by posting either $p = \bar{v} + \Delta + \sigma_b$ or $p = \bar{v} + \Delta$.

The seller thus posts the medium price $p = \bar{v} + \Delta$ whenever:

$$\begin{aligned} \bar{v} + \left(1 - \frac{1}{4}\pi_1\pi_2\right) \Delta &\geq \bar{v} + \frac{1}{2} \left(\pi_1 + \pi_2 - \frac{1}{2}\pi_1\pi_2\right) (\Delta + \sigma_b) \\ \Leftrightarrow \frac{\Delta}{\sigma_b} &\geq \frac{1}{2} \left(\frac{2\pi_1 + 2\pi_2 - \pi_1\pi_2}{2 - \pi_1 - \pi_2}\right). \end{aligned} \quad (\text{A4})$$

and in this case, the social surplus from trade is $(1 - \frac{1}{4}\pi_1\pi_2) \Delta + \frac{1}{4}(\pi_1 + \pi_2 + \pi_1\pi_2) \sigma_b$. Buyer i 's surplus is then:

$$\frac{\pi_i}{2} \left((1 - \pi_j) \frac{1}{2} + \pi_j \left(\frac{1}{2} \frac{1}{2} + \frac{1}{2} \right) \right) \sigma_b = \frac{\pi_i}{4} \left(1 + \frac{\pi_j}{2} \right) \sigma_b. \quad (\text{A5})$$

Otherwise, the seller posts the high price $p = \bar{v} + \Delta + \sigma_b$ and the social surplus from trade is

$$\frac{1}{2} \left(\pi_1 + \pi_2 - \frac{1}{2}\pi_1\pi_2 \right) (\Delta + \sigma_b) \quad (\text{A6})$$

as neither buyer collects any surplus. ■

Proof of Lemma 2: We solve for the equilibrium pricing strategy using backward induction. Since $\sigma_v = 0$ here, a rejection by the first buyer is uninformative about the private valuation of the second buyer. By quoting the high price $p = \bar{v} + \Delta + \sigma_b$ to the second buyer, the seller collects an expected payoff of:

$$\frac{\pi_2}{2} (\bar{v} + \Delta + \sigma_b) + \left(1 - \frac{\pi_2}{2}\right) \bar{v} = \bar{v} + \frac{\pi_2}{2} (\Delta + \sigma_b). \quad (\text{A7})$$

The seller may instead quote a medium price $p = \bar{v} + \Delta$, which is low enough to also be accepted by a second buyer who does not have private information about his v_i . By quoting this price, the seller collects an expected payoff of:

$$\left[\frac{\pi_2}{2} + (1 - \pi_2) \right] (\bar{v} + \Delta) + \frac{\pi_2}{2} \bar{v} = \bar{v} + \left(1 - \frac{\pi_2}{2}\right) \Delta. \quad (\text{A8})$$

Finally, the seller may quote a low price $p = \bar{v} + \Delta - \sigma_b$, which is always accepted by the second buyer, but quoting this price is dominated by keeping the asset which in expectation is worth \bar{v} to him. Keeping the

asset is, in turn, dominated by quoting the high price $p = \bar{v} + \Delta + \sigma_b$. The seller thus quotes the medium price $p = \bar{v} + \Delta$ to the second buyer whenever:

$$\begin{aligned} \bar{v} + \left(1 - \frac{\pi_2}{2}\right) \Delta &\geq \bar{v} + \frac{\pi_2}{2}(\Delta + \sigma_b) \\ \Leftrightarrow \frac{\Delta}{\sigma_b} &\geq \frac{1}{2} \left(\frac{\pi_2}{1 - \pi_2} \right), \end{aligned} \quad (\text{A9})$$

otherwise he quotes the high price $p = \bar{v} + \Delta + \sigma_b$.

When choosing a price to quote to the second buyer, the seller picks the price that maximizes his expected payoff. We denote the seller's maximal payoff from trade conditional on the first buyer rejecting the first price quote as $\bar{v} + \rho W^*(\pi_2)$, where $W^*(\pi_2) \equiv \max\{\frac{\pi_2}{2}(\Delta + \sigma_b), (1 - \frac{\pi_2}{2}) \Delta\}$. Knowing that he can still collect $\bar{v} + \rho W^*(\pi_2)$ in expectation if his first price quote is rejected, the seller can quote a high price $p = \bar{v} + \Delta + \sigma_b$ to the first buyer and collect:

$$\frac{\pi_1}{2}(\bar{v} + \Delta + \sigma_b) + \left(1 - \frac{\pi_1}{2}\right) (\bar{v} + \rho W^*(\pi_2)) = \bar{v} + \frac{\pi_1}{2}(\Delta + \sigma_b) + \left(1 - \frac{\pi_1}{2}\right) \rho W^*(\pi_2). \quad (\text{A10})$$

The seller may instead quote a medium price $p = \bar{v} + \Delta$ to the first buyer and collect:

$$\left[\frac{\pi_1}{2} + (1 - \pi_1) \right] (\bar{v} + \Delta) + \frac{\pi_1}{2}(\bar{v} + \rho W^*(\pi_2)) = \bar{v} + \left(1 - \frac{\pi_1}{2}\right) \Delta + \frac{\pi_1}{2} \rho W^*(\pi_2). \quad (\text{A11})$$

Finally, the seller may quote a low price $p = \bar{v} + \Delta - \sigma_b$, which is always accepted by the first buyer, but quoting this price is dominated by keeping the asset which in expectation is worth \bar{v} to him. As before, keeping the asset is, in turn, dominated by quoting either $p = \bar{v} + \Delta + \sigma_b$ or $p = \bar{v} + \Delta$.

The seller thus quotes the medium price $p = \bar{v} + \Delta$ to the first buyer whenever:

$$\begin{aligned} \bar{v} + \left(1 - \frac{\pi_1}{2}\right) \Delta + \frac{\pi_1}{2} \rho W^*(\pi_2) &\geq \bar{v} + \frac{\pi_1}{2}(\Delta + \sigma_b) + \left(1 - \frac{\pi_1}{2}\right) \rho W^*(\pi_2) \\ \Leftrightarrow \frac{\Delta}{\sigma_b} &\geq \frac{\rho W^*(\pi_2)}{\sigma_b} + \frac{1}{2} \left(\frac{\pi_1}{1 - \pi_1} \right), \end{aligned} \quad (\text{A12})$$

otherwise he quotes the high price $p = \bar{v} + \Delta + \sigma_b$. Since $W^*(\pi_2) > 0$, we know that this inequality is at least as restrictive as condition (A9) whenever $\pi_1 \geq \pi_2$. This implies that if the seller quotes $p = \bar{v} + \Delta$ to the first buyer, he will quote $p = \bar{v} + \Delta$ to the second buyer when he contacts him.

