The Effect of Collusion on Efficiency in Experimental Auctions

Charles N. Noussair[*] Gyula Seres[†]

November 20, 2019

Abstract

This paper examines the effect of collusion on allocative efficiency in a second-price sealed-bid auction, in which bidders' valuations have both private and common value components. We present a theoretical model which shows that explicit collusion improves average efficiency. Furthermore, a reduction in common value signal variance increases the efficiency of allocations when a cartel is present. We test for the presence of these patterns in a laboratory experiment. Subjects can choose whether to compete or to form a cartel. Colluding bidders can communicate and make side payments using a knockout auction. Our results show that a large majority of bidders joins a cartel and collusion has a negative impact on efficiency.

JEL Codes: D44, D82, L41, C92
Keywords: Auction; Bidding ring; Information asymmetry; Experiment

1 Introduction

In an auction market for a single good, full *ex-post* allocative efficiency is achieved if the player with the highest valuation is awarded the item. When

[*]Department of Economics and Economic Science Laboratory, Eller College of Management, University of Arizona. Email: cnoussair@email.arizona.edu

[†]Humboldt University Berlin, Faculty of Economics and Business Administration. Email: gyula.seres@hu-berlin.edu. We thank the CentER for Economic Research at Tilburg University for financial support. We are grateful to Jan Boone, Patrick Rey, Eric van Damme, Theo Offerman, Jan Potters, Nicholas Treich, Gary Charness, two anonymous referees, as well as participants at the Experimental Economics Meeting at Tilburg University, at the 2018 World Meeting of the ESA, and at the EARIE 2016 Conference, for their valuable comments.

bidders' valuations for a good are known at the time of bidding, even when they are only privately known, it is typically straightforward to achieve an efficient allocation with a number of different auction rules (Vickrey, 1961). When the valuations are correlated, such as in the generalized mineral rights auction described by Milgrom and Weber (1982), efficiency is also easy to achieve (Jehiel and Moldovanu, 2001). If the item sold has a common value to all bidders, even if the value of the item is not known at the time of bidding, it is equally efficient to allocate the unit to any demander, so that preventing inefficiency is a trivial matter.

However, consider an environment in which bidders' private information consists of a private value component, known with certainty, as well as a signal about a common value component. This structure is, for example, a plausible way to model how individuals value artwork, which is typically sold by auction. A bidder has an intrinsic preference for the painting based on her own private tastes, a private value component, but may also have beliefs about the authenticity and artistic value of the artwork, a noisy common value signal. Yet another example is construction procurement, in which bidders are sellers rather than buyers. Some costs are uncertain but common to all bidders, for example the market prices for inputs such as fuel or cement, but the cost effects of other inputs, including experience or access to capital, are private and vary by bidder.

In these situations, for an efficient allocation to occur, the bidder with the highest private value must receive the item. Nevertheless, it is possible for an auction system, even one that always awards the item to the highest bidder, to allocate an item inefficiently, despite all bidders behaving optimally. This is because an individual with a low private value, but a common value signal that happens to be much higher than the true common value component, might submit the highest bid.[1] In general, no *ex post* efficient, incentive compatible mechanism exists if types are multi-dimensional (Jehiel and Moldovanu, 2001).

If bidders could obtain more precise estimates of the common value, the extent of inefficiency could be reduced. One way to potentially allow this to happen is to permit bidders to collude. As noted by Groenewegen (1994) and Goeree and Offerman (2003), collusion with the possibility of explicit communication is actually beneficial for allocative efficiency. It is commonly accepted that cartels have a detrimental effect on the seller's revenue, but an

[1] The winner's curse is not the source of the inefficiency. Equilibrium bidding strategies of rational bidders also can result in efficiency loss. Goeree and Offerman (2002) find experimental evidence that naive bidding itself does not have a significant impact on efficiency.

increase in overall efficiency would provide a rationale for permitting bidder collusion.[2]

We examine this issue in this paper, where we report a laboratory experimental study on second-price auctions. The source of our hypotheses is a theoretical model assuming rational bidders. The model yields the result that collusion increases expected allocative efficiency. The intuition stems from information sharing that occurs during the collusion process. This sharing increases the likelihood that the bidder with the highest valuation is chosen to submit the highest bid on behalf of the cartel. The model also predicts that all potential bidders join the cartel, and that an exogenous reduction in common value uncertainty increases allocative efficiency, given that a cartel is formed.

