

# Can Decentralized Markets Be More Efficient?

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Decentralized markets attract large amounts of trade volume, even though they exhibit frictions absent in centralized exchanges. We develop a model with asymmetric information and expertise acquisition where some traders try to exploit any market structure to inefficiently screen their counterparties. In this environment, frictions characteristic of decentralized markets, such as time-consuming search, can promote higher efficiency. First, screening behavior may be less aggressive when traders reach fewer counterparties. Second, for asset classes where information improves allocative efficiency, decentralized markets with predictable trading encounters may dominate by encouraging expertise acquisition. In contrast, when information causes adverse selection, centralized markets dominate. (JEL D82, G23, L10)

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# 1 Introduction

Many assets are primarily traded in decentralized markets: real estate, bonds, credit and interest-rate derivatives, foreign exchange instruments, and securitized products to name only a few. According to the Securities Industry and Financial Markets Association and the Bank of International Settlements, *daily* volume reaches \$5.4T in the global foreign exchange market, \$2.3T in the U.S. interest-rate derivative market, and \$0.8T in the U.S. bond market. But despite their prevalence, decentralized markets are commonly thought of as opaque and illiquid compared to centralized exchanges that serve as primary trading venues for assets like stocks. Many commentators and policy makers even blamed decentralized trading for exacerbating the recent financial crisis and suggested significant reforms, which often amounted to centralizing trading.<sup>1</sup> It is, however, worth highlighting that for some assets like currencies and bonds, investors already have the option to trade in a centralized venue but often decide not to.<sup>2</sup> Sophisticated agents choose to trade large quantities of certain assets using “inferior” decentralized technologies (e.g., phone calls) while they prefer to trade other types of assets in centralized markets.

This paper attempts to shed light on the potential merits of decentralized markets that can be subject to costly trading delays, due for example to search frictions. 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 potentially informed counterparties. The fact that such traders do not act as price takers, but instead use pricing strategies to maximize their own profits is consistent with evidence of concentrated holding and trading for many of the assets currently traded in decentralized markets.<sup>3</sup> Asymmetric information is another important feature of our model, as it helps us capture the documented heterogeneity in traders’ expertise.<sup>4</sup> Our model identifies specific situations for which decentralized trading socially dominates centralized trading, as well as situations for which the opposite is true. In particular, we show that moving assets currently traded in decentralized venues toward centralized venues could impede the efficiency of trade by lowering some

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<sup>1</sup>For specific examples, see “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.

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

<sup>3</sup>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.

<sup>4</sup>See, 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.

traders' incentives to acquire information and by increasing other traders' incentives to screen their privately informed counterparties.

Our model features the owner of an asset who can sell the asset to two prospective buyers and realize exogenous, but potentially uncertain, gains to trade. When the market is decentralized, the seller first contacts one buyer and quotes him a price. If the buyer rejects the offer, the seller searches for a second buyer, and, provided he finds one, quotes him a potentially different price. This search for the second buyer may, however, delay the realization of the trade surplus which can be costly due to immediacy or liquidity concerns. When the market is centralized instead, no delay is necessary in reaching both buyers: the seller posts a price and the two buyers simultaneously decide whether to pick up this "limit order."

We start by comparing the social efficiency of trade in these two types of market assuming that traders' information sets are independent of the market structure. Then, we perform a similar analysis but allow traders to choose how much information to acquire given the market structure. In our model, information can be either about an asset's fundamental value (common to all traders), or about a trader's own idiosyncratic valuation (independent across traders). When the market structure does not change buyers' expertise acquisition nor the seller's pricing strategies, and trade delays lead to the destruction of social surplus, centralized trading socially dominates decentralized trading. We show, however, that decentralizing trading can incentivize traders to change their behaviors in socially beneficial ways.

First, since centralized trading makes it more likely that a high price quote will be accepted quickly by at least one buyer, a seller may choose more aggressive trading strategies in these markets than in decentralized markets. Aggressive screening behavior by a trader endowed with market power may in turn inefficiently reduce trade volume and jeopardize gains to trade. Second, search frictions in decentralized markets that make it easier to reach some counterparties than others create predictability in trading encounters and guarantee a larger volume of offers to a subset of counterparties. These offers are furthermore exclusive, as counterparties in decentralized 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 have to invest in specialized infrastructure that yields private information about asset valuations. In some cases, allocative efficiency requires traders to acquire information as it 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. Our paper shows that if 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. The opposite is, however, true if traders are likely to acquire information about the asset's common value. This type of information only improves traders' rent-seeking ability and impedes trade due to adverse selection, making centralized markets more beneficial. Which market dominates thus depends on the extent to which traders' are likely to acquire information about private- or common value components, which as we will argue below, likely varies by asset class. Overall, our model highlights the potential benefits of search frictions present in decentralized markets by considering how asymmetrically informed traders strategically respond to these frictions, contrasting with the unequivocal social losses observed in search-based models with symmetrically informed traders like Duffie, Gârleanu, and Pedersen (2005).

Our paper differs from the related market microstructure literature in several 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 both when traders' information is exogenous and independent of the market structure and when traders' information is endogenous to the market structure. Third, our focus 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 market structures also differentiates this paper from Glode and Opp (2016) who take the decentralized market structure as given and show that trading through intermediation chains may improve the efficiency of trade in environments with market power and asymmetric information problems.

The idea that decentralized markets allow traders to reach various potential counterparties in a sequen-

tial/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.<sup>5</sup> 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. Hence, unlike in our model, all agents trying to buy the asset are informed. The main result in Bulow and Klemperer (2009) differs greatly from ours: in their model sequential entry and bidding socially dominates simultaneous bidding through an auction, regardless of whether the uncertainty is in common or private values. 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.

Although our economic environment differs from theirs, how we model both types of markets 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

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<sup>5</sup>See also Pagano and Röell (1996), de Frutos and Manzano (2002), and Yin (2005) who study the impact of transparency on market liquidity in settings similar to that in Biais (1993), but allowing for adverse selection, generalized risk aversion, and search costs, respectively.

traders' arrival process to differentiate the types of market in which traders operate. In our centralized 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 decentralized market. In our decentralized 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 market. Finally, we assume as in Glosten (1989) that the liquidity provider has market power — his temptation to inefficiently screen privately informed counterparties will play a key role in determining the optimal market structure in our model. 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.<sup>6</sup>

In the next section, we describe the economic environment we will study throughout the paper. Section 3 derives equilibrium trading outcomes in centralized and decentralized markets when some traders have private information about their idiosyncratic valuation of the asset. There, we compare the efficiency of trade first when traders' information is exogenous and second, when it is endogenous to the market structure. 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 the implementation of the socially dominating market structure, and Section 6 concludes. Unless stated otherwise, proofs of our results are relegated to Appendix A.

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<sup>6</sup>While 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.

## 2 Model

The owner of an asset considers selling it to one of two prospective buyers. Each agent  $i$  is risk neutral and values the asset as the sum of two components:  $v_i = v + b_i$ . The common value component  $v$  matters to all traders and is distributed as  $v \in \{\bar{v} - \sigma_v, \bar{v} + \sigma_v\}$  with equal probabilities. 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  $i$ . In expectation, moving the asset from the seller to a buyer creates a social surplus of  $E[b_i] = \Delta > 0$ .

Agents are asymmetrically informed about the value of the asset. To eliminate the possibility of multiple equilibria due to signaling games, we assume the seller of the asset only knows the ex-ante distributions for  $v$  and  $b_i$  when he tries to sell the asset. Each buyer  $i$  is, however, privately informed about his own realization of  $v_i$  with probability  $\pi_i \in (0, 1)$  when deciding whether to buy the asset.

While the number of prospective buyers is a fundamental of the economy, how easily the seller can access them and make them an offer depends on the market structure. In a centralized 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 a decentralized 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 rejected, the seller moves on to the second buyer. This delay in the timing of the trade can, however, be socially costly. We model this cost by assuming that, once the first price has been rejected, contacting a second buyer who can help realize the surplus from trade is possible only with probability  $\rho$ . This reduction in surplus can capture any search friction that makes locating a second buyer costly (Ashcraft and Duffie 2007, Green, Hollifield, and Schürhoff 2007, Feldhütter 2012) or be the result of traders' 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) and Di Maggio, Kermani, and Song (2016).

Assuming sequential and exclusive ultimatum offers in the decentralized 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 markets 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. We nonetheless investigate the robustness of our theoretical results to alternative models of centralized trading in Appendix B and show how the seller’s screening behavior resembles that observed in our baseline model.

In the paper, we focus on two specific characterizations of the uncertainty in asset values: a case where  $\sigma_b$  is large and  $\sigma_v = 0$  and another case where  $\sigma_v$  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 optimality of each market structure. We then compare across market types the social utilitarian welfare (i.e., the expected surplus from trade) as well as the owner’s expected profit from selling the asset. 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 the optimal market structure in a benchmark case. We look at a case where  $\sigma_v \rightarrow 0$  and  $\sigma_b \rightarrow 0$ , meaning that asymmetric information plays no role in determining the optimal market structure. In such 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 market) or sequentially (i.e., in a decentralized market). The expected social surplus generated by trade is then  $\Delta$  in both types of market.



### 3 Uncertainty in Private Values

In this section, we study the case where  $\sigma_v$  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.,  $\Delta$  and  $\sigma_b$ ). Moreover, we assume that the uncertainty in private valuations is large enough to have  $\sigma_b \geq \Delta$ , meaning that trading the asset from the seller to the buyer does not always create a social surplus. Analyzing a setting where most of the uncertainty and private information relate to traders' private valuations should shed light on the optimal market structure for securities like highly rated municipal and corporate bonds or foreign-exchange and interest-rate derivatives that are primarily traded for hedging purposes.

#### 3.1 Centralized Trading Game

We first consider how trade occurs in a market where the seller posts a price that can be accepted by any of the two prospective buyers, whose probabilities of being informed  $\pi_1$  and  $\pi_2$  are taken as given. If both buyers are willing to pay the posted price, then one of them is randomly chosen to participate in the trade.

The highest price with a positive probability of being accepted 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  $v_i = \bar{v} + \Delta + \sigma_b$ . The seller may instead 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  $v_i$ . Since  $\sigma_v = 0$  and buyers only condition their trading decision on a private value component, a buyer does not have to protect himself against the private information of the other buyer. In contrast, when we later look at cases where  $\sigma_v > 0$ , adverse selection will affect trading outcomes. Finally, the seller may consider posting a 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 lemma that follows summarizes the equilibrium trading outcome that arises in this centralized market.

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

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

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

Since buyers' valuations are uncertain, the seller must make a price concession to encourage uninformed traders to buy the asset. This price concession also leaves rents for any informed buyer who decides to buy the asset. When the expected surplus from trade ( $\Delta$ ) is large, the seller is willing to make this price concession. However, when the uncertainty in the surplus from trade ( $\sigma_b$ ) is large, the price concession needed is too high and the seller prefers to post a higher price to screen informed buyers. This "aggressive" trading strategy eliminates the rents going to informed buyers, and 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 low 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 since we assume that  $\pi_i \in (0, 1)$ .