Thus, in cases where $\pi_1 \geq \pi_2$ we have three possible trading strategies for the seller. First, the seller quotes the medium $p = \bar{v} + \Delta$ to both buyers whenever:

$$\begin{aligned} \frac{\Delta}{\sigma_b} &\geq \frac{\rho W^*(\pi_2)}{\sigma_b} + \frac{1}{2} \left(\frac{\pi_1}{1 - \pi_1} \right) \\ &= \left(1 - \frac{\pi_2}{2} \right) \rho \frac{\Delta}{\sigma_b} + \frac{1}{2} \left(\frac{\pi_1}{1 - \pi_1} \right), \end{aligned} \quad (\text{A13})$$

which can be rewritten as:

$$\frac{\Delta}{\sigma_b} \geq \frac{1}{2} \left(\frac{1}{1 - \rho + \frac{\rho\pi_2}{2}} \right) \left(\frac{\pi_1}{1 - \pi_1} \right). \quad (\text{A14})$$

In this case, the social surplus from trade is: $\left[1 - \frac{\pi_1}{2} + \frac{\rho\pi_1}{2} \left(1 - \frac{\pi_2}{2} \right) \right] \Delta + \frac{\pi_1}{2} \left(1 + \frac{\rho\pi_2}{2} \right) \sigma_b$.

Second, the seller quotes the high price $p = \bar{v} + \Delta + \sigma_b$ to the first buyer and the medium price $p = \bar{v} + \Delta$ to the second buyer if needed whenever:

$$\frac{1}{2} \left(\frac{\pi_2}{1 - \pi_2} \right) \leq \frac{\Delta}{\sigma_b} < \frac{1}{2} \left(\frac{1}{1 - \rho + \frac{\rho\pi_2}{2}} \right) \left(\frac{\pi_1}{1 - \pi_1} \right), \quad (\text{A15})$$

and, in this case, the social surplus from trade is $\left[\frac{\pi_1}{2} + \rho \left(1 - \frac{\pi_1}{2} \right) \left(1 - \frac{\pi_2}{2} \right) \right] \Delta + \left[\frac{\pi_1}{2} + \rho \left(1 - \frac{\pi_1}{2} \right) \frac{\pi_2}{2} \right] \sigma_b$.

Third, the seller quotes the high price $p = \bar{v} + \Delta + \sigma_b$ to both buyers whenever:

$$\frac{\Delta}{\sigma_b} < \frac{1}{2} \left(\frac{\pi_2}{1 - \pi_2} \right), \quad (\text{A16})$$

and, in this case, the social surplus from trade is $\left[\frac{\pi_1}{2} + \rho \left(1 - \frac{\pi_1}{2} \right) \frac{\pi_2}{2} \right] (\Delta + \sigma_b)$. ■

Proof of Lemma 3: In a centralized market, the high price $p = \bar{v} + \Delta + \sigma_v$ is accepted only if at least one

of the two buyers is informed that $v = \bar{v} + \sigma_v$, which occurs with probability:

$$\frac{1}{2} [\pi_1 + (1 - \pi_1)\pi_2] = \frac{1}{2} (\pi_1 + \pi_2 - \pi_1\pi_2). \quad (\text{A17})$$

By posting this price, the seller collects an expected payoff of:

$$(\pi_1 + \pi_2 - \pi_1\pi_2) \left[\frac{1}{2}(\bar{v} + \Delta + \sigma_v) + \frac{1}{2}(\bar{v} - \sigma_v) \right] + [1 - (\pi_1 + \pi_2 - \pi_1\pi_2)] \bar{v} = \bar{v} + \frac{1}{2} (\pi_1 + \pi_2 - \pi_1\pi_2) \Delta. \quad (\text{A18})$$

The seller may also consider posting a price that is low enough to be accepted by buyers who do not have private information, yet is higher than the value of keeping the asset. An informed buyer accepts a price $p > \bar{v}$ only when $v = \bar{v} + \sigma_v$. Since informed buyers now condition their trading decision on a common-value component, an uninformed buyer needs to protect himself against the private information of competing buyers. There is thus adverse selection among buyers as any uninformed buyer recognizes that once he accepts a price quote he is sure to get the asset if the other buyer is informed that $v = \bar{v} - \sigma_v$, but he only gets the asset with probability $1/2$ if the other buyer is informed that $v = \bar{v} + \sigma_v$. The highest price an uninformed buyer i is willing to pay for the asset, given his adverse selection concerns regarding buyer j 's private information, is:

$$\frac{\frac{\pi_j}{2}(\bar{v} - \sigma_v) + \frac{\pi_j}{2}(\bar{v} + \sigma_v)\frac{1}{2} + (1 - \pi_j)\bar{v}\frac{1}{2}}{\frac{\pi_j}{2} + \frac{\pi_j}{2}\frac{1}{2} + (1 - \pi_j)\frac{1}{2}} + \Delta = \bar{v} - \left(\frac{\pi_j}{2 + \pi_j} \right) \sigma_v + \Delta. \quad (\text{A19})$$

If $\pi_1 \geq \pi_2$, a price $p = \bar{v} - \left(\frac{\pi_1}{2 + \pi_1} \right) \sigma_v + \Delta$ is rejected only if both buyers are informed that $v = \bar{v} - \sigma_v$. Hence, the seller collects an expected payoff of:

$$\begin{aligned} & \frac{\pi_1\pi_2}{2}(\bar{v} - \sigma_v) + \left(1 - \frac{\pi_1\pi_2}{2}\right) \left[\bar{v} - \left(\frac{\pi_1}{2 + \pi_1} \right) \sigma_v + \Delta \right] \\ &= \bar{v} + \left(1 - \frac{\pi_1\pi_2}{2}\right) \Delta - \pi_1 \left(\frac{1 + \pi_2}{2 + \pi_1} \right) \sigma_v. \end{aligned} \quad (\text{A20})$$

If $\pi_1 > \pi_2$, the seller might also consider posting a slightly higher price $p = \bar{v} - \left(\frac{\pi_2}{2 + \pi_2} \right) \sigma_v + \Delta$, which

is rejected whenever buyer 1 is informed that $v = \bar{v} - \sigma_v$. If he does so, the seller collects an expected payoff of:

$$\begin{aligned} & \frac{\pi_1}{2}(\bar{v} - \sigma_v) + \left(1 - \frac{\pi_1}{2}\right) \left[\bar{v} - \left(\frac{\pi_2}{2 + \pi_2}\right) \sigma_v + \Delta \right] \\ = & \bar{v} + \left(1 - \frac{\pi_1}{2}\right) \Delta - \left(\frac{\pi_1 + \pi_2}{2 + \pi_2}\right) \sigma_v. \end{aligned} \quad (\text{A21})$$

This expected payoff is, however, lower than the expected payoff from quoting $p = \bar{v} - \left(\frac{\pi_1}{2 + \pi_1}\right) \sigma_v + \Delta$, which is accepted with a higher probability.