Our experiment consists of four treatments. In the first two treatments of the study, there are two potential bidders who can decide to collude before the auction takes place. Their valuations consist of both private and common value components. The difference between the two treatments is the spread of the common value distribution. The *LoVar* treatment has a lower common value variance than *HiVar*. Comparison of these two treatments tests an implication of our model: that higher common value variance has a negative effect on efficiency. It also addresses the question of whether an authority interested in efficiency should make public any information it has that might reduce common value uncertainty.[3] A third treatment, *NoColl*, has the same parametric structure as HiVar, but collusion is prohibited. Comparison of HiVar and NoColl provides a measure of the consequences of prohibiting collusion. In a fourth treatment, *PVOnly*, bidders' valuations consist of only a private value component, but bidders may collude. In PVOnly, at least according to our model, collusion can provide no additional efficiency, since there is no common value uncertainty to resolve. If the process of collusion tends to introduce inefficiencies that are unanticipated in our model, collusion would lower efficiency in this treatment.

We observe support for some predictions of the model. A large majority of bidders attempts to form a ring. Treatments with different variance of the

[2]This argument was made by members of the long-standing Dutch construction cartel, who testified in 2002 that the primary motivation of their operation as a cartel was information pooling (Boone, Chen, Goeree, and Polydoro, 2009). For details of the parliamentary hearings, see Parlementaire Enquêtecommissie Bouwnijverheid (2003).

[3]Milgrom and Weber (1982) show that an auctioneer can increase revenue by releasing any private information she has that can reduce common value uncertainty on the part of bidders. In the context of one of our motivating examples, the auctioneer in a construction procurement auction typically does have some private information about the construction site, related projects, or estimated cost.

common value signal produce a result predicted by the model, which is that more variance leads to greater efficiency loss. However, we also find that cartels fail to increase efficiency. Imperfections in the process of assigning the designated bidder and the side payment to the other bidder at times leads to a failure to make an efficient assignment. This more than offsets the gain in efficiency from the information sharing among cartel members. In the PVOnly treatment, where there is no common value uncertainty, and thus no gain from pooling information, bidding rings reduce efficiency substantially. We also observe that if cartels are prohibited, outcomes differ from a situation in which bidders voluntarily decline the opportunity to form a cartel. Players bid more aggressively if cartels are interdicted.

The work reported here fits into the large literature on using laboratory experiments to evaluate game-theoretic models of collusion in auctions. Early contributions mainly focus on the auction mechanism and include Sherstyuk (1999, 2002), Kwasnica and Sherstyuk (2007), Brown, Plott, and Sullivan (2009) and Phillips, Menkhaus, and Coatney (2003). Recent lines of research address leniency programs (Bigoni, Fridolfsson, Le Coq, and Spagnolo, 2015; Apesteguia, Dufwenberg, and Selten, 2007; Hinloopen and Soetevent, 2014), cartel detection (Hinloopen and Onderstal, 2014), communication within the cartel (Agranov and Yariv, 2016; Llorente-Saguer and Zultan, 2014) and the effect of reference prices (Armantier, Holt, and Plott, 2013).

The paper is structured as follows. Section 2 describes the model, and characterizes an equilibrium with risk neutral, rational bidders. Details of the experimental design are given in Section 3. Section 4 formally states our hypotheses. Section 5 reports our data analysis and summarizes our results. Finally, Section 6 concludes with a discussion.

2 Model and equilibrium

In this section, we analyze the auction game that we study in our experiment. The game proceeds in a number of stages. Nature chooses the private information of the three bidders who have the right to participate in the auction. Two of the bidders then choose whether or not to create a bidding ring. If a ring is created, the ring members use a bidding process called a knockout auction (Mailath and Zemsky, 1991) to determine who will be the designated bidder in the subsequent main auction, and the side payment that the other ring member receives in exchange for withdrawing from the main auction. The designated bidder then participates in the main auction against the third bidder.