### 3.2 Decentralized Trading Game

We now consider how trade occurs in a market where the seller quotes a price to a first buyer, who is informed with probability  $\pi_1$ , and if this price is rejected, he tries to contact a second buyer, who is informed with probability  $\pi_2$ . If trade is delayed due to the first buyer's rejection however, the surplus from trade disappears with probability  $1 - \rho$  (or equivalently, the second buyer cannot be found). Hence, only with probability  $\rho$  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 the surplus from trade is lost. To capture the significant persistence and predicability of OTC trading interactions documented by Li and Schürhoff (2014), Hendershott et al. (2015) and Di Maggio, Kermani, and Song (2016), we assume that buyers' order in the seller's trading sequence is known to all agents.<sup>7</sup>

<sup>7</sup>See also Hagströmer and Menkveld (2016) who provide an empirical methodology to measure OTC trading network maps and find that dealers in foreign exchange markets form a strongly connected cluster.

Since  $\sigma_v = 0$  in the case we study here, a rejection by the first buyer is only informative about the private valuation of the first buyer. Hence, after a rejection the seller reaches the second buyer with probability  $\rho$  and quotes him one of the following prices:  $p = \bar{v} + \Delta + \sigma_b$ ,  $p = \bar{v} + \Delta$ , or  $p = \bar{v} + \Delta - \sigma_b$ . With probability  $(1 - \rho)$ , the surplus from trade disappears and the seller retains the asset, which is worth  $\bar{v}$  to him. 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 a 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  $v_i$ . Finally, the seller may quote a price  $p = \bar{v} + \Delta - \sigma_b$ , which is always accepted by the second buyer.

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  $\bar{v} + \rho W^*(\pi_2)$ . The seller thus chooses whether to quote a price  $p = \bar{v} + \Delta + \sigma_b$ ,  $p = \bar{v} + \Delta$ , 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 market, we can eliminate strategies that involve quoting a price  $p = \bar{v} + \Delta - \sigma_b$  to any of the buyers.

**Lemma 2** *In a decentralized market with uncertain private values and where  $\pi_1 \geq \pi_2$ , the seller quotes  $p = \bar{v} + \Delta$  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 is then:  $[1 - \frac{\pi_1}{2} + \frac{\rho\pi_1}{2} (1 - \frac{\pi_2}{2})] \Delta + \frac{\pi_1}{2} (1 + \frac{\rho\pi_2}{2}) \sigma_b$ . The seller, however, quotes  $p = \bar{v} + \Delta + \sigma_b$  to the first buyer and  $p = \bar{v} + \Delta$  to the second buyer if needed whenever:*

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

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

Thanks to the continuation value  $\rho W^*(\pi_2) > 0$  associated with a first buyer's rejection, the downside of quoting a high price to the first buyer is smaller than the downside of quoting such a price to the second buyer. Hence, whenever  $\pi_1 \geq \pi_2$ , which as will become clear later is the relevant case once we endogenize traders' information levels, a strategy of quoting a low price  $p = \bar{v} + \Delta$  to the first buyer and a higher price  $p = \bar{v} + \Delta + \sigma_b$  to the second buyer is suboptimal.

As in the centralized market, the seller must 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 he would collect conditional on a sale. The sequential and exclusive nature of decentralized trading changes the incentives the seller has to screen privately informed buyers, relative to the centralized market.

### 3.3 Comparing Market Structures with Exogenous Information

Now, we compare the social efficiency of trade across the two types of market when traders' information is exogenous. For tractability, we focus in this subsection on cases where the two buyers are equally likely to possess private information about their  $v_i$ , that is, we set  $\pi_1 = \pi_2 \equiv \pi$ .

We begin by considering the scenario where  $\Delta$  is small enough relative to  $\sigma_b$  to have the seller quoting the same price  $p = \bar{v} + \Delta + \sigma_b$ , regardless of whether he is simultaneously trading with both buyers in the centralized market or sequentially trading with them in the decentralized market. For this to be the case, we need:

$$\frac{\Delta}{\sigma_b} < \left(\frac{\pi}{1-\pi}\right) \min\left\{\left(1 - \frac{\pi}{4}\right), \frac{1}{2}\right\} = \frac{1}{2} \left(\frac{\pi}{1-\pi}\right). \quad (6)$$

If this condition is satisfied, the social surplus created by trade simplifies to  $\pi(1 - \frac{\pi}{4})(\Delta + \sigma_b)$  in the centralized market and to  $\frac{\pi}{2}(1 + \rho - \frac{\rho\pi}{2})(\Delta + \sigma_b)$  in the decentralized market. The centralized market is socially optimal whenever:

$$\begin{aligned} \pi \left(1 - \frac{\pi}{4}\right) (\Delta + \sigma_b) &\geq \frac{\pi}{2} \left(1 + \rho - \frac{\rho\pi}{2}\right) (\Delta + \sigma_b) \\ \Leftrightarrow 1 - \frac{\pi}{4} &\geq \frac{1}{2} \left(1 + \rho - \frac{\rho\pi}{2}\right) \\ \Leftrightarrow 1 - \rho &\geq \frac{\pi}{2}(1 - \rho), \end{aligned} \quad (7)$$

which always holds and becomes a strict inequality when  $\rho < 1$ . The centralized market allows the seller

to simultaneously quote the same high price to both buyers instead of sequentially contacting them. Thus, when the uncertainty in  $b_i$  is high relative to  $\Delta$  and delaying trade is costly, the centralized market socially dominates the decentralized one.

At the other extreme, we consider the scenario where  $\Delta$  is large enough relative to  $\sigma_b$  to have the seller quoting the same price  $p = \bar{v} + \Delta$ , regardless of whether he is simultaneously trading with both buyers in the centralized market or sequentially trading with them in the decentralized market. For this to be the case, we need:

$$\frac{\Delta}{\sigma_b} \geq \left( \frac{\pi}{1-\pi} \right) \max \left\{ \left( 1 - \frac{\pi}{4} \right), \frac{1}{2} \left( \frac{1}{1-\rho + \frac{\rho\pi}{2}} \right) \right\}. \quad (8)$$

If this condition is satisfied, the social surplus created by trade simplifies to  $(1 + \frac{\pi}{2}) [(1 - \frac{\pi}{2}) \Delta + \frac{\pi}{2} \sigma_b]$  in the centralized market and to  $(1 + \frac{\rho\pi}{2}) [(1 - \frac{\pi}{2}) \Delta + \frac{\pi}{2} \sigma_b]$  in the decentralized market. The centralized market is socially optimal whenever:

$$\begin{aligned} \left( 1 + \frac{\pi}{2} \right) \left[ \left( 1 - \frac{\pi}{2} \right) \Delta + \frac{\pi}{2} \sigma_b \right] &\geq \left( 1 + \frac{\rho\pi}{2} \right) \left[ \left( 1 - \frac{\pi}{2} \right) \Delta + \frac{\pi}{2} \sigma_b \right] \\ \Leftrightarrow 1 + \frac{\pi}{2} &\geq 1 + \frac{\rho\pi}{2} \end{aligned} \quad (9)$$

which always holds and becomes a strict inequality when  $\rho < 1$ . As in the earlier case, the centralized market allows the seller to simultaneously reach both buyers and when delaying trade is costly, a centralized market socially dominates a decentralized market.

The common feature in the two scenarios above is that the market structure does not change the type of buyers the seller targets with his price quotes. In these cases, simultaneous trading is socially better than sequential trading with a positive probability of delay. Comparing the two types of market, however, yields different implications for intermediate values of  $\frac{\Delta}{\sigma_b}$ , that is, when:

$$\frac{1}{2} \left( \frac{\pi}{1-\pi} \right) \leq \frac{\Delta}{\sigma_b} < \left( \frac{\pi}{1-\pi} \right) \max \left\{ \left( 1 - \frac{\pi}{4} \right), \frac{1}{2} \left( \frac{1}{1-\rho + \frac{\rho\pi}{2}} \right) \right\}. \quad (10)$$

Within these bounds, we have instances where the market structure influences the seller's pricing strategy such that decentralized trading socially dominates centralized trading. To see this, we set  $\bar{v} = 100$ ,  $\sigma_v = 0$ ,  $\sigma_b = 10$ ,  $\Delta = 1$ , and  $\pi = 0.1$ . In a centralized market, the seller finds it optimal to quote the high price  $p = 111$  and collect a surplus of 1.0725 rather than quoting a lower price  $p = 101$  and collecting a surplus of 0.9975. The social surplus from trade is then 1.0725 in the centralized market. The seller's

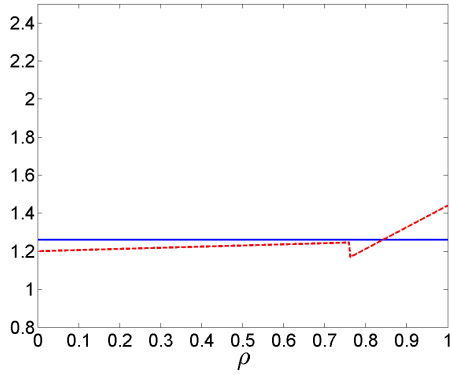
optimal trading strategy in the decentralized market depends on the consequences of delaying trade. In the current parameterization, the seller always finds it optimal to quote  $p = 101$  to the second buyer rather than  $p = 111$ . When  $\rho = 1$  and the seller knows for sure that he will be able to contact the second buyer (delay is thus costless), he prefers to quote the high price  $p = 111$  to the first buyer and collect a surplus of 1.4525 over quoting a lower price  $p = 101$  and collecting a surplus of 0.9975. The social surplus is then 1.9275 in the decentralized market, which is higher than the surplus in the centralized market. Now when  $\rho = 0.5$ , the seller still quotes the high price  $p = 111$  to the first buyer, but since delay is costly, the social surplus from trade drops to 1.23875. Finally, when  $\rho = 0$ , the seller changes his strategy to quoting the low price  $p = 101$  to the first buyer and he then collects a surplus of 0.95 (rather than quoting  $p = 111$  and collecting a surplus of 0.55). The social surplus from trade is 1.45 in the decentralized market, which is higher than the social surplus available in the centralized market.

Interestingly, the social surplus is higher when  $\rho = 0$  than when  $\rho = 0.5$ , as an “opaque” decentralized market (i.e., with lower  $\rho$ ) may occasionally better incentivize traders to behave in socially efficient ways than more a transparent decentralized market or even a centralized market. This social benefit of opacity 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. The seller behaves less aggressively if there is a high probability that the surplus from trading with the second buyer will vanish. 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 among them using Nash bargaining.<sup>8</sup> This difference explains why these models do not feature the social benefit of search frictions that we uncover here, and instead associate unequivocal social losses to these frictions.<sup>9</sup>

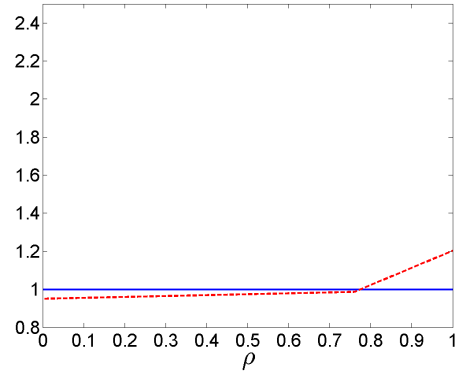
The relationship between  $\rho$  and the social surplus from trade is more broadly illustrated in Figure 1. Panels (c) and (d) set  $\sigma_b = 10$  just as above and show that decentralized trading then socially dominates centralized trading for any value of  $\rho$ . When  $\rho$  is small, the seller quotes a low price to the first buyer to ensure that trade occurs with a higher probability. This trading strategy helps preserve a higher surplus from trade in the decentralized market than in the centralized market, where the seller posts the socially inefficient,

<sup>8</sup>See, however, Duffie, Malamud, and Manso (2014) who study an environment with search frictions where pairs of asymmetrically informed traders participate in double auctions (but these authors do not solve for the optimal market structure as we do in this paper).