The seller thus posts this medium price $p = \bar{v} - \left(\frac{\pi_1}{2 + \pi_1}\right) \sigma_v + \Delta$ whenever:

$$\begin{aligned} \bar{v} + \left(1 - \frac{\pi_1 \pi_2}{2}\right) \Delta - \pi_1 \left(\frac{1 + \pi_2}{2 + \pi_1}\right) \sigma_v & \geq \bar{v} + \frac{1}{2} (\pi_1 + \pi_2 - \pi_1 \pi_2) \Delta \\ \Leftrightarrow \frac{\Delta}{\sigma_v} & \geq \left(\frac{1 + \pi_2}{2 + \pi_1}\right) \left(\frac{2\pi_1}{2 - \pi_1 - \pi_2}\right), \end{aligned} \quad (\text{A22})$$

and in this case, the social surplus from trade is $(1 - \frac{\pi_1 \pi_2}{2}) \Delta$. Otherwise, the seller posts the high price $p = \bar{v} + \Delta + \sigma_v$ and the social surplus from trade is $\frac{1}{2} (\pi_1 + \pi_2 - \pi_1 \pi_2) \Delta$. ■

Proof of Lemma 4: First, consider a pricing strategy where the seller quotes a medium price $p = \bar{v} + \Delta$ to the first buyer. This price is only rejected by an informed buyer who knows that $v = \bar{v} - \sigma_v$. In case of a rejection, both the seller and the second buyer know that the asset is then worth $v_2 = \bar{v} + \Delta - \sigma_v$ to the second buyer while it is only worth $v = \bar{v} - \sigma_v$ to the seller. The seller quotes a low price $p = \bar{v} + \Delta - \sigma_v$ to the second buyer, which is accepted with probability 1. Under this strategy, the seller's expected payoff is:

$$\left(1 - \frac{\pi_1}{2}\right) (\bar{v} + \Delta) + \frac{\pi_1}{2} (\bar{v} + \rho \Delta - \sigma_v). \quad (\text{A23})$$

Alternatively, the seller quotes a high price $p = \bar{v} + \Delta + \sigma_v$ to the first buyer. If this price is rejected, this rejection reveals that the first buyer was either uninformed or informed and knew that the common-

value component had a low realization. Thus, if the second buyer does not receive a signal his maximum willingness to pay for the asset is:

$$\begin{aligned}
& \frac{\frac{\pi_1}{2}}{\frac{\pi_1}{2} + (1 - \pi_1)} (\bar{v} + \Delta - \sigma_v) + \frac{(1 - \pi_1)}{\frac{\pi_1}{2} + (1 - \pi_1)} (\bar{v} + \Delta) \\
&= \bar{v} + \Delta - \frac{\frac{\pi_1}{2}}{\frac{\pi_1}{2} + (1 - \pi_1)} \sigma_v \\
&= \bar{v} + \Delta - \frac{\pi_1}{2 - \pi_1} \sigma_v. \tag{A24}
\end{aligned}$$

If the second buyer is informed, his maximum willingness to pay is either the high price or the low price. If the first buyer rejects and the second buyer is reached and receives information, he sees a good common-value realization with conditional probability:

$$\frac{1 - \pi_1}{2 - \pi_1}, \tag{A25}$$

and conversely, a bad realization with conditional probability:

$$1 - \frac{1 - \pi_1}{2 - \pi_1} = \frac{1}{2 - \pi_1}. \tag{A26}$$

Thus, the seller's expected payoff from first quoting a high price, and then quoting the uninformed buyer's willingness to pay is:

$$\begin{aligned}
& \frac{\pi_1}{2} (\bar{v} + \Delta + \sigma_v) \\
&+ \left(1 - \frac{\pi_1}{2}\right) \rho \left[\left((1 - \pi_2) + \pi_2 \frac{1 - \pi_1}{2 - \pi_1} \right) \left(\bar{v} + \Delta - \frac{\pi_1}{2 - \pi_1} \sigma_v \right) + \pi_2 \frac{1}{2 - \pi_1} (\bar{v} - \sigma_v) \right] \\
&+ \left(1 - \frac{\pi_1}{2}\right) (1 - \rho) \left(\bar{v} - \frac{\pi_1}{2 - \pi_1} \sigma_v \right). \tag{A27}
\end{aligned}$$

The seller finds it optimal to quote a medium price $p = \bar{v} + \Delta$ to both buyer 1 and buyer 2 rather than a high price $p = \bar{v} + \Delta + \sigma_v$ to buyer 1 and a price targeting an uninformed buyer type 2 whenever (A23) exceeds

(A27), which yields the condition:

$$\frac{\Delta}{\sigma_v} \geq \frac{\pi_1^2 - 2\pi_1(\pi_2\rho + 1) + 2\pi_2\rho}{(\pi_1 - 2)(2\pi_1(\rho - 1) + (\pi_2 - 2)\rho + 2)}. \quad (\text{A28})$$

Finally, the seller's expected payoff from first quoting a high price and then quoting the low price is:

$$\frac{\pi_1}{2}(\bar{v} + \Delta + \sigma_v) + \left(1 - \frac{\pi_1}{2}\right) \left[\rho(\bar{v} + \Delta - \sigma_v) + (1 - \rho) \left(\bar{v} - \frac{\pi_1}{2 - \pi_1} \sigma_v \right) \right]. \quad (\text{A29})$$

The seller prefers (A23) to (A29) whenever:

$$\begin{aligned} \left(1 - \frac{\pi_1}{2}\right) (\bar{v} + \Delta) + \frac{\pi_1}{2}(\bar{v} + \rho\Delta - \sigma_v) &\geq \frac{\pi_1}{2}(\bar{v} + \Delta + \sigma_v) \\ &+ \left(1 - \frac{\pi_1}{2}\right) \left[\rho(\bar{v} + \Delta - \sigma_v) + (1 - \rho) \left(\bar{v} - \frac{\pi_1}{2 - \pi_1} \sigma_v \right) \right] \\ \Leftrightarrow \frac{\Delta}{\sigma_v} &\geq \frac{\pi_1 + 2\pi_1\rho - 2\rho}{2(1 - \pi_1)(1 - \rho)}. \end{aligned} \quad (\text{A30})$$

Finally, the seller prefers (A29) over (A27) whenever:

$$\frac{\Delta}{\sigma_v} \geq \frac{2(1 - \pi_1)((2 - \pi_1)/\pi_2 - 1)}{(2 - \pi_1)}. \quad (\text{A31})$$

We will show in the proof of Proposition 2 that endogenous expertise acquisition implies that the seller, after quoting a high price to the first buyer, will never quote the low price to the second buyer with probability 1, since in that case buyer 2 would set $\pi_2 = 0$, implying that condition (A31) is violated. Instead, the seller quotes a medium price with probability $m_2 \in (0, 1]$. Thus, in the equilibrium with endogenous expertise, condition (A31) either holds with equality (when the seller mixes, $m_2 \in (0, 1)$), or it is violated (when the seller quotes the medium price, $m_2 = 1$).

Thus, the relevant strategies for the seller are:

1. charging a medium price to the first buyer and the low price to the second buyer, which yields the seller an expected surplus equal to (A23).

2. charging the high price to the first buyer and quoting the second buyer a medium price with probability $m_2 \in (0, 1]$ and the low price with probability $(1 - m_2)$, which yields the seller an expected surplus equal to (A27). (This is because the seller either gets (A27) when setting $m_2 = 1$, and when he is mixing, for $m_2 \in (0, 1)$, it must be that (A27) and (A29) are equal.)
3. mixing between strategies 1 and 2, choosing strategy 1 with probability $m_1 \in (0, 1]$.

The seller will choose strategy 1 if condition (A28) holds with strict inequality and choose to mix when (A28) holds with equality. ■

B Proofs of Propositions

Proof of Proposition 1: In a mixed strategy equilibrium the seller mixes between a high price and a price that would be accepted by an uninformed buyer type. Let m denote the probability with which the seller quotes the uninformed buyer's valuation, that is, the "medium price."