The environment is one in which bidders' valuations for the item have both a private value and a common value component, as in Goeree and Offerman (2003). The private value component is known with certainty, and bidders have unbiased signals about the common value component. The auction follows second-price sealed-bid rules. In the pure-strategy perfect Bayesian equilibrium to the game that we derive, players always form a cartel, and the cartel agrees on a transfer from the designated bidder to the withdrawn bidder[4]

2.1 Model

Two strong and one weak bidder have valuations for an item sold in a second-price sealed-bid auction. The strong bidders i and j are symmetric and risk neutral. Strong bidders' valuations consist of two additively separable components: a private value (PV) and a common value (CV). The private value of each strong bidder i, denoted by x_i, is drawn independently from a uniform distribution with support $[x_L, x_H]$.[5] The common value component y is the average of the two strong bidders' independently and identically distributed common value signals, denoted as y_i and y_j. The signals are each drawn from a uniform distribution, so that $y_i \in [y_L, y_H]$. The distributions of private values and common value signals are common knowledge. Thus, the valuation of bidder i, denoted by v_i, has the structure shown in Equation (1).[6]

$$v_i = x_i + y = x_i + \frac{y_i}{2} + \frac{y_j}{2} \tag{1}$$

The third bidder, called l, is weak in the following sense. Her valuation consists entirely of a private value component, c, drawn from a uniform dis-

[4]This form of collusion is a strong cartel in the sense of McAfee and McMillan (1987), who define a strong cartel as one that can specify and enforce side payments between ring members. It is also a strong cartel in the sense of Marshall and Marx (2007), in that it can enforce a restriction that only the designated bidder submits a meaningful bid.

[5]We restrict attention to uniform distributions since these are employed in our experiment. This is standard in auction experiments as uniform distributions are relatively easy for participants to comprehend and the theoretical predictions are relatively simple. This makes uniform distributions conducive to creating reasonable conditions for the testing of equilibrium bidding models.

[6]The existence of equilibria is not guaranteed in general in multi-dimensional auctions (Goeree and Offerman, 2003). Consequently, it is not assured that multi-dimensional auctions have a Bayesian equilibrium under any distribution of types (Goeree and Offerman, 2003; Jackson and Swinkels, 2005).

tribution with support $c \in [c_L, c_H]$, where $c_L \leq x_L$, $c_H \leq x_H$. We included a weak bidder because we were interested in an environment, in which the cartel did not include all potential bidders. All-inclusive membership is not typical of industrial cartels, and we are unaware of any examples. We assume that c_L, x_L and y_L are all non-negative. In what follows, the *type* of a bidder refers to the realization of her own values.

Bidders participate in a second-price sealed-bid auction. Bids are submitted simultaneously. The player submitting the highest bid is awarded the item for a price equal to the second highest bid. If there is a tie for the highest bid, the tie is broken randomly. Before the auction, the two strong bidders can form a cartel by mutual agreement. The game consists of the following sequence of events.

1. Nature chooses bidders' private values and common value signals: x_i, y_i x_j, y_j, and c.

2. The two strong bidders decide whether or not to form a bidding ring. They make their choices simultaneously. A cartel is formed if they both choose to join. Otherwise, no cartel is formed and the game proceeds to Stage 4.

3. If a bidding ring is formed, the cartel members participate in a knockout auction and simultaneously submit their knockout bids k_i and k_j. The higher bidder is awarded the right to participate in the subsequent main auction. This designated bidder pays the lower of the two knockout bids to the other ring member, who is forced to bid 0 in the main auction. Ties are broken randomly. Knockout bids are observed by both members of the ring.

4. The main auction takes place, following second-price, sealed-bid auction rules. If a cartel is formed, the auction has two active bidders, the designated bidder and the weak bidder. If no ring is created, there are three bidders in the main auction, the two strong and the one weak bidder.

2.2 Equilibrium analysis

In this subsection, we derive a perfect Bayesian equilibrium to the game. We assume that the two strong bidders use the same strategy. In Subsections 2.2.1 and 2.2.2, we consider the subgames in which no bidding ring is formed, and in which one is formed, respectively. In Subsection 2.2.3, we analyze the knockout auction, and in Subsection 2.2.4, we consider the decision about whether or not to collude. We show that all types of bidder benefit from collusion. In Subsection 2.2.5, we derive two results regarding allocative efficiency. We show that efficiency is greater on average when collusion is permitted than when it is not. We also establish that efficiency is higher when common value uncertainty is smaller. We solve the game by backward induction, beginning with the main auction in Stage 4.