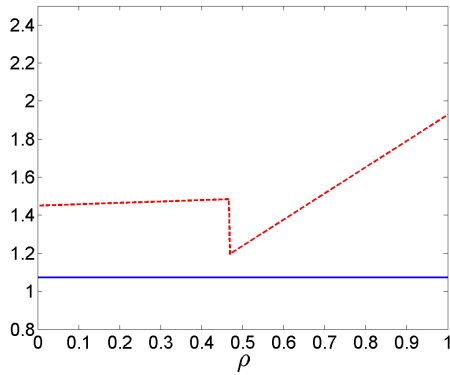
<sup>9</sup>See also Lester et al. (2015) who show that increasing competition can worsen the efficiency of trade in an environment where markets are relatively competitive already, information is exogenous, and relates to an asset’s common value.



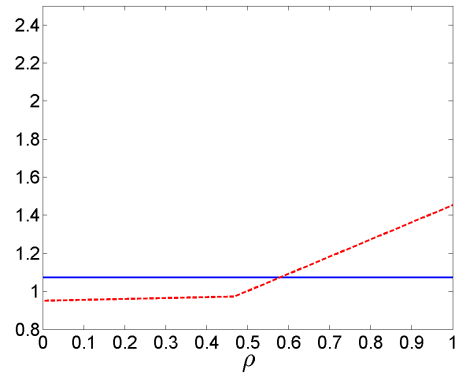
(a) Social surplus for  $\sigma_b = 5$ .



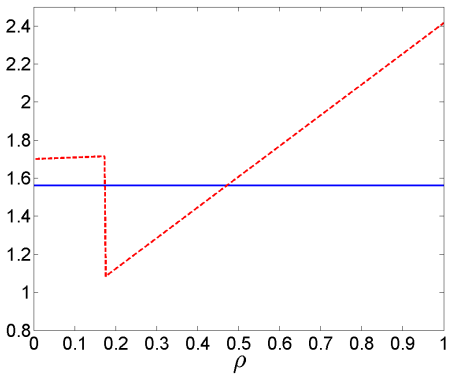
(b) Seller's surplus for  $\sigma_b = 5$ .



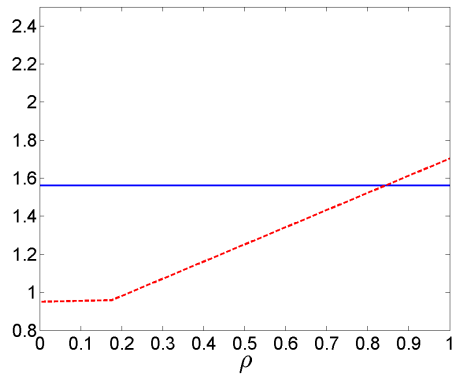
(c) Social surplus for  $\sigma_b = 10$ .



(d) Seller's surplus for  $\sigma_b = 10$ .



(e) Social surplus for  $\sigma_b = 15$ .



(f) Seller's surplus for  $\sigma_b = 15$ .

Figure 1: **Surplus from trade with uncertain private values.** In these figures, we set  $\Delta = 1$ ,  $\sigma_v = 0$ , and  $\pi = 0.1$  and plot the social surplus from trade and the seller's expected surplus as functions of the delay parameter  $\rho$ . The dash line represents the surplus in a decentralized market while the solid line represents the surplus in a centralized market.

high price (see condition (2)). As  $\rho$  increases, however, the seller faces stronger incentives to quote the high price to the first buyer, since the surplus from trade available when trying to contact the second buyer grows with  $\rho$ . Once the seller starts quoting the high price to the first buyer, the social surplus from trade drops, but since enough surplus can be created by trading with the second buyer, decentralized trading still socially dominates centralized trading. As far as the seller is concerned, trading in a decentralized market allows to collect a higher surplus from trade whenever delay is not too costly. Hence, for large values of  $\rho$ , the decentralized market dominates the centralized market from both the seller's and the social planner's standpoints.

When we increase the uncertainty in private valuations to  $\sigma_b = 15$  (panels (e)-(f)), the seller still finds it optimal to quote the low price to the second buyer in the decentralized market. As earlier, the decentralized market generates a higher social surplus and a higher seller's profit than a centralized market as long as delay is not too costly, that is,  $\rho$  is high enough. Decentralized trading is, however, socially dominated by centralized trading when  $\rho$  is moderate. That is due to the fact that the expected surplus from trade when trying to contact the second buyer is small compared to the benefit of quoting a price to both buyers simultaneously. When  $\rho$  is small, the seller switches to quoting a low price to the first buyer, which ensures that trade occurs with a high enough probability to socially dominate centralized trading. Finally, when we decrease the uncertainty in private valuations to  $\sigma_b = 5$  (panels (a)-(b)), the seller posts the low price in the centralized market. Since this price is socially optimal within the centralized market (see condition (2)), it becomes harder for decentralized trading to socially dominate centralized trading. Yet, a decentralized market can socially dominate a centralized market when delays are not too costly.

Note that we can also go beyond the Glosten and Milgrom-type framework and allow for dynamic, strategic behavior by traders in the centralized market. In Appendix B, we model two periods of centralized trading between the seller and his two buyers and assume that there is also a delay parameter  $\rho_c$  associated with waiting until the second period before realizing the gains to trade (e.g., due to immediacy needs or investor inattention). This second period of centralized trading then strengthens the seller's incentives to post an aggressive price in the first period of centralized trading, just as was the case in the decentralized market. Thus, on the one hand, the second period of trade provides an additional opportunity to implement efficient trade, but on the other hand, it incentivizes inefficient screening by the seller in the first period. Consistent with setting  $\rho = 0$  in our baseline model (where effectively we have  $\rho_c = 0$ ), if both  $\rho$  and  $\rho_c$  are set to be small enough (e.g., immediacy needs are high in both markets) in this alternative setting, the



more severe screening in the centralized market leads to the decentralized market being socially optimal (see Figure 1, panels (c) and (e)). Additionally, we show in Appendix B that panels (c)-(f) in Figure 1 would remain unchanged if centralized trading occurred through a second-price auction with a reserve price instead of through our baseline model of a limit order market.

We should emphasize that, although our baseline model assumes that the seller screening buyers is a monopolist, this type of inefficient trading behavior would still occur with oligopolistic sellers. Screening can arise as long as each seller faces a somewhat inelastic “residual” demand curve, meaning that he must trade off the price he collects when a sale occurs with the probability of that sale occurring. In our simple 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 optimal trading mechanisms. Moreover, the roles of buyers and sellers could be reversed without affecting our main results. Overall, the idea that decentralization can steepen the above-mentioned price-probability tradeoff, thereby weakening the incentives to inefficiently screen privately informed counterparties, strikes us as fairly robust.

### 3.4 Comparing Market Structures with Endogenous Information

We now endogenize the probabilities with which buyers obtain private information about their valuation of the asset, that is, buyer  $i$  can incur a cost  $\frac{c}{2}\pi_i^2$  and learn his own  $v_i$  with probability  $\pi_i$  before the seller can contact anyone. We analyze how the market structure affects traders’ incentives to acquire information.

For now, we restrict our attention to equilibria where the seller picks a pure-strategy price quote. We will revisit this restriction later in this subsection. In both markets, we can rule out equilibria where  $\pi_i$  and  $\pi_j$  are high enough for the seller to always quote the high price. In this case, buyers would be better off not acquiring information and the high price would thus always be rejected. We can also rule out equilibria where buyers never acquire information since the marginal cost of acquiring information is  $c\pi_i$  and increasing  $\pi_i$  is strictly profitable when the seller quotes the low price. Hence, in equilibrium the seller must quote the low price  $p = \bar{v} + \Delta$  and both buyers must choose  $\pi_i \in (0, 1)$ . This outcome implies that any difference in the social efficiency of trade across markets we uncover in this subsection is caused by variations in optimal information acquisition strategies as opposed to being caused by the variations in optimal pricing strategies we discussed so far.

Using derivations from the proof of Lemma 2, we know that if the seller posts the low price  $p = \bar{v} + \Delta$  in the centralized market buyer  $i$  chooses  $\pi_i$  to maximize:

$$\frac{\pi_i}{4} \left(1 + \frac{\pi_j}{2}\right) \sigma_b - \frac{c}{2} \pi_i^2. \quad (11)$$

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

$$\pi_i^* = \left(1 + \frac{\pi_j}{2}\right) \frac{\sigma_b}{4c}, \quad (12)$$

which by symmetry implies that in the unique pure-strategy equilibrium, both buyers acquire:

$$\pi^* = \frac{\sigma_b}{\left(4c - \frac{\sigma_b}{2}\right)}. \quad (13)$$

For this  $\pi^*$  to be sustained in equilibrium, it must be that the seller optimally posts the low price, which we know from condition (1) only occurs when:

$$\frac{\Delta}{\sigma_b} \geq \left(1 - \frac{\pi^*}{4}\right) \left(\frac{\pi^*}{1 - \pi^*}\right). \quad (14)$$

Now, if the seller quotes the low price  $p = \bar{v} + \Delta$  to both buyers in the decentralized market, the first buyer picks  $\pi_1$  to maximize:

$$\frac{\pi_1}{2} \sigma_b - \frac{c}{2} \pi_1^2, \quad (15)$$

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

$$\pi_1^* = \frac{\sigma_b}{2c}. \quad (16)$$

Further, the second buyer picks  $\pi_2$  to maximize:

$$\frac{\pi_1^* \pi_2}{2} \rho \sigma_b - \frac{c}{2} \pi_2^2, \quad (17)$$

meaning that in an interior optimum where  $\pi_2^* \in (0, 1)$  we obtain:

$$\pi_2^* = \frac{\pi_1^* \rho \sigma_b}{4c}. \quad (18)$$

Note that, for any interior optimum with  $\pi_1^* \in (0, 1)$ , it follows that  $\pi_2^* < \pi_1^*$  and  $\pi_2^* \in (0, 1)$ . Finally, we know from condition (3) that in order for the seller to indeed prefer to quote the low price to both buyers sequentially, we need:

$$\frac{\Delta}{\sigma_b} \geq \frac{1}{2} \left( \frac{1}{1 - \rho + \frac{\rho \pi_2^*}{2}} \right) \left( \frac{\pi_1^*}{1 - \pi_1^*} \right). \quad (19)$$

As earlier, we parameterize the model and compare the social efficiency of trade across the two market structures. In contrast to the earlier analysis however, buyers' information sets are now endogenous to the market structure. Both conditions for the conjectured equilibria in the centralized and decentralized markets are satisfied for high enough values of the cost parameter  $c$ . We normalize  $\Delta = 1$  and set  $c = 15$ . In Figures 2 and 3 we plot the social surplus from trade, net of information acquisition costs, and the privately optimal information acquisition as a function of the uncertainty in private valuations ( $\sigma_b$ ), for various parameterizations of  $\rho$ .

The plots highlight that the trading venue that maximizes the social surplus from trade, net of information acquisition costs, varies with asset characteristics and with the social cost of trade delays in decentralized markets. Panel (a) in Figure 2 shows that, when trade delays are not too costly (e.g.,  $\rho = 0.8$ ), a decentralized market socially dominates a centralized market. The exclusivity associated with decentralized trading gives the first buyer greater assurance that information acquisition will be worthwhile — the first buyer obtains the asset with probability 1 when accepting to pay the quoted price and can thus realize the gains to trade whenever he knows that he values the asset at  $v_i = \bar{v} + \Delta + \sigma_b$ . In contrast, in the centralized market buyers are competing for the asset and may not obtain the asset every time they accept the seller's posted price. Even if a buyer knows that he values the asset at  $v_i = \bar{v} + \Delta + \sigma_b$ , he might still lose the asset to the other buyer. In the centralized venue, the threat of competition thus reduces each buyer's private incentives for information production, potentially leading to lower allocative efficiency and welfare.