(i) Limit-order market. From equation (A5), we know that if the seller quotes the medium price $p = \bar{v} + \Delta$ with probability m in the centralized market, buyer i must choose π_i to maximize:

$$m \frac{\pi_i}{4} \left(1 + \frac{\pi_j}{2} \right) \sigma_b - \frac{c}{2} \pi_i^2, \quad (\text{B1})$$

which takes into account that with probability $(1 - m)$ the seller quotes a high price $p = \bar{v} + \Delta + \sigma_b$, in which case each buyer obtains zero surplus from trade. The first-order condition yields:

$$\pi_i = \left(1 + \frac{\pi_j}{2} \right) \frac{m \sigma_b}{4c}, \quad (\text{B2})$$

which, from using an analogous condition for π_j , implies that both buyers acquire the same level of expertise:

$$\pi^*(m) = \frac{1}{\left(\frac{4c}{m \sigma_b} - \frac{1}{2} \right)}, \quad (\text{B3})$$

where $m = 1$ if

$$\frac{\Delta}{\sigma_b} > \left(1 - \frac{\pi^*(1)}{4}\right) \left(\frac{\pi^*(1)}{1 - \pi^*(1)}\right), \quad (\text{B4})$$

and otherwise, $m \in (0, 1)$ solves:

$$\frac{\Delta}{\sigma_b} = \left(1 - \frac{\pi^*(m)}{4}\right) \left(\frac{\pi^*(m)}{1 - \pi^*(m)}\right). \quad (\text{B5})$$

The surplus from trade is given by the weighted average of trade surpluses from a low and a high price, where the weights are given by m and $(1 - m)$, respectively:

$$\begin{aligned} m \left[\left(1 - \frac{1}{4}(\pi^*(m))^2\right) \Delta + \frac{1}{4} (2\pi^*(m) + (\pi^*(m))^2) \sigma_b \right] \\ + (1 - m) \frac{1}{2} \left(2\pi^*(m) - \frac{1}{2}(\pi^*(m))^2 \right) (\Delta + \sigma_b). \end{aligned} \quad (\text{B6})$$

(ii) OTC market. We know from our previous analysis that the seller has stronger incentives to quote a high price when contacting the first buyer than when contacting the second buyer. In addition, we know that equilibria where the seller quotes a buyer a high price with probability one cannot be sustained. Thus, the only type of equilibrium featuring mixed strategies that is sustainable is one where the seller mixes between the high and a medium price when facing the first buyer and quotes a medium price when facing the second buyer. We now characterize this mixed-strategy equilibrium.

If the seller mixes and quotes the medium price $p = \bar{v} + \Delta$ with probability m to the first buyer in the decentralized market, the first buyer picks π_1 to maximize:

$$m \frac{\pi_1}{2} \sigma_b - \frac{c}{2} \pi_1^2, \quad (\text{B7})$$

implying that in an interior optimum where $\pi_1^* \in (0, 1)$ we obtain:

$$\pi_1^*(m) = \frac{m\sigma_b}{2c}. \quad (\text{B8})$$

Further, the second buyer is always quoted a medium price and picks π_2 to maximize:

$$\left(1 - m + \left(m - \frac{1}{2}\right) \pi_1^*\right) \frac{\pi_2}{2} \rho \sigma_b - \frac{c}{2} \pi_2^2, \quad (\text{B9})$$

implying that we obtain:

$$\pi_2^*(m) = \left(1 - m + \left(m - \frac{1}{2}\right) \pi_1^*(m)\right) \frac{\rho \sigma_b}{2c}. \quad (\text{B10})$$

Using Lemma 2, we know that $m = 1$ if

$$\frac{\Delta}{\sigma_b} > \frac{1}{2 - \rho(2 - \pi_2^*(1))} \left(\frac{\pi_1^*(1)}{1 - \pi_1^*(1)} \right), \quad (\text{B11})$$

and otherwise, $m \in (0, 1)$ solves:

$$\frac{\Delta}{\sigma_b} = \frac{1}{2 - \rho(2 - \pi_2^*(m))} \left(\frac{\pi_1^*(m)}{1 - \pi_1^*(m)} \right). \quad (\text{B12})$$

The social surplus from trade in equilibrium is then:

$$\begin{aligned} & \pi_1^*(m) \left[\frac{1}{2} (\Delta + \sigma_b) + \frac{1}{2} \left(\frac{\pi_2^*(m)}{2} \rho (\Delta + \sigma_b) + (1 - \pi_2^*(m)) \rho \Delta \right) \right] \\ & + (1 - \pi_1^*(m)) \left[m \Delta + (1 - m) \left(\frac{\pi_2^*(m)}{2} \rho (\Delta + \sigma_b) + (1 - \pi_2^*(m)) \rho \Delta \right) \right]. \end{aligned} \quad (\text{B13})$$

■

Proof of Proposition 2: As with uncertain private valuations, we can rule out equilibria where π_i and π_j are high enough for the seller to always quote the high price, that is, we know that equilibria with $m = 0$ are not sustainable. In this case, buyers would be better off not acquiring information and the high price would be rejected.

(i) **Limit-order market.** Conjecture an equilibrium in the centralized trading game where $0 < m < 1$.

For sake of comparison with the case of uncertain private valuations, we will focus on symmetric equilibria where the two buyers acquire the same level of information in the centralized market, that is, $\pi_1 = \pi_2 \equiv \pi$. If buyer j acquires information with probability π and believes that buyer i will do the same, buyer i optimally responds to these beliefs and actions by picking π_i that maximizes:

$$\begin{aligned} & m \frac{\pi_i}{2} \frac{1}{2} \left(\bar{v} + \sigma_v + \Delta - \left(\bar{v} - \left(\frac{\pi}{2 + \pi} \right) \sigma_v + \Delta \right) \right) - \frac{c}{2} \pi_i^2 \\ &= \frac{m \pi_i}{2} \sigma_v \left(\frac{1 + \pi}{2 + \pi} \right) - \frac{c}{2} \pi_i^2. \end{aligned} \quad (\text{B14})$$

Given an interior solution $\pi_i \in (0, 1)$ we obtain:

$$\pi_i = \frac{m \sigma_v}{2c} \left(\frac{1 + \pi}{2 + \pi} \right). \quad (\text{B15})$$

Further, in a symmetric equilibrium we have $\pi_i = \pi_j = \pi^*(m)$, which yields:

$$\pi^*(m) = \frac{m \sigma_v}{2c} \left(\frac{1 + \pi^*(m)}{2 + \pi^*(m)} \right). \quad (\text{B16})$$

This equation has the following two roots:

$$-1 + \frac{m \sigma_v \pm \sqrt{16c^2 + (m \sigma_v)^2}}{4c}, \quad (\text{B17})$$

but since $\pi \in [0, 1]$, only the positive root can be a solution, that is,

$$\pi^*(m) = \frac{m \sigma_v + \sqrt{16c^2 + (m \sigma_v)^2}}{4c} - 1, \quad (\text{B18})$$

Using Lemma 3, we know that the seller quotes the medium price with probability 1 ($m = 1$) if:

$$\frac{\Delta}{\sigma_v} > \left(\frac{1 + \pi^*(1)}{2 + \pi^*(1)} \right) \left(\frac{\pi^*(1)}{1 - \pi^*(1)} \right), \quad (\text{B19})$$

and otherwise, $m \in (0, 1)$ solves:

$$\frac{\Delta}{\sigma_v} = \left(\frac{1 + \pi^*(m)}{2 + \pi^*(m)} \right) \left(\frac{\pi^*(m)}{1 - \pi^*(m)} \right). \quad (\text{B20})$$

The social surplus from trade is then given by the weighted average of trade surpluses from a medium and a high price, where the weights are given by m and $(1 - m)$, respectively:

$$m \left(1 - \frac{(\pi^*(m))^2}{2} \right) \Delta + (1 - m) \frac{1}{2} (2\pi^*(m) - (\pi^*(m))^2) \Delta. \quad (\text{B21})$$

(ii) OTC market. Again, we can focus on equilibria where the seller mixes with probability m_1 when contacting the first buyer. When quoted a medium price $p = \bar{v} + \Delta$ by the seller with probability m_1 and a high price with probability $(1 - m_1)$, the first buyer picks π_1 to maximize his expected profit of:

$$m_1 \frac{\pi_1}{2} [\bar{v} + \sigma_v + \Delta - (\bar{v} + \Delta)] - \frac{c}{2} \pi_1^2 = \frac{m_1 \pi_1}{2} \sigma_v - \frac{c}{2} \pi_1^2. \quad (\text{B22})$$

In equilibrium we thus have:

$$\pi_1^*(m_1) = \frac{m_1 \sigma_v}{2c}. \quad (\text{B23})$$

To abstract from issues of price opacity in decentralized markets and instead focus on the role of exclusivity and sequentiality we suppose that the price that was quoted in the first round is observable by all agents. This implies that the proposer in the second round of trade (the seller) does not have any private information and signaling is not a concern. Thus, the second buyer knows whether he is reached after a high price was quoted in the first round, or after a medium price. If a medium price was quoted in the first round and it was rejected then the second buyer knows with certainty that the common-value component had a negative realization. Thus, his willingness to pay is $\bar{v} - \sigma_v + \Delta$. If a high price was quoted in the first round,

and it was rejected then the second buyer's valuation, provided he did not receive a signal himself, is:

$$\frac{\frac{\pi_1}{2}(\bar{v} - \sigma_v) + (1 - \pi_1)\bar{v}}{\frac{\pi_1}{2} + (1 - \pi_1)} + \Delta = \bar{v} - \frac{\pi_1}{2 - \pi_1}\sigma_v + \Delta. \quad (\text{B24})$$

As before, in the considered equilibrium where the seller mixes with the first buyer the second buyer is either quoted a medium price or a low price since the seller's incentives to quote a high price are lower in the second round than in the first round.

If a high price was quoted in the first round and it was rejected, then the probability of receiving a good signal, conditional on receiving a signal, is equal to the conditional probability of a high realization, which is given by:

$$\frac{\frac{\pi_1}{2} \cdot 0 + (1 - \pi_1)\frac{1}{2}}{\frac{\pi_1}{2} + (1 - \pi_1)} = \frac{1 - \pi_1}{2 - \pi_1}. \quad (\text{B25})$$

As discussed in the proof of Lemma (4), the second buyer may be quoted one of two prices, either the willingness to pay of an uninformed buyer type, or the lowest possible price. The condition under which the seller prefers to choose the low price is given by (A31), that is,

$$\frac{\Delta}{\sigma_v} \geq \frac{2(1 - \pi_1)((2 - \pi_1)/\pi_2 - 1)}{(2 - \pi_1)}. \quad (\text{B26})$$

If the seller quotes the second buyer the low price with probability one, the second buyer's expected surplus is:

$$(1 - m_1) \left(1 - \frac{\pi_1}{2}\right) \rho \left(\frac{1 - \pi_1}{2 - \pi_1}\right) 2\sigma_v - \frac{c}{2}\pi_2^2. \quad (\text{B27})$$

which implies that zero information acquisition $\pi_2 = 0$ is optimal. Yet, given $\pi_2 = 0$, condition (A31) implies that the seller optimally quotes the medium price (targeting an uninformed buyer type). Thus, a pure strategy equilibrium where the seller quotes the low price with probability one to the second buyer does not exist.

If the seller instead quotes a price equal to the uninformed second buyer type's willingness to pay with probability m_2 , the second buyer's expected surplus is:

$$m_2(1 - m_1) \left(1 - \frac{\pi_1}{2}\right) \rho \pi_2 \frac{1 - \pi_1}{(2 - \pi_1)^2} 2\sigma_v \\ + (1 - m_2)(1 - m_1) \left(1 - \frac{\pi_1}{2}\right) \rho \frac{1 - \pi_1}{2 - \pi_1} 2\sigma_v - \frac{c}{2} \pi_2^2, \quad (\text{B28})$$

which yields :

$$\pi_2^*(m_1, m_2) = \frac{2\rho\sigma_v}{c} (1 - m_1) m_2 \left(1 - \frac{\pi_1^*(m_1)}{2}\right) \frac{1 - \pi_1^*(m_1)}{(2 - \pi_1^*(m_1))^2}, \quad (\text{B29})$$

where $m_1 = 1$ if

$$\frac{\Delta}{\sigma_v} > \frac{\pi_1^*(1)^2 - 2\pi_1^*(1)(\pi_2^*(1)\rho + 1) + 2\pi_2^*(1)\rho}{(\pi_1^*(1) - 2)(2\pi_1^*(1)(\rho - 1) + (\pi_2^*(m_1, m_2) - 2)\rho + 2)}, \quad (\text{B30})$$

and otherwise, $m_1 \in (0, 1)$ solves:

$$\frac{\Delta}{\sigma_v} = \frac{\pi_1^*(m_1)^2 - 2\pi_1^*(m_1)(\pi_2^*(m_1)\rho + 1) + 2\pi_2^*(m_1)\rho}{(\pi_1^*(m_1) - 2)(2\pi_1^*(m_1)(\rho - 1) + (\pi_2^*(m_1, m_2) - 2)\rho + 2)}, \quad (\text{B31})$$

and where $m_2 = 1$ if

$$\frac{\Delta}{\sigma_v} < \frac{2(1 - \pi_1^*(m_1))((2 - \pi_1^*(m_1))/\pi_2^*(m_1, 1) - 1)}{2 - \pi_1^*(m_1)}, \quad (\text{B32})$$

and otherwise, $m_2 \in (0, 1)$ solves:

$$\frac{\Delta}{\sigma_v} = \frac{2(1 - \pi_1^*(m_1))((2 - \pi_1^*(m_1))/\pi_2^*(m_1, m_2) - 1)}{2 - \pi_1^*(m_1)}. \quad (\text{B33})$$

C Alternative Models of Centralized Trading

In this Appendix, we investigate the robustness of our results to two alternative models of centralized trading. In both cases, we can show that the seller's screening behavior resembles that observed in our baseline model (i.e., one round of limit-order trading). Solely for tractability, we restrict our attention to situations where both buyers acquire the same level of information $\pi_1 = \pi_2 \equiv \pi^*$.

C.1 Two Rounds of Limit-Order Trading

Here, we model two periods of limit-order trading between the seller and the two buyers and assume that there is also a delay parameter ρ_c associated with waiting until the second period before realizing the gains to trade. In particular, we show that when ρ_c is small, that is, when delay costs are high in the centralized market due to immediacy needs or investor inattention, screening behavior in the two rounds of centralized trading resembles that observed in our baseline model with exogenous information.