From a welfare perspective, decentralized trading can, however, be inferior to centralized trading when delays are very costly. This result is evidenced by Panels (c) and (e), which compare the social surplus when  $\rho = 0.5$  and  $\rho = 0.2$ . Yet, as shown in Figure 3, even when  $\rho = 0$ , that is, when all surplus is destroyed once

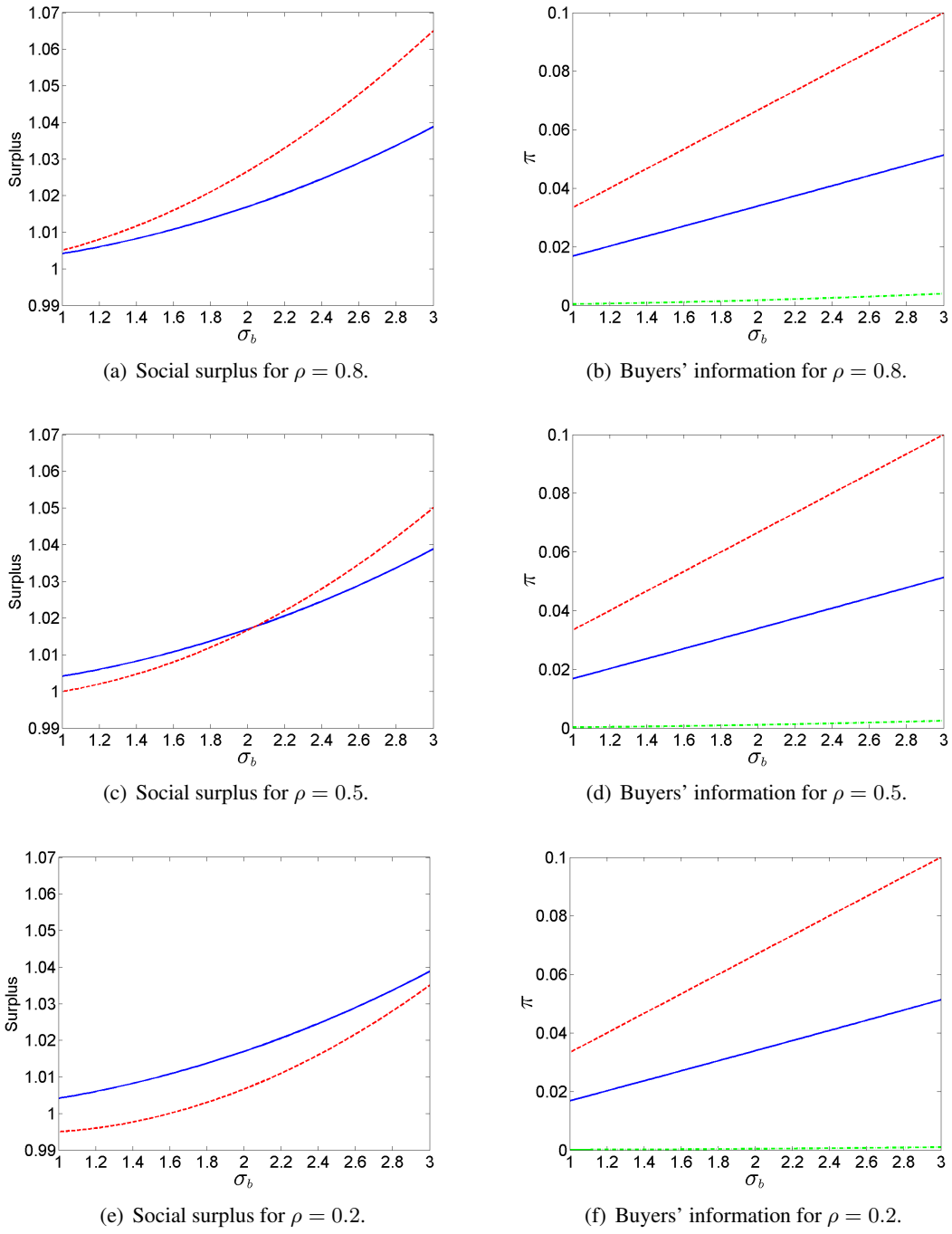


Figure 2: **Surplus from trade and information acquisition with uncertain private values.** In these figures, we set  $\Delta = 1$ ,  $\sigma_v = 0$ , and  $c = 15$  and plot the social surplus from trade, net of the information costs, and the buyers' information as functions of the uncertainty in private valuations. In panels (a), (c), and (e), the dash line represents the surplus in the decentralized market while the solid line represents the surplus in the centralized market. In panels (b), (d), and (f), the dash line represents the first buyer's information  $\pi_1$  and the dotted line represents the second buyer's information  $\pi_2$  in the decentralized market, while the solid line represents the buyers' symmetric information in the centralized market.

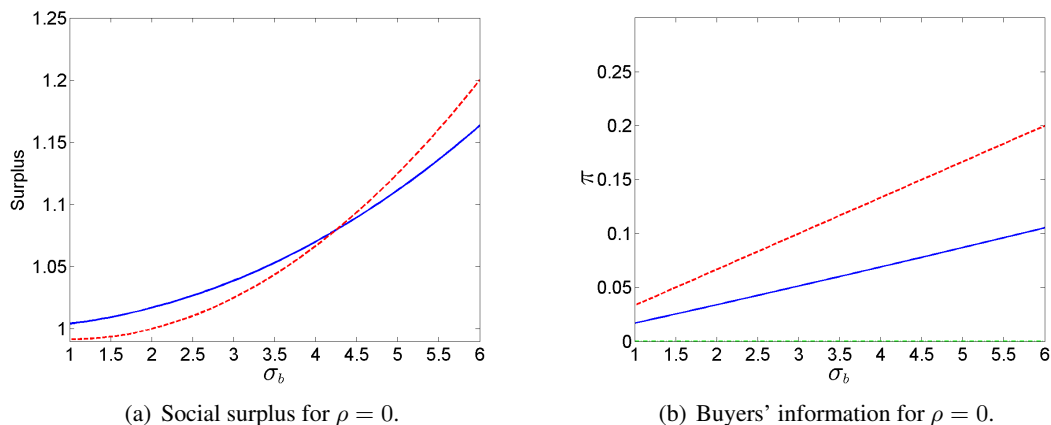


Figure 3: **Surplus from trade and information acquisition with uncertain private values and  $\rho = 0$ .** In these figures, we set  $\Delta = 1$ ,  $\sigma_v = 0$ , and  $c = 15$  and plot the social surplus from trade, net of the information costs, and the buyers' information as functions of the uncertainty in private valuations. In panel (a), the dash line represents the surplus in the decentralized market while the solid line represents the surplus in the centralized market. In panel (b), the dash line represents the first buyer's information  $\pi_1$  and the dotted line represents the second buyer's information  $\pi_2$  in the decentralized market, while the solid line represents the buyers' symmetric information in the centralized market.

the first buyer rejects a price quote, it is still possible for the decentralized market to be more efficient than a centralized market, provided that the uncertainty in private valuations  $\sigma_b$  is sufficiently large. When  $\sigma_b$  is large, the provision of sufficient incentives for information acquisition is essential and it is better achieved in a decentralized market.

The analysis above focused on equilibria where the seller always quotes the same price. In Appendix C, however, we show that under our parameterization the pure-strategy equilibrium we analyzed for the centralized market is unique. Thus, our results show that there exists an equilibrium in the decentralized market (i.e., its unique pure-strategy equilibrium) that socially dominates all equilibria that exist in the centralized market.

We should also emphasize that allowing for more than two prospective buyers would strengthen these results. If we increased the number of buyers the seller faces in our model, each buyer's marginal payoff from acquiring information in a centralized market would decrease. Thus, decentralized trading would further dominate centralized trading in terms of incentivizing information acquisition by buyers. More generally, a decentralized market structure with its search frictions effectively commits the seller to contact certain, easier-to-reach traders first, which increases these traders' incentives to specialize and become informed in

the first place. Just like the limit-order market we consider, alternative centralized market structures such as the optimal auctions from Myerson (1981) would leave small profits for buyers that become informed, and would therefore impede allocative efficiency.

## 4 Uncertainty in Common Value

In this section, we analyze the case where equilibrium trading outcomes are driven by the average surplus from trade ( $\Delta$ ) and the volatility of the asset's common value ( $\sigma_v$ ). We set  $\sigma_b = 0$  and assume that the uncertainty in common value is large enough to have  $\sigma_v \geq \Delta$ , meaning that the seller is better off keeping the asset than quoting a low price  $p = \bar{v} + \Delta - \sigma_v$ . Analyzing a setting where most of the uncertainty and private information relate to common/fundamental valuations should shed light on the optimal market structure for securities like stocks or derivatives that are primarily traded for speculation purposes.

### 4.1 Centralized Trading Game

As we did in Section 3, we start by analyzing how trade occurs in a market where the seller posts a price that can be accepted by any of the two prospective buyers, whose probabilities of being informed  $\pi_1$  and  $\pi_2$  are taken as given. The highest price with a positive probability of being accepted is  $p = \bar{v} + \Delta + \sigma_v$ . In the centralized market, this price is accepted only if at least one of the two buyers is informed that  $v = \bar{v} + \sigma_v$ . The seller may instead post a price that is low enough to also 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 this informed trading decision is based 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 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  $v = \bar{v} + \sigma_v$ . As we show in the proof of the lemma below, 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:

$$p = \bar{v} - \left( \frac{\pi_j}{2 + \pi_j} \right) \sigma_v + \Delta. \quad (20)$$

Finally, the seller may consider posting a price  $p = \bar{v} + \Delta - \sigma_v$ , which is accepted by all buyers, but posting this price is again dominated by keeping the asset which is, in turn, dominated by posting the high price  $p = \bar{v} + \Delta + \sigma_v$ .

**Lemma 3** *In a centralized market with uncertain common values where  $\pi_1 \geq \pi_2$ , the seller posts the price  $p = \bar{v} - \left(\frac{\pi_1}{2+\pi_1}\right) \sigma_v + \Delta$  in equilibrium whenever:*

$$\frac{\Delta}{\sigma_v} \geq \left(\frac{1+\pi_2}{2+\pi_1}\right) \left(\frac{2\pi_1}{2-\pi_1-\pi_2}\right), \quad (21)$$

*and the social surplus from trade is then:  $(1 - \frac{\pi_1\pi_2}{2}) \Delta$ . Otherwise, the seller posts the 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 low price  $p = \bar{v} - \left(\frac{\pi_1}{2+\pi_1}\right) \sigma_v + \Delta$  rather than the high price  $p = \bar{v} + \Delta + \sigma_v$ , as it maximizes the probability of trade and the potential gains to trade are a constant  $\Delta$ . Hence, in the region where  $\frac{\Delta}{\sigma_v} < \left(\frac{1+\pi_2}{2+\pi_1}\right) \left(\frac{2\pi_1}{2-\pi_1-\pi_2}\right)$ , the seller posts a socially inefficient, high price.