Throughout, we assume that the seller cannot commit ex ante to charging a particular price in the second trading round. Thus, the seller's price strategy has to be subgame perfect.

C.1.1 Uncertainty in Private Values

We start by establishing the following result:

Lemma 5 *Any equilibrium where only the high buyer type accepts the seller's offer in the first trading round has to feature a price that is accepted by the uninformed buyer type in the second trading round.*

Proof. This result simply follows from subgame perfection. Once we reach the second round the seller knows that only uninformed types and low types are in the market. Thus, the seller strictly prefers to quote the uninformed type's valuation in this second round. ■

High/uninformed equilibrium. First, we consider a possible equilibrium where the seller posts a price in the first round that is accepted by the high buyer type, and in the second round a price that is accepted

by the uninformed buyer type. The offer in the first round is accepted only if there is at least one informed buyer with a high valuation for the asset, which happens with probability $\frac{3}{4}\pi^{*2} + \pi^*(1 - \pi^*)$. In this case the surplus from trade is $\Delta + \sigma_b$. With probability $\rho_c(1 - (\frac{3}{4}\pi^{*2} + \pi^*(1 - \pi^*)))$ the second trading round is reached. Conditional on reaching the second round, the probability that there is at least one uninformed buyer is given by:

$$\frac{\pi^*(1 - \pi^*)\frac{1}{2} + (1 - \pi^*)\pi^*\frac{1}{2} + (1 - \pi^*)^2}{1 - (\frac{3}{4}\pi^{*2} + \pi^*(1 - \pi^*))}. \quad (C1)$$

The total ex ante surplus in this type of equilibrium is thus given by:

$$\begin{aligned} & \left(\frac{3}{4}\pi^{*2} + \pi^*(1 - \pi^*) \right) (\Delta + \sigma_b) + \rho_c(\pi^*(1 - \pi^*) + (1 - \pi^*)^2)\Delta \\ &= \left(\frac{3}{4}\pi^{*2} + (1 + \rho_c)\pi^*(1 - \pi^*) + \rho_c(1 - \pi^*)^2 \right) \Delta + \left(\frac{3}{4}\pi^{*2} + \pi^*(1 - \pi^*) \right) \sigma_b \\ &= \left(\rho_c + \pi^*(1 - \rho_c) - \frac{\pi^{*2}}{4} \right) \Delta + \left(\frac{3}{4}\pi^{*2} + \pi^*(1 - \pi^*) \right) \sigma_b. \end{aligned} \quad (C2)$$

Incentive compatibility for the high buyer type. We need to determine what prices the seller would have to post in the first trading round to incentivize high buyer types to accept in that round, rather than to wait for the lower, second-round price. By subgame perfection we know that in an equilibrium where in the second round uninformed buyers are still in the market it is optimal for the seller to post a price $\bar{v} + \Delta$ in that second round. To determine the price that needs to be posted in the first round to ensure that a high buyer type accepts we compute a high buyer type's expected payoff from a unilateral deviation. Consider a high buyer type who believes that if the other buyer in the market is a high type he will accept the price quoted in the first round. Given these beliefs, a high buyer type who deviates and waits for the second trading round expects to obtain the asset at the uninformed price in the second round with the following probability:

$$\rho_c \left(1 - \frac{\pi^*}{2} \right) \frac{\left(\frac{\pi^*}{2} + \frac{(1 - \pi^*)}{2} \right)}{\left(1 - \frac{\pi^*}{2} \right)} = \rho_c \left(\frac{\pi^*}{2} + \frac{(1 - \pi^*)}{2} \right) = \frac{\rho_c}{2}. \quad (C3)$$

Thus, it is incentive compatible for a high type to accept the posted price p_1 in the first round if

$$\left(1 - \frac{\pi^*}{4}\right) ((\bar{v} + \Delta + \sigma_b) - p_1) \geq \frac{\rho_c}{2} \sigma_b, \quad (\text{C4})$$

which yields the following restriction for the price:

$$p_1 \leq \bar{v} + \Delta + \sigma_b \left(\frac{1 - \frac{\rho_c}{2} - \frac{\pi^*}{4}}{1 - \frac{\pi^*}{4}} \right). \quad (\text{C5})$$

The seller will optimally post the lowest possible price that is incentive compatible. The seller's expected payoff is then given by:

$$\begin{aligned} & \bar{v} + \left(\frac{3}{4} \pi^{*2} + \pi^*(1 - \pi^*) \right) \left[\Delta + \sigma_b \left(\frac{1 - \frac{\rho_c}{2} - \frac{\pi^*}{4}}{1 - \frac{\pi^*}{4}} \right) \right] + \rho_c (\pi^*(1 - \pi^*) + (1 - \pi^*)^2) \Delta \\ & = \bar{v} + \left(\rho_c + \pi^*(1 - \rho_c) - \frac{\pi^{*2}}{4} \right) \Delta + \left(\frac{3}{4} \pi^{*2} + \pi^*(1 - \pi^*) \right) \sigma_b \left(\frac{1 - \frac{\rho_c}{2} - \frac{\pi^*}{4}}{1 - \frac{\pi^*}{4}} \right). \end{aligned} \quad (\text{C6})$$

As $\rho_c \rightarrow 0$ this payoff converges to the high-price strategy in the one-period centralized market featured in our baseline setup.

Uninformed/low equilibrium. In this equilibrium high and uninformed buyer types already accept the first price offer. If these two types accept in the first round, the seller knows that in the second only low types are present. He will optimally not sell the asset in that case, since the gains to trade are negative, that is, $\Delta - \sigma_b < 0$. Anticipating this, high and uninformed buyer types (at least weakly) optimally accept a price $v + \Delta$ in the first trading round, that is, they do not have a strict incentive to reject the price offer in the first round. The seller's expected payoff from this strategy is:

$$\bar{v} + \left(1 - \frac{\pi^{*2}}{4} \right) \Delta. \quad (\text{C7})$$

This is the same payoff as the one from targeting the uninformed type in the one-period centralized market featured in our baseline setup.

Infinite/high equilibrium. In this equilibrium no buyer accepts to pay the first price and only the high type accepts to pay the second price. By subgame perfection the second price is $\bar{v} + \Delta + \sigma_b$ while the first price is infinite (or any price that is sufficiently high not to be accepted by any buyer type). The seller's expected payoff from this strategy is:

$$\bar{v} + \rho_c \left(\frac{\pi^*}{2} + \frac{\pi^* \pi^*}{2} + (1 - \pi^*) \frac{\pi^*}{2} \right) (\Delta + \sigma_b) = \bar{v} + \rho_c \pi^* \left(1 - \frac{\pi^*}{4} \right) (\Delta + \sigma_b). \quad (\text{C8})$$

This strategy is never optimal when $\rho_c \rightarrow 0$.

Optimal pricing strategy. We can immediately see that as $\rho_c \rightarrow 0$ the seller's problem reduces to the one we considered in the baseline setup with one trading round.

C.1.2 Uncertainty in Common Value

Below we analyze the same types of pricing strategies across the two trading rounds but for the case of common-value uncertainty.

High/uninformed equilibrium. Here the seller quotes a price in the first round that is accepted by the high buyer type, and in the second round a price that is accepted by the uninformed buyer type. The offer in the first round is accepted only if there is at least one high buyer type, which happens with probability $\frac{1}{2}(\pi^{*2} + 2\pi^*(1 - \pi^*)) = \pi^* - \frac{\pi^{*2}}{2}$. In this case the surplus from trade is then given by Δ . With probability $\rho_c(1 - \pi^* + \frac{\pi^{*2}}{2})$ the second trading round is reached. Conditional on reaching the second round, the probability that there is at least one uninformed buyer is given by:

$$\frac{2\pi^*(1 - \pi^*)\frac{1}{2} + (1 - \pi^*)^2}{1 - \frac{1}{2}(\pi^{*2} + 2\pi^*(1 - \pi^*))} = \frac{1 - \pi^*}{1 - \pi^* + \frac{\pi^{*2}}{2}}. \quad (\text{C9})$$

The total ex ante surplus in this type of equilibrium is thus given by:

$$\left(\pi^* - \frac{\pi^{*2}}{2} + \rho_c(1 - \pi^*) \right) \Delta. \quad (\text{C10})$$

Incentive compatibility for the high buyer type. We need to determine what prices the seller would need to post in the first trading round to incentivize high buyer types to accept in that round, rather than to wait for the lower, second-round price.

In this type of equilibrium the fact that the first price is not accepted yields an informative signal to the seller and to any uninformed buyer. After the second trading round is reached the seller and uninformed buyer types thus assign the following probability to the event that the asset has a high common-value realization:

$$\frac{\frac{1}{2}(1 - \pi^*)^2}{1 - \pi^* + \frac{\pi^{*2}}{2}}. \quad (\text{C11})$$

The corresponding expected value of the common-value component is thus:

$$\bar{v} - \sigma_v \pi^* \left(\frac{1 - \frac{\pi^*}{2}}{1 - \pi^* + \frac{\pi^{*2}}{2}} \right). \quad (\text{C12})$$

By posting a price equal to the sum of this expected value and Δ the seller collects an expected payoff of:

$$(\pi_1^* + \pi_2^* - \pi_1^* \pi_2^*) \left[\frac{1}{2}(\bar{v} + \Delta + \sigma_v) + \frac{1}{2}(\bar{v} - \sigma_v) \right] + [1 - (\pi_1^* + \pi_2^* - \pi_1^* \pi_2^*)] \bar{v} = \bar{v} + \frac{1}{2} (\pi_1^* + \pi_2^* - \pi_1^* \pi_2^*) \Delta. \quad (\text{C13})$$

By subgame perfection we know that in an equilibrium where in the second round uninformed buyers are still in the market it is optimal for the seller to post a price equal to this conditional expected value plus Δ . To determine the price that needs to be posted in the first round to ensure that a high buyer type does not wait for the second trading round we compute a high buyer type's expected payoff from such a unilateral deviation. Consider a higher buyer type who believes that if the other buyer in the market is a high type he will accept the price posted in the first round. Given these beliefs, a high buyer type who deviates and waits

for the second trading round expects to obtain the asset at the uninformed price in the second round with the following probability:

$$(1 - \pi^*) \frac{\rho_c}{2}. \quad (\text{C14})$$

Thus, it is incentive compatible for a high type to accept the price p_1 quoted in the first round if:

$$\left(1 - \frac{\pi^*}{2}\right) ((\bar{v} + \Delta + \sigma_v) - p_1) \geq \frac{\rho_c}{2} (1 - \pi^*) \left(\sigma_v + \sigma_v \pi^* \left(\frac{1 - \frac{\pi^*}{2}}{1 - \pi^* + \frac{\pi^{*2}}{2}} \right) \right), \quad (\text{C15})$$

which yields the following restriction for the price:

$$p_1 \leq \bar{v} + \Delta + \sigma_v \left(1 - \frac{\frac{\rho_c}{2} (1 - \pi^*) \left(1 + \pi^* \left(\frac{1 - \frac{\pi^*}{2}}{1 - \pi^* + \frac{\pi^{*2}}{2}} \right) \right)}{\left(1 - \frac{\pi^*}{2}\right)} \right). \quad (\text{C16})$$

The seller will optimally post the highest possible price that is incentive compatible. Using

$$((1 - \pi^*)^2 + \pi^*(1 - \pi^*)) = 1 - \pi^* \quad (\text{C17})$$

we can rewrite the seller's expected payoff as:

$$\begin{aligned} & \frac{1}{2} (2\pi^* - \pi^{*2}) p_1^{\max} \\ & + \rho_c (1 - \pi^*) \left(\bar{v} + \Delta - \sigma_v \pi^* \left(\frac{1 - \frac{\pi^*}{2}}{1 - \pi^* + \frac{\pi^{*2}}{2}} \right) \right) \\ & + (1 - \rho_c) (1 - \pi^*) \left(\bar{v} - \sigma_v \pi^* \left(\frac{1 - \frac{\pi^*}{2}}{1 - \pi^* + \frac{\pi^{*2}}{2}} \right) \right) \\ & + \frac{1}{2} \pi^{*2} (\bar{v} - \sigma_v). \end{aligned} \quad (\text{C18})$$

As $\rho_c \rightarrow 0$ this expected payoff converges to the expected payoff from targeting the uninformed buyer type in the one-period centralized market featured in our baseline setup.

Uninformed/low equilibrium. In this equilibrium high and uninformed buyer types accept the first price quote and the seller knows that in the second round only low types are present. The seller then optimally sells the asset at the price $\bar{v} - \sigma_v + \Delta$ in the second round. We need to determine the maximum incentive compatible price in the first round that ensures that neither the high type nor the low type wishes to deviate and wait for the second round.

For an uninformed agent the probability that the common-value component has a high realization, given that the agent receives the asset, is:

$$p_H = \frac{\frac{\pi^*}{2} \frac{1}{2} + (1 - \pi^*) \frac{1}{2} \frac{1}{2}}{\frac{\pi^*}{2} \frac{1}{2} + (1 - \pi^*) \frac{1}{2} + \frac{\pi^*}{2}} = \frac{1}{\pi^* + 2}. \quad (\text{C19})$$

Thus, the expected value of the common-value component conditional on receiving the asset is:

$$\bar{v} + (2p_H - 1)\sigma_v = \bar{v} - \frac{\pi^*}{\pi^* + 2}\sigma_v. \quad (\text{C20})$$