## 4.2 Decentralized Trading Game

We now analyze how trade occurs in the decentralized market. Since  $\sigma_v > 0$ , a rejection by the first buyer can be informative about the common value of the asset and will affect the trading behaviors of the seller and of any uninformed buyer. To keep the analysis simple and as comparable to the analysis from Section 3 as possible, we shut down the signaling game between the seller and an uninformed second buyer by solving for equilibria where the second buyer's beliefs about how trade occurred with the first buyer is unaffected by the price the seller quotes to the second buyer. In other words, the second buyer's off-equilibrium beliefs about the value of the asset are constrained to be the same as his equilibrium beliefs.

We first conjecture an equilibrium in which the seller quotes a low, efficient price  $p = \bar{v} + \Delta$  to the first buyer. This price is only rejected by an informed buyer who knows that  $v = \bar{v} - \sigma_v$ . Hence, both the seller and the second buyer know that the asset is then worth  $v_i = \bar{v} + \Delta - \sigma_v$  to the second buyer while it is only worth  $v = \bar{v} - \sigma_v$  to the seller. The seller quotes a price  $p = \bar{v} + \Delta - \sigma_v$  to the second buyer, which is accepted with probability 1. To ensure that our conjectured equilibrium exists, we need to verify that the seller finds it optimal to quote a price  $p = \bar{v} + \Delta$  rather than  $p = \bar{v} + \Delta + \sigma_v$  to the first buyer.

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

$$\frac{\Delta}{\sigma_v} \geq \max\left\{\frac{2 - 2\pi_1}{2 - \pi_1}, \frac{\pi_1 + 2\pi_1\rho - 2\rho}{2(1 - \pi_1)(1 - \rho)}\right\}, \quad (22)$$

or

$$\frac{\pi_1}{2(1 - \pi_1 + \frac{\rho\pi_1}{2})} \leq \frac{\Delta}{\sigma_v} < \frac{2 - 2\pi_1}{2 - \pi_1}. \quad (23)$$

The social surplus from trade is then:  $[1 - \frac{\pi_1}{2}(1 - \rho)] \Delta$ .

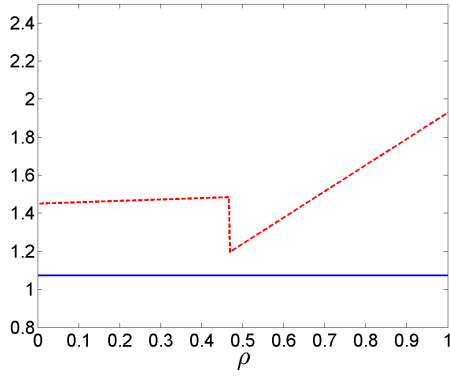
When it exists, this equilibrium socially dominates any potential equilibrium where the seller quotes the first buyer a high price  $p = \bar{v} + \Delta + \sigma_v$ , since such equilibrium can at most create a surplus of  $[\frac{\pi_1}{2} + (1 - \frac{\pi_1}{2})\rho] \Delta$ . When the seller quotes 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 accepts with probability 1 the price quoted by the seller when he contacts him, the surplus is strictly lower than the surplus in the equilibrium above due to the social cost of delay. Moreover, as in a centralized market, there is no equilibrium where the seller quotes a price  $p = \bar{v} + \Delta - \sigma_v$  to the first buyer, since it is dominated by the strategy of keeping the asset, which in expectation is worth  $\bar{v}$  to the seller. Keeping the asset is, in turn, dominated by posting the high price  $p = \bar{v} + \Delta + \sigma_v$ . Thus, when it exists the equilibrium characterized in Lemma 4 offers the highest social surplus of all equilibria possible in a decentralized market.

### 4.3 Comparing Market Structures with Exogenous Information

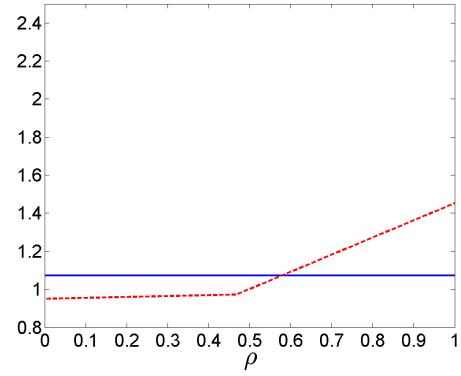
Here, we compare the social efficiency of trade across the different types of market when traders' information is exogenous. For tractability, we again focus in this subsection on cases where the two buyers are equally likely to possess private information about their  $v_i$ , that is, we set  $\pi_1 = \pi_2 \equiv \pi$ . It is easy to check that if we replace  $\sigma_v$  by  $\sigma_b$  in our parameterizations for Figure 1 of Subsection 3.3 conditions (22) and (23) are both satisfied. In Figure 4 we produce similar plots for the case where the uncertainty is about the common value ( $\sigma_b = 0$  and  $\sigma_v = 10$ ) and compare them with those for the case where the uncertainty is about private values ( $\sigma_b = 10$  and  $\sigma_v = 0$ ).

First note that in this specific parameterization, the seller posts the high price  $p = \bar{v} + \Delta + \sigma_b$  in a

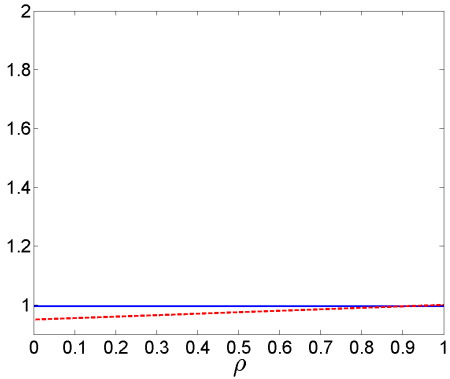




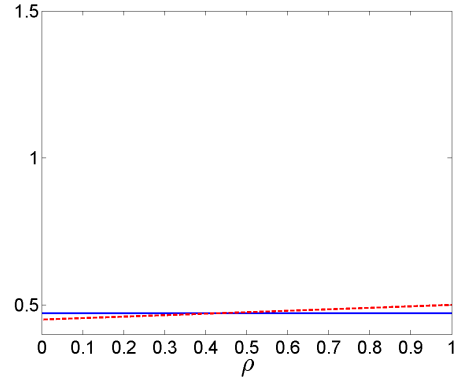
(a) Social surplus for  $\sigma_b = 10$  and  $\sigma_v = 0$ .



(b) Seller's surplus for  $\sigma_b = 10$  and  $\sigma_v = 0$ .



(c) Social surplus for  $\sigma_b = 0$  and  $\sigma_v = 10$ .



(d) Seller's surplus for  $\sigma_b = 0$  and  $\sigma_v = 10$ .

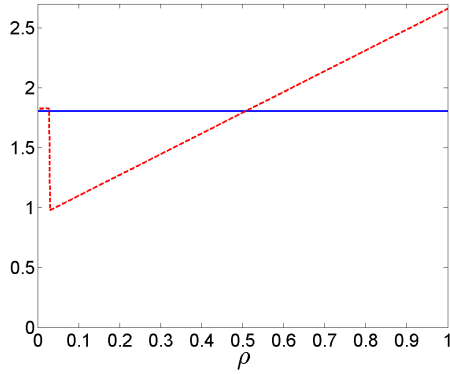
Figure 4: **Surplus from trade with low uncertainty in private vs. common values.** In these figures, we set  $\Delta = 1$  and  $\pi = 0.1$  and plot the social surplus from trade and the seller's expected surplus as functions of the delay parameter  $\rho$ . The dash line represents the surplus in a decentralized market while the solid line represents the surplus in a centralized market.

centralized market with uncertainty in private valuations but he does not quote the high price  $p = \bar{v} + \Delta + \sigma_v$  in a centralized market with uncertainty in common value. This difference is due to the fact that when  $\pi \in (0, 1)$  the cutoff on  $\frac{\Delta}{\sigma_v}$  in condition (21) is always lower than the cutoff on  $\frac{\Delta}{\sigma_b}$  in condition (1). For a given level of uncertainty the seller's incentives to quote a high price are stronger when this uncertainty is in private values rather than in the common value. Hence, as we can observe from the parameterization of Figure 4, the difference in the social efficiency of trade between the two types of market is much larger quantitatively when the uncertainty is in private rather than in common values. In the former (see panel (a)), decentralizing trading is socially optimal for any value of  $\rho$ , whereas in the latter (see panel (c)) it is optimal only for  $\rho$  close to 1. The reason why decentralizing trading is socially optimal for  $\rho \rightarrow 1$  when  $\sigma_v = 10$  and  $\sigma_b = 0$  is that in equilibrium trade occurs whenever the second buyer can be contacted since both traders involved have learned from the refusal of the first buyer to pay  $p = \bar{v} + \Delta$  that  $v = \bar{v} - \sigma_v$  and therefore, these traders are symmetrically informed. The seller thus never ends up with the asset in a decentralized market, which is not the case under centralized trading where the seller must retain the asset whenever both buyers are informed that  $v = \bar{v} - \sigma_v$ . When  $\rho$  is close to 1, this higher probability of trade swamps the small cost of delay incurred by the sequential nature of trade and makes decentralized trading socially optimal.

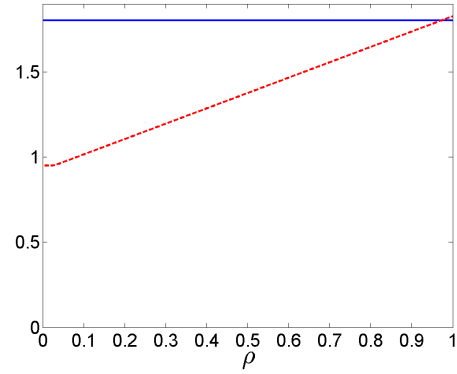
In Figure 5, we increase the level of uncertainty until the seller finds it optimal to quote the high, less efficient price in a centralized market, regardless of whether this uncertainty is in private values or in the common value. In this case, decentralizing trading becomes socially optimal for any value of  $\rho$  when the uncertainty relates to the common value, but this is not the case when the uncertainty relates to private values. In panel (c), we can see that the surplus from trade in a decentralized market when the seller quotes  $p = \bar{v} + \Delta$  to the first buyer and  $p = \bar{v} + \Delta - \sigma_v$  to the second buyer is very close to the full surplus  $\Delta = 1$ , whereas it is much lower in a centralized market where the seller quotes the high, less efficient price  $p = \bar{v} + \Delta + \sigma_v$ . Overall, these findings illustrate that regardless of whether asymmetric information relates to private or common values, decentralized trading may incentivize asymmetrically informed agents to choose their trading behaviors in ways that are socially beneficial.

#### 4.4 Comparing Market Structures with Endogenous Information

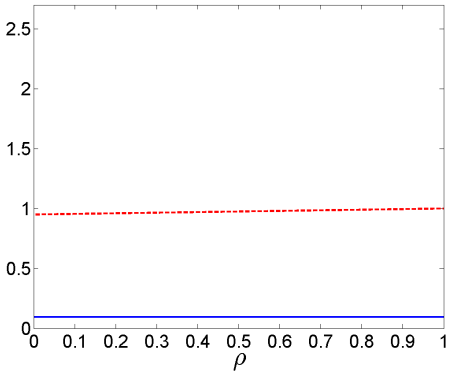
We now extend our analysis to allow buyer to acquire private information about the common value of the asset. Buyer  $i$  can incur a cost  $\frac{c}{2}\pi_i^2$  to learn  $v$  with probability  $\pi_i$  before the seller can contact any buyer. This specific type of information, however, solely improves traders' rent-seeking ability and impedes trade due



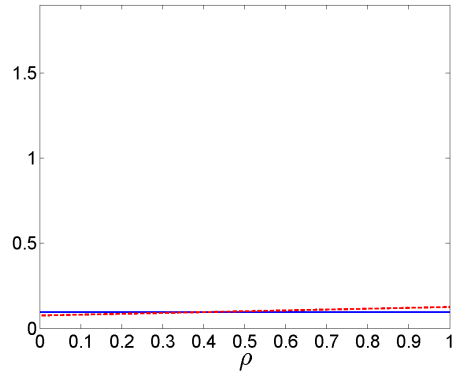
(a) Social surplus for  $\sigma_b = 17.5$  and  $\sigma_v = 0$ .



(b) Seller's surplus for  $\sigma_b = 17.5$  and  $\sigma_v = 0$ .



(c) Social surplus for  $\sigma_b = 0$  and  $\sigma_v = 17.5$ .



(d) Seller's surplus for  $\sigma_b = 0$  and  $\sigma_v = 17.5$ .

Figure 5: **Surplus from trade with high uncertainty in private vs. common values.** In these figures, we set  $\Delta = 1$  and  $\pi = 0.1$  and plot the social surplus from trade and the seller's expected surplus as functions of the delay parameter  $\rho$ . The dash line represents the surplus in a decentralized market while the solid line represents the surplus in a centralized market.

to adverse selection. Thus, in this context, acquiring information is socially harmful, in line with Hirshleifer (1971), Glode, Green, and Lowery (2012), Dang, Gorton, and Holmström (2015), and Yang (2015). The choice of a market structure can then be used to minimize this inefficient behavior.

As in the case with uncertain private valuations, we can rule out for both markets equilibria where  $\pi_i$  and  $\pi_j$  are high enough for the seller to always quote the high price. In this case, buyers would be better off not acquiring information and the high price would be rejected. We thus conjecture an equilibrium in the centralized trading game where both buyers acquire the same level of information, that is,  $\pi_1 = \pi_2 \equiv \pi$  and with probability 1 the seller quotes a price that is accepted by uninformed buyers.

If buyer  $j$  acquires information with probability  $\pi$  and believes that buyer  $i$  will do the same, buyer  $i$  optimally responds to these beliefs and actions by picking  $\pi_i$  that maximizes:

$$\begin{aligned} & \frac{\pi_i}{2} \frac{1}{2} \left( \bar{v} + \sigma_v + \Delta - \left( \bar{v} - \left( \frac{\pi}{2 + \pi} \right) \sigma_v + \Delta \right) \right) - \frac{c}{2} \pi_i^2 \\ &= \frac{\pi_i}{2} \sigma_v \left( \frac{1 + \pi}{2 + \pi} \right) - \frac{c}{2} \pi_i^2. \end{aligned} \quad (24)$$

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

$$\pi_i^* = \frac{\sigma_v}{2c} \left( \frac{1 + \pi}{2 + \pi} \right), \quad (25)$$

and in a symmetric equilibrium we must have:

$$\pi^* = \frac{\sigma_v}{2c} \left( \frac{1 + \pi^*}{2 + \pi^*} \right). \quad (26)$$

This equation has the following two roots:

$$-1 + \frac{\sigma_v \pm \sqrt{16c^2 + \sigma_v^2}}{4c}, \quad (27)$$

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

$$\pi^* = -1 + \frac{\sigma_v + \sqrt{16c^2 + \sigma_v^2}}{4c}. \quad (28)$$

This is an equilibrium as long as  $\pi^* \in (0, 1)$  and the seller finds it optimal to quote the low price, that is:

$$\frac{\Delta}{\sigma_v} \geq \left( \frac{1 + \pi^*}{2 + \pi^*} \right) \left( \frac{\pi^*}{1 - \pi^*} \right). \quad (29)$$

For the decentralized market, we conjecture an equilibrium in which the seller always quotes a low price  $p = \bar{v} + \Delta$  to the first buyer, for reasons stated above. This price is only rejected by an informed buyer who knows that  $v = \bar{v} - \sigma_v$ . In this case, both the seller and the second buyer conclude from the first buyer's rejection that the asset is worth  $v_i = \bar{v} + \Delta - \sigma_v$  to the second buyer and  $v = \bar{v} - \sigma_v$  to the seller. The seller thus quotes a price  $p = \bar{v} + \Delta - \sigma_v$  if he is able to contact the second buyer, which is then accepted with probability 1. The second buyer is reached only if the first buyer knew that  $v = \bar{v} - \sigma_v$ . Since being contacted by the seller reveals this information to the second buyer, acquiring information is useless to the second buyer and  $\pi_2^* = 0$ .

When he expects to be quoted a price  $p = \bar{v} + \Delta$ , the first buyer picks  $\pi_1$  to maximize:

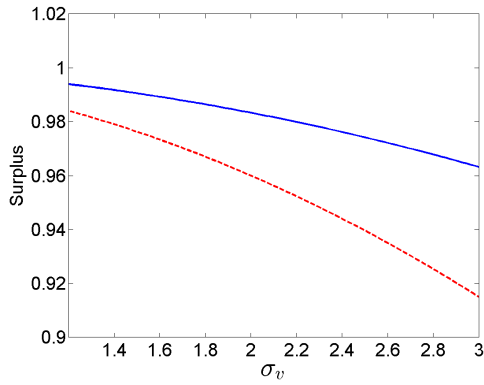
$$\frac{\pi_1}{2} [\bar{v} + \sigma_v + \Delta - (\bar{v} + \Delta)] - \frac{c}{2} \pi_1^2 = \frac{\pi_1}{2} \sigma_v - \frac{c}{2} \pi_1^2. \quad (30)$$

In an interior solution  $\pi_1 \in (0, 1)$  we have:

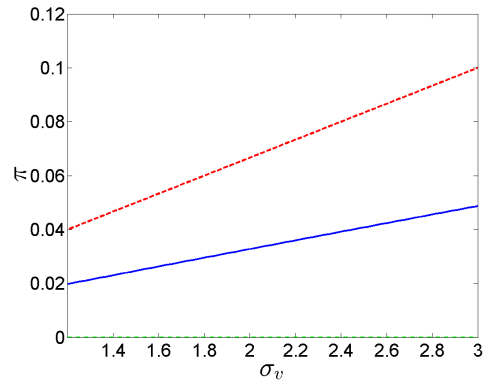
$$\pi_1^* = \frac{\sigma_v}{2c}. \quad (31)$$

The two buyers' information strategies  $\pi_1^* = \frac{\sigma_v}{2c}$  and  $\pi_2^* = 0$  sustain an equilibrium whenever  $\pi_1^* \in (0, 1)$  and the conditions for the equilibrium, as characterized by inequalities (22) and (23), are satisfied. Note that all the conditions for the conjectured equilibrium are satisfied for high enough values of the cost parameter  $c$ .

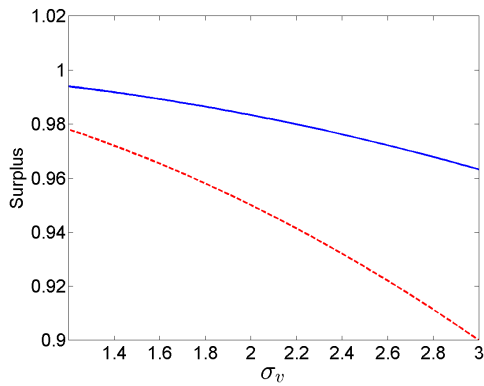
Figure 6 compares the social surplus and the buyers' information acquisition in the two types of market as a function of  $\sigma_v$ . In all our parameterizations, centralizing trading is socially optimal. A key reason for this result is the fact that, in the presence of common value uncertainty, information generates an adverse selection problem that reduces the efficiency of trade, but unlike with private value uncertainty, this information is not required to allocate the asset to its efficient holder. Thus, the trading venue that provides lower incentives for information acquisition becomes the socially optimal one. Since competition between buyers in the centralized market lowers their ex ante incentives for information acquisition in comparison to the de-



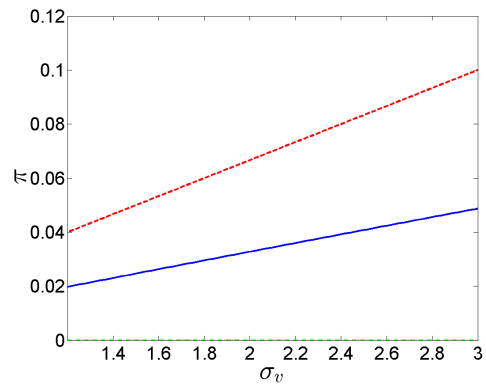
(a) Social surplus for  $\rho = 0.8$ .



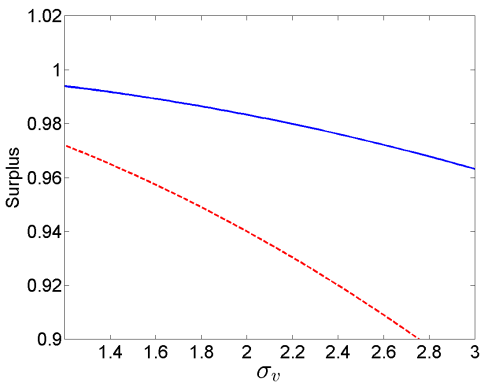
(b) Buyers' information for  $\rho = 0.8$ .



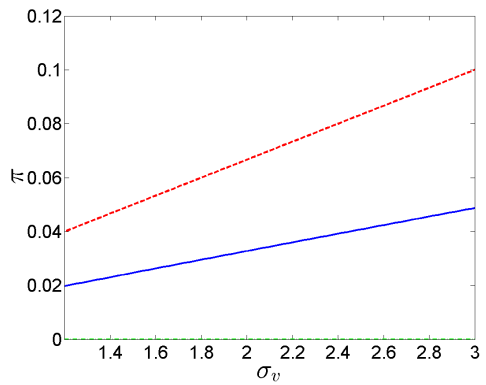
(c) Social surplus for  $\rho = 0.5$ .



(d) Buyers' information for  $\rho = 0.5$ .



(e) Social surplus for  $\rho = 0.2$ .



(f) Buyers' information for  $\rho = 0.2$ .

Figure 6: **Surplus from trade and information acquisition with uncertain common value.** In these figures, we set  $\Delta = 1$ ,  $\sigma_b = 0$ , and  $c = 15$  and plot the social surplus from trade, net of the information costs, and the buyers' information as functions of the uncertainty in private valuations. In panels (a), (c), and (e), the dash line represents the surplus in the decentralized market while the solid line represents the surplus in the centralized market. In panels (b), (d), and (f), the dash line represents the first buyer's information  $\pi_1$  and the dotted line represents the second buyer's information  $\pi_2$  in the decentralized market, while the solid line represents the buyers' symmetric information in the centralized market.

centralized market, centralization increases the surplus from trade. Moreover, as we increase  $\sigma_v$ , buyers face higher (private) incentives to acquire (socially costly) information and the gap between the social efficiency of centralized and decentralized markets widens.

When compared to Figure 2, these plots clearly highlight that asymmetric information about the common value has very different implications than asymmetric information about private values. Since centralization typically weakens traders' incentives to acquire information, decentralized markets tend to socially dominate centralized markets when information is socially valuable (see Figure 2). Figure 6, however, shows that when information has no social value, as it solely provides an advantage to its acquirer in a rent-seeking game, centralization can be used to lower the socially wasteful acquisition of information and improve the social efficiency of trade.