Incentive-compatible prices in the first round. We need to determine what prices the seller would need to post in the first trading round to incentivize the high and uninformed buyer types to accept in that round, rather than to wait for the lower, second-round price. To do so we first compute a buyer's expected payoff from a unilateral deviation. Consider a buyer who is either a high type or an uninformed type and who believes that if the other buyer in the market is a high type or an uninformed type he will accept the price posted in the first round. A high buyer type who deviates and waits for the second trading round expects to obtain the asset at the price $\bar{v} - \sigma_v + \Delta$ in the second round with probability 0 — the other buyer will definitely be either a high informed type or an uninformed type, and both accept the price. An uninformed buyer type who deviates and waits for the second trading round expects to obtain the asset at the price $\bar{v} - \sigma_v + \Delta$ in the second round only if the other buyer is a low informed type, implying that the probability of obtaining the asset in the second round is:

$$\pi^* \frac{\rho_c}{2}. \quad (\text{C21})$$

Yet in this case the price $\bar{v} - \sigma_v + \Delta$ leaves no surplus with the uninformed buyer either. Thus, by posting a price of

$$\bar{v} - \frac{\pi^*}{\pi^* + 2}\sigma_v + \Delta \quad (\text{C22})$$

in the first round, the seller can sustain an equilibrium where both high buyer types and uninformed buyer types accept in the first round. The seller's expected payoff from this strategy is then given by:

$$\left(1 - \frac{\pi^{*2}}{2}\right) \left(\bar{v} - \frac{\pi^*}{\pi^* + 2}\sigma_v + \Delta\right) + \frac{\pi^{*2}}{2}\rho_c (\bar{v} - \sigma_v + \Delta) + \frac{\pi^{*2}}{2}(1 - \rho_c) (\bar{v} - \sigma_v). \quad (\text{C23})$$

As $\rho_c \rightarrow 0$ this expected payoff converges to the expected payoff from targeting the uninformed buyer type in the one-period centralized market featured in our baseline setup.

Infinite/high equilibrium. In this equilibrium no buyer accepts the first price and only the high buyer type accepts the second price. By subgame perfection the second price is $\bar{v} + \Delta + \sigma_b$ while the first price is infinite (or any price that is sufficiently high not to be accepted by any buyer type). The conditional probability that the common-value component is high if both prices are rejected is:

$$p_H = \frac{\frac{1}{2}(1 - \pi^*)^2}{1 - \frac{1}{2}(\pi^{*2} + 2\pi^*(1 - \pi^*))} \quad (\text{C24})$$

Thus, the conditional expected value of the common-value component after two rejections is:

$$\bar{v} + p_H\sigma_v - (1 - p_H)\sigma_v = \bar{v} + (2p_H - 1)\sigma_v. \quad (\text{C25})$$

Further, with probability $(1 - \rho_c)$ no trade occurs at all, which is completely uninformative about the common-value realization. The seller's expected payoff from this strategy is:

$$\begin{aligned} & \frac{\rho_c}{2}(\pi^{*2} + 2\pi^*(1 - \pi^*))(\bar{v} + \Delta + \sigma_b) + (1 - \rho_c)\bar{v} \\ & + \rho_c \left(1 - \frac{1}{2}(\pi^{*2} + 2\pi^*(1 - \pi^*)) \right) (\bar{v} + (2p_H - 1)\sigma_v). \end{aligned} \quad (\text{C26})$$

For $\rho_c = 0$ this is never an optimal strategy.

Optimal pricing strategy. We can immediately see that as $\rho_c \rightarrow 0$ the seller's problem reduces to that from the one-period centralized market featured in our baseline setup.

C.2 Reserve-Price Auction

Here, we replace our centralized limit-order market by an auction with a reserve price. In particular, we show that the seller's optimal choice of a reserve price closely resembles the screening behavior we observe in our baseline model.

To simplify the analysis of bidding behaviors, we model a second-price auction and focus on the case where the uncertainty is in private valuations and $\sigma_b > \Delta$ as in Section 3. In a second-price auction with private-value uncertainty, each buyer finds it optimal to bid his actual valuation for the asset. As we show below, there exist reserve prices r that ensure that a second-price auction leads to socially efficient trade when taking buyers information π^* as given. However, we also show that this existence result does not imply that the auction is indeed more efficient. Consistent with our results for the limit-order market, the seller often has incentives to pick a reserve price that leads to the inefficient screening of informed buyers.

Note also that as we argue at the end of Subsection 3.3, whenever the auction allows the seller to lower informed buyers' surplus, it discourages information acquisition and lowers the social surplus in the private value setting. Thus, increasing the seller's ability to reduce informed buyers' rents via an optimal auction mechanism as in Myerson (1981) could worsen the seller's commitment problem, whereby he cannot

credibly promise to choose trading strategies or mechanisms that leave informed buyers with enough surplus ex post.

Low reserve price. If the seller picks a low reserve price $r \leq \bar{v} + \Delta - \sigma_b$, trade always occurs and the seller collects the second-highest private valuation among the two buyers. There is thus a positive probability that the seller will end up receiving $\bar{v} + \Delta - \sigma_b$, which is lower than his private valuation for the asset. This strategy is thus dominated by picking $r = \bar{v}$.

Medium reserve price. Picking any reserve price $r \in [\bar{v}, \bar{v} + \Delta]$ leads to trade occurring whenever at least one buyer values the asset at $v_i \geq \bar{v} + \Delta$. This strategy yields for the seller an expected payoff of:

$$\frac{\pi^{*2}}{4}(\bar{v} + \Delta + \sigma_b) + \left(1 - \frac{\pi^{*2}}{2}\right)r + \frac{\pi^{*2}}{4}\bar{v}. \quad (\text{C27})$$

Within this region of potential reserve prices, setting $r = \bar{v} + \Delta$ is then the dominant strategy and yields an expected payoff of:

$$\bar{v} + \left(1 - \frac{\pi^{*2}}{4}\right)\Delta + \frac{\pi^{*2}}{4}\sigma_b. \quad (\text{C28})$$

Since the asset goes to the buyer with the highest valuation whenever that valuation is above \bar{v} and stays with the seller otherwise, this mechanism leads to socially efficient trading given traders' information.

High reserve price. Although a second-price auction with a medium reserve price leads to socially efficient trading in our model, the seller may still find it optimal to pick a high reserve price and inefficiently screen informed buyers. In particular, by picking a reserve price $r = \bar{v} + \Delta + \sigma_b$, the seller is able to collect $\bar{v} + \Delta + \sigma_b$ whenever at least one of the buyers is informed that he has a high valuation for the asset. Setting this reserve price leads to identical payoffs to a strategy of quoting the high price in the baseline limit-order market. Thus, the seller expects to collect a payoff of:

$$\bar{v} + \frac{1}{2} \left(2\pi^* - \frac{1}{2}\pi^{*2}\right) (\Delta + \sigma_b) \quad (\text{C29})$$

and the social surplus from trade is $\frac{1}{2} (2\pi^* - \frac{1}{2}\pi^{*2}) (\Delta + \sigma_b)$.

Optimal reserve price. When choosing between the two possible candidates for an optimal reserve price, i.e., $r = \bar{v} + \Delta$ and $r = \bar{v} + \Delta + \sigma_b$, the seller picks r to maximize his expected payoff. He thus chooses the medium, efficient reserve price whenever:

$$\begin{aligned} \bar{v} + \left(1 - \frac{\pi^{*2}}{4}\right) \Delta + \frac{\pi^{*2}}{4} \sigma_b &\geq \bar{v} + \frac{1}{2} \left(2\pi^* - \frac{1}{2}\pi^{*2}\right) (\Delta + \sigma_b) \\ \Leftrightarrow \frac{\Delta}{\sigma_b} &\geq \frac{2\pi^* - \pi^{*2}}{2 - 2\pi^*}. \end{aligned} \tag{C30}$$

It is then easy to check that this condition is violated when π^* is large enough, meaning that the seller behaves identically in a second-price auction with a reserve price and in our baseline model of a limit-order market when the cost of acquiring information for the buyer, c , is small enough.

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