## 5 Implementation

In the previous sections we have shown that depending on the characteristics of an asset class either centralized or decentralized markets can yield higher efficiency. One obvious way to have the socially optimal market structure being implemented 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 the 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

We compare the social efficiency centralized and decentralized markets in an environment with asymmetric information and endogenous expertise acquisition, where some traders try to exploit any market structure to screen other market participants. Since decentralized trading involves costly delays due to search frictions, we find that centralized trading is socially optimal when agents' expertise acquisition and trading strategies are unaffected by the market structure. However, traders' strategies generally vary across market structures, which can render decentralized markets more efficient. First, screening behavior may be less aggressive and inefficient in decentralized markets where traders reach fewer counterparties. Second, when private information improves allocative efficiency, decentralized markets with predictable trading patterns may dominate as they encourage expertise acquisition. The opposite is, however, true when expertise yields private information that only benefits a trader's ability to extract private rents and causes adverse selection.

Clearly, the specific market structure we observe for each type of assets at a given point in time can, to some extent, be rooted to historical circumstances (Biais and Green 2007). We do not claim to supply the only reason for the coexistence of different types of markets. We show, however, that contrary to a popular belief search frictions characteristic of decentralized markets are not necessarily inefficient, as they may positively affect pricing and information acquisition strategies. We find that the optimal market structure is likely to depend on the characteristics of the assets being traded, namely whether traders' private information relates to common or private valuations. These conclusions strike us as important for understanding why bonds, exotic derivatives, currencies and their derivatives are mostly traded in decentralized markets, whereas stocks and standardized derivatives such as corporate call options are mostly traded in centralized markets.



# Appendix

## A Proofs Omitted from the Text

**Proof of Lemma 1:** The highest 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 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 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 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  $\left(1 - \frac{1}{4}\pi_1\pi_2\right)\Delta + \frac{1}{4}(\pi_1 + \pi_2 + \pi_1\pi_2)\sigma_b$ . 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  $\frac{1}{2} (\pi_1 + \pi_2 - \frac{1}{2} \pi_1 \pi_2) (\Delta + \sigma_b)$  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:

$$\frac{\pi_2}{2} (\bar{v} + \Delta + \sigma_b) + \left( 1 - \frac{\pi_2}{2} \right) \bar{v} = \bar{v} + \frac{\pi_2}{2} (\Delta + \sigma_b). \quad (\text{A6})$$

The seller may instead quote a 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:

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

Finally, the seller may quote a 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 price  $p = \bar{v} + \Delta$  to the second buyer whenever:

$$\begin{aligned} \bar{v} + \left( 1 - \frac{\pi_2}{2} \right) \Delta &\geq \bar{v} + \frac{\pi_2}{2} (\Delta + \sigma_b) \\ \Leftrightarrow \frac{\Delta}{\sigma_b} &\geq \frac{1}{2} \left( \frac{\pi_2}{1 - \pi_2} \right), \end{aligned} \quad (\text{A8})$$

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  $W^*(\pi_2) \equiv \max\left\{ \frac{\pi_2}{2} (\Delta + \sigma_b), \left( 1 - \frac{\pi_2}{2} \right) \Delta \right\}$ . 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 price

$p = \bar{v} + \Delta + \sigma_b$  to the first buyer and collect:

$$\frac{\pi_1}{2}(\bar{v} + \Delta + \sigma_b) + \left(1 - \frac{\pi_1}{2}\right)(\bar{v} + \rho W^*(\pi_2)) = \bar{v} + \frac{\pi_1}{2}(\Delta + \sigma_b) + \left(1 - \frac{\pi_1}{2}\right)\rho W^*(\pi_2). \quad (\text{A9})$$

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

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

Finally, the seller may quote a 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 low price  $p = \bar{v} + \Delta$  to the first buyer whenever:

$$\begin{aligned} \bar{v} + \left(1 - \frac{\pi_1}{2}\right)\Delta + \frac{\pi_1}{2}\rho W^*(\pi_2) &\geq \bar{v} + \frac{\pi_1}{2}(\Delta + \sigma_b) + \left(1 - \frac{\pi_1}{2}\right)\rho W^*(\pi_2) \\ \Leftrightarrow \frac{\Delta}{\sigma_b} &\geq \frac{\rho W^*(\pi_2)}{\sigma_b} + \frac{1}{2}\left(\frac{\pi_1}{1 - \pi_1}\right), \end{aligned} \quad (\text{A11})$$

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 (A8) 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  $p = \bar{v} + \Delta$  to both buyers whenever:

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

which can be rewritten as:

$$\frac{\Delta}{\sigma_b} \geq \frac{1}{2}\left(\frac{1}{1 - \rho + \frac{\rho\pi_2}{2}}\right)\left(\frac{\pi_1}{1 - \pi_1}\right). \quad (\text{A13})$$

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  $p = \bar{v} + \Delta + \sigma_b$  to the first buyer and  $p = \bar{v} + \Delta$  to the second buyer if needed

whenever:

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

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  $p = \bar{v} + \Delta + \sigma_b$  to both buyers whenever:

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

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:

$$\frac{1}{2} [\pi_1 + (1 - \pi_1)\pi_2] = \frac{1}{2} (\pi_1 + \pi_2 - \pi_1\pi_2). \quad (\text{A16})$$

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

$$(\pi_1 + \pi_2 - \pi_1\pi_2) \left[ \frac{1}{2}(\bar{v} + \Delta + \sigma_v) + \frac{1}{2}(\bar{v} - \sigma_v) \right] + [1 - (\pi_1 + \pi_2 - \pi_1\pi_2)] \bar{v} = \bar{v} + \frac{1}{2} (\pi_1 + \pi_2 - \pi_1\pi_2) \Delta. \quad (\text{A17})$$

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 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:

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

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:

$$\begin{aligned} & \frac{\pi_1 \pi_2}{2} (\bar{v} - \sigma_v) + \left(1 - \frac{\pi_1 \pi_2}{2}\right) \left[ \bar{v} - \left(\frac{\pi_1}{2 + \pi_1}\right) \sigma_v + \Delta \right] \\ = & \bar{v} + \left(1 - \frac{\pi_1 \pi_2}{2}\right) \Delta - \pi_1 \left(\frac{1 + \pi_2}{2 + \pi_1}\right) \sigma_v. \end{aligned} \quad (\text{A19})$$

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, the seller collects an expected payoff of:

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

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

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

$$\begin{aligned} \bar{v} + \left(1 - \frac{\pi_1 \pi_2}{2}\right) \Delta - \pi_1 \left(\frac{1 + \pi_2}{2 + \pi_1}\right) \sigma_v & \geq \bar{v} + \frac{1}{2} (\pi_1 + \pi_2 - \pi_1 \pi_2) \Delta \\ \Leftrightarrow \frac{\Delta}{\sigma_v} & \geq \left(\frac{1 + \pi_2}{2 + \pi_1}\right) \left(\frac{2\pi_1}{2 - \pi_1 - \pi_2}\right), \end{aligned} \quad (\text{A21})$$

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:** We conjecture an equilibrium in which the seller quotes a low, efficient price  $p = \bar{v} + \Delta$  to the first buyer. This price is only rejected by an informed buyer who knows that  $v = \bar{v} - \sigma_v$ . Hence, both the seller and the second buyer know that the asset is then worth  $v_i = \bar{v} + \Delta - \sigma_v$  to the second buyer while it is only worth  $v = \bar{v} - \sigma_v$  to the seller. The seller quotes a price  $p = \bar{v} + \Delta - \sigma_v$  to the second buyer, which is accepted with probability 1. For this outcome to be an equilibrium, we need to verify that the seller finds it optimal to quote a price  $p = \bar{v} + \Delta$  rather than  $p = \bar{v} + \Delta + \sigma_v$  to the first buyer. Note that if he were to deviate to quoting the high price to the first buyer, the seller could be tempted to retain the asset instead of trading with the second buyer. The seller, however, still finds it optimal to quote the second buyer a low

price  $p = \bar{v} + \Delta - \sigma_v$  after deviating with the first buyer whenever:

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

If this condition is satisfied, then the seller finds it optimal to quote a price  $p = \bar{v} + \Delta$  to the first buyer whenever:

$$\begin{aligned} \left(1 - \frac{\pi_1}{2}\right)(\bar{v} + \Delta) + \frac{\pi_1}{2}(\bar{v} + \rho\Delta - \sigma_v) &\geq \frac{\pi_1}{2}(\bar{v} + \Delta + \sigma_v) \\ &+ \left(1 - \frac{\pi_1}{2}\right) \left[ \rho(\bar{v} + \Delta - \sigma_v) + (1 - \rho) \left( \bar{v} - \frac{\pi_1}{2 - \pi_1}\sigma_v \right) \right] \\ \Leftrightarrow \frac{\Delta}{\sigma_v} &\geq \frac{\pi_1 + 2\pi_1\rho - 2\rho}{2(1 - \pi_1)(1 - \rho)}. \end{aligned} \quad (\text{A23})$$

If condition (A22) is violated however, the condition that guarantees that the seller quotes a price  $p = \bar{v} + \Delta$  to the first buyer is replaced by:

$$\begin{aligned} \left(1 - \frac{\pi_1}{2}\right)(\bar{v} + \Delta) + \frac{\pi_1}{2}(\bar{v} + \rho\Delta - \sigma_v) &\geq \frac{\pi_1}{2}(\bar{v} + \Delta + \sigma_v) + \left(1 - \frac{\pi_1}{2}\right) \left( \bar{v} - \frac{\pi_1}{2 - \pi_1}\sigma_v \right) \\ \Leftrightarrow \frac{\Delta}{\sigma_v} &\geq \frac{\pi_1}{2(1 - \pi_1 + \frac{\rho\pi_1}{2})}. \end{aligned} \quad (\text{A24})$$

■

## B Alternative Models of Centralized Trading

In this section, 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).

### B.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  $\rho_c$  associated with waiting until the second period before realizing the gains

to trade. In particular, we show that when  $\rho_c$  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.

### B.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 charge 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:

$$\frac{\pi(1 - \pi)\frac{1}{2} + (1 - \pi)\pi\frac{1}{2} + (1 - \pi)^2}{1 - (\frac{3}{4}\pi^2 + \pi(1 - \pi))}. \quad (\text{B1})$$

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

$$\begin{aligned} & \left(\frac{3}{4}\pi^2 + \pi(1 - \pi)\right) (\Delta + \sigma_b) + \rho_c(\pi(1 - \pi) + (1 - \pi)^2)\Delta \\ &= \left(\frac{3}{4}\pi^2 + (1 + \rho_c)\pi(1 - \pi) + \rho_c(1 - \pi)^2\right) \Delta + \left(\frac{3}{4}\pi^2 + \pi(1 - \pi)\right) \sigma_b \\ &= \left(\rho_c + \pi(1 - \rho_c) - \frac{\pi^2}{4}\right) \Delta + \left(\frac{3}{4}\pi^2 + \pi(1 - \pi)\right) \sigma_b. \end{aligned} \quad (\text{B2})$$

*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:

$$\rho_c \left(1 - \frac{\pi}{2}\right) \frac{\left(\frac{\pi}{2} + \frac{(1-\pi)}{2}\right)}{\left(1 - \frac{\pi}{2}\right)} = \rho_c \left(\frac{\pi}{2} + \frac{(1-\pi)}{2}\right) = \frac{\rho_c}{2}. \quad (\text{B3})$$

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

$$\left(1 - \frac{\pi}{4}\right) ((\bar{v} + \Delta + \sigma_b) - p_1) \geq \frac{\rho_c}{2} \sigma_b, \quad (\text{B4})$$

which yields the following restriction for the price:

$$p_1 \leq \bar{v} + \Delta + \sigma_b \left(\frac{1 - \frac{\rho_c}{2} - \frac{\pi}{4}}{1 - \frac{\pi}{4}}\right). \quad (\text{B5})$$

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

$$\begin{aligned} & \bar{v} + \left(\frac{3}{4}\pi^2 + \pi(1-\pi)\right) \left[\Delta + \sigma_b \left(\frac{1 - \frac{\rho_c}{2} - \frac{\pi}{4}}{1 - \frac{\pi}{4}}\right)\right] + \rho_c(\pi(1-\pi) + (1-\pi)^2)\Delta \\ = & \bar{v} + \left(\rho_c + \pi(1-\rho_c) - \frac{\pi^2}{4}\right) \Delta + \left(\frac{3}{4}\pi^2 + \pi(1-\pi)\right) \sigma_b \left(\frac{1 - \frac{\rho_c}{2} - \frac{\pi}{4}}{1 - \frac{\pi}{4}}\right). \end{aligned} \quad (\text{B6})$$

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:

$$\bar{v} + \left(1 - \frac{\pi^2}{4}\right) \Delta. \quad (\text{B7})$$

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:

$$\bar{v} + \rho_c \left( \frac{\pi}{2} + \frac{\pi}{2} \frac{\pi}{2} + (1 - \pi) \frac{\pi}{2} \right) (\Delta + \sigma_b) = \bar{v} + \rho_c \pi \left( 1 - \frac{\pi}{4} \right) (\Delta + \sigma_b). \quad (\text{B8})$$

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.

### B.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  $\Delta$ . 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:

$$\frac{2\pi(1-\pi)\frac{1}{2} + (1-\pi)^2}{1 - \frac{1}{2}(\pi^2 + 2\pi(1-\pi))} = \frac{1-\pi}{1-\pi + \frac{\pi^2}{2}}. \quad (\text{B9})$$

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

$$\left( \pi - \frac{\pi^2}{2} + \rho_c(1-\pi) \right) \Delta. \quad (\text{B10})$$

*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:

$$\frac{\frac{1}{2}(1-\pi)^2}{1-\pi + \frac{\pi^2}{2}}. \quad (\text{B11})$$

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

$$\bar{v} - \sigma_v \pi \left( \frac{1 - \frac{\pi}{2}}{1 - \pi + \frac{\pi^2}{2}} \right). \quad (\text{B12})$$

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

$$(\pi_1 + \pi_2 - \pi_1\pi_2) \left[ \frac{1}{2}(\bar{v} + \Delta + \sigma_v) + \frac{1}{2}(\bar{v} - \sigma_v) \right] + [1 - (\pi_1 + \pi_2 - \pi_1\pi_2)] \bar{v} = \bar{v} + \frac{1}{2}(\pi_1 + \pi_2 - \pi_1\pi_2) \Delta. \quad (\text{B13})$$

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  $\Delta$ . 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:

$$(1 - \pi) \frac{\rho_c}{2}. \quad (\text{B14})$$

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

$$\left(1 - \frac{\pi}{2}\right) ((\bar{v} + \Delta + \sigma_v) - p_1) \geq \frac{\rho_c}{2} (1 - \pi) \left( \sigma_v + \sigma_v \pi \left( \frac{1 - \frac{\pi}{2}}{1 - \pi + \frac{\pi^2}{2}} \right) \right), \quad (\text{B15})$$

which yields the following restriction for the price:

$$p_1 \leq \bar{v} + \Delta + \sigma_v \left( 1 - \frac{\frac{\rho_c}{2} (1 - \pi) \left( 1 + \pi \left( \frac{1 - \frac{\pi}{2}}{1 - \pi + \frac{\pi^2}{2}} \right) \right)}{\left(1 - \frac{\pi}{2}\right)} \right). \quad (\text{B16})$$

The seller will optimally post the highest possible price that is incentive compatible. Using  $((1 - \pi)^2 + \pi(1 - \pi)) = 1 - \pi$  we can rewrite the seller's expected payoff as:

$$\begin{aligned} & \frac{1}{2}(2\pi - \pi^2)p_1^{\max} \\ & + \rho_c (1 - \pi) \left( \bar{v} + \Delta - \sigma_v \pi \left( \frac{1 - \frac{\pi}{2}}{1 - \pi + \frac{\pi^2}{2}} \right) \right) \\ & + (1 - \rho_c) (1 - \pi) \left( \bar{v} - \sigma_v \pi \left( \frac{1 - \frac{\pi}{2}}{1 - \pi + \frac{\pi^2}{2}} \right) \right) \\ & + \frac{1}{2}\pi^2 (\bar{v} - \sigma_v). \end{aligned} \quad (\text{B17})$$

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:

$$p_H = \frac{\frac{\pi}{2} \frac{1}{2} + (1 - \pi) \frac{1}{2} \frac{1}{2}}{\frac{\pi}{2} \frac{1}{2} + (1 - \pi) \frac{1}{2} + \frac{\pi}{2}} = \frac{1}{\pi + 2}. \quad (\text{B18})$$

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

$$\bar{v} + (2p_H - 1)\sigma_v = \bar{v} - \frac{\pi}{\pi + 2}\sigma_v. \quad (\text{B19})$$

*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:

$$\pi \frac{\rho_c}{2}. \quad (\text{B20})$$

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

$$\bar{v} - \frac{\pi}{\pi + 2}\sigma_v + \Delta \quad (\text{B21})$$

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:

$$\left(1 - \frac{\pi^2}{2}\right) \left(\bar{v} - \frac{\pi}{\pi + 2}\sigma_v + \Delta\right) + \frac{\pi^2}{2}\rho_c(\bar{v} - \sigma_v + \Delta) + \frac{\pi^2}{2}(1 - \rho_c)(\bar{v} - \sigma_v). \quad (\text{B22})$$

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:

$$p_H = \frac{\frac{1}{2}(1 - \pi)^2}{1 - \frac{1}{2}(\pi^2 + 2\pi(1 - \pi))} \quad (\text{B23})$$

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

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

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:

$$\begin{aligned} & \frac{\rho_c}{2}(\pi^2 + 2\pi(1 - \pi))(\bar{v} + \Delta + \sigma_b) + (1 - \rho_c)\bar{v} \\ & + \rho_c \left(1 - \frac{1}{2}(\pi^2 + 2\pi(1 - \pi))\right) (\bar{v} + (2p_H - 1)\sigma_v). \end{aligned} \quad (\text{B25})$$

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.

## B.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 qualities  $\pi_i$  as exogenously 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 3.4, 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:

$$\frac{\pi_1 \pi_2}{4} (\bar{v} + \Delta + \sigma_b) + \left(1 - \frac{\pi_1 \pi_2}{2}\right) r + \frac{\pi_1 \pi_2}{4} \bar{v}. \quad (\text{B26})$$

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

$$\bar{v} + \left(1 - \frac{\pi_1\pi_2}{4}\right) \Delta + \frac{\pi_1\pi_2}{4}\sigma_b. \quad (\text{B27})$$

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:

$$\bar{v} + \frac{1}{2} \left( \pi_1 + \pi_2 - \frac{1}{2} \pi_1 \pi_2 \right) (\Delta + \sigma_b) \quad (\text{B28})$$

and the social surplus from trade is  $\frac{1}{2} (\pi_1 + \pi_2 - \frac{1}{2} \pi_1 \pi_2) (\Delta + \sigma_b)$ .

**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:

$$\begin{aligned} \bar{v} + \left(1 - \frac{\pi_1\pi_2}{4}\right) \Delta + \frac{\pi_1\pi_2}{4}\sigma_b &\geq \bar{v} + \frac{1}{2} \left( \pi_1 + \pi_2 - \frac{1}{2} \pi_1 \pi_2 \right) (\Delta + \sigma_b) \\ \Leftrightarrow \frac{\Delta}{\sigma_b} &\geq \frac{\pi_1 + \pi_2 - \pi_1\pi_2}{2 - \pi_1 - \pi_2}. \end{aligned} \quad (\text{B29})$$

It is then easy to check that this condition is violated when  $\Delta = 1$ ,  $\pi_1 = \pi_2 = 0.1$ , and  $\sigma_b \geq 9.5$ , meaning that panels (c)-(f) in Figure 1 would remain unchanged if centralized trading occurred through a second-price auction with a reserve price rather than through our baseline model of a limit order market.

## C Mixed-Strategy Equilibria in Pricing and Information Acquisition

In subsection 3.4, we showed that for some parameterization decentralized trading socially dominates centralized trading as it provides the first buyer with stronger incentives to acquire socially valuable information. For simplicity, we then restricted the analysis to equilibria where the seller always posts the same price. This Appendix shows that within this particular parameterization the pure-strategy equilibrium we analyzed for the centralized market with endogenous information is unique. Consequently, we know that the pure-strategy equilibrium we analyzed for the decentralized market socially dominates any equilibrium in the centralized market.

In a mixed-strategy equilibrium, the seller mixes between posting a high price and a price that would be accepted by an uninformed buyer type. Let  $m_L$  denote the probability with which the seller posts the uninformed buyer's valuation, that is, the "low price."

If the seller posts the low price  $p = \bar{v} + \Delta$  with probability  $m_L$  in the centralized market, each buyer  $i$  chooses  $\pi_i$  to maximize:

$$m_L \frac{\pi_i}{4} \left(1 + \frac{\pi_j}{2}\right) \sigma_b - \frac{c}{2} \pi_i^2, \quad (\text{C1})$$

which takes into account that with probability  $(1 - m_L)$  the seller quotes a high price  $p = \bar{v} + \Delta + \sigma_b$ , in which case each buyer obtains zero surplus from trade. Given an interior optimum  $\pi_i \in (0, 1)$ , we obtain:

$$\pi_i^* = \left(1 + \frac{\pi_j}{2}\right) \frac{m_L \sigma_b}{4c}, \quad (\text{C2})$$

which by symmetry implies that both buyers acquire:

$$\pi^* = \frac{1}{\left(\frac{4c}{m_L \sigma_b} - \frac{1}{2}\right)}. \quad (\text{C3})$$

For this  $\pi^*$  to be sustained in equilibrium, it must be the case that the seller is indifferent between posting the high and low prices, which we know from condition (1) only occurs when:

$$\frac{\Delta}{\sigma_b} = \left(1 - \frac{\pi^*}{4}\right) \left(\frac{\pi^*}{1 - \pi^*}\right). \quad (\text{C4})$$



**Existence.** Consider the case where the pure-strategy equilibrium we characterized in subsection 3.4 exists. Now suppose the seller were to instead mix his price quotes such that with  $m_L < 1$ . In anticipation of this pricing strategy, buyers would acquire less information than in the pure-strategy equilibrium — the gains from information acquisition decline with the probability of seeing a high price offer. A lower  $\pi^*$  would in turn decrease the right-hand side of equation (C4) — the seller has lower incentives to post a high price when facing buyers with a lower  $\pi^*$ . Thus, if the pure-strategy equilibrium exists, which means that the right-hand side of equation (C4) is lower than its left-hand side, then this inequality would still be satisfied if the seller were to deviate to  $m_L < 1$  and buyers rationally anticipated such deviation. Thus, if a pure-strategy equilibrium exists, a mixed-strategy equilibrium of the type conjectured above cannot exist.

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