2.2.1 The main auction without collusion

Consider the subgame reached in the last stage of the game if the strong bidders choose not to collude.[7] We shall refer to this situation as a competitive auction. In this subgame, players place bids in the main auction independently and competitively. Define the *composite signal*, which we shall at times also refer to as the *surplus*, of strong bidder i as $s_i = x_i + \frac{y_i}{2}$. The optimal bid of a player is a function of her composite signal.[8] To see this, note that the valuation of bidder i consists of the composite signal, which is known to i at the time of bidding, and an unknown part $y_j/2$. The private value auction is a special case of this environment, in which $s_i = x_i$ and player i has a dominant strategy to submit a bid of x_i, as in Vickrey (1961). However, the existence of a dominant strategy does not carry over to auctions with common value uncertainty, and a strong bidder's best response depends upon the strategy the other strong bidder uses.[9]

We derive a Bayesian equilibrium $b^* = \left(b_i^*\left(x_i, y_i\right), b_j^*\left(x_j, y_j\right), b_l^*(c)\right)$ to this subgame, where b_i^* is the bidding strategy of bidder i. First note that the weak player submits a bid equal to her valuation c, which is her dominant strategy.[10] As standard in the literature, we assume that $b_i^{*\prime}(s_i) > 0$ and

[7] As we shall see later, this stage is reached with probability 0 in equilibrium. We assume that the out-of-equilibrium beliefs about other players' private values and common value signals are the same as the initial priors.

[8] The derivation provided here is similar to the one given in Goeree and Offerman (2003). They refer to the composite signal as surplus.

[9] Consider a bidder with a very low composite signal. Conditional on winning, the CV of the other bidder is also low. For a higher composite signal, the CV of the other bidder is not similarly constrained. Consequently, the equilibrium bidding strategy is typically a piecewise linear function of s_i.

[10] The assumption that the weak bidder's information (type) is one-dimensional rather than two-dimensional, is made only to simplify the notation and does not affect our results. As Marshall and Marx (2007) show, two-dimensional second-price auctions have a symmetric equilibrium strategy which is a function of surplus (composite signal) only. Hence, the weak bidder's strategy boils down to a $\mathbb{R}^1 \to \mathbb{R}^1$ mapping from surplus to bid, regardless of how the surplus is composed.

therefore invertible, and strategy profiles that are symmetric, so that $b_i^*(s) = b_j^*(s), \forall s$. We show that the strategy profile in which

$$\begin{aligned} b_i^*(x_i, y_i) = E[v_i | b_i^*(s_i) = b_j^*(s_j) \geq c \vee b_i^*(s_i) = c \geq b_j^*(s_j)] = \\ s_i + \frac{1}{2}(t \cdot E[y_j | b_i^*(s_i) = b_j^*(s_j) \geq c] + (1-t)E[y_j | b_i^*(s_i) = c \geq b_j^*(s_j)]) = \\ s_i + \frac{1}{2}(t \cdot E[y_j | s_i = s_j] + (1-t)E[y_j | s_i \geq s_j]), \end{aligned} \tag{2}$$

bidder j uses the same strategy, and the weak bidder bids c, is a Bayesian equilibrium to this subgame.

In equation (2), $t = \frac{h(s_i) \cdot F(b_i^*(s_i))}{h(s_i) \cdot F(b_i^*(s_i)) + H(s_i) \cdot f(b_i^*(s_i))}$ is the probability, conditional on being tied for highest bid with another player, of submitting the same bid as the other strong bidder. The coefficient $1-t$ is then the conditional probability of being tied with the weak bidder for the highest bid. $F(\cdot)$ is the cumulative distribution function of c and $f(\cdot)$ is the corresponding probability density function. As we assume that c is uniformly distributed, we have that $t = \frac{h(s_i) \cdot \frac{b_i^*(s_i) - c_L}{c_H - c_L}}{h(s_i) \cdot \frac{b_i^*(s_i) - c_L}{c_H - c_L} + H(s_i) \cdot \frac{1}{c_H - c_L}} = \frac{h(s_i) \cdot (b_i^*(s_i) - c_L)}{h(s_i) \cdot (b_i^*(s_i) - c_L) + H(s_i)}$ if $b_i^*(c_i) < c_H$ and $t = 1$ otherwise. Thus, $b_i^*(c_i)$ is well-defined by (2).

Under strategy $b_i^*(s_i)$, bidder i submits an amount equal to her expected valuation conditional on having an identical opposing bid. This opposing bid may come from the other strong bidder or the weak bidder. Under the assumption of symmetric strategies, the strategy of j is analogous. The intuition for why $b_i^*(s_i)$ is a best response to itself is analogous to the well-known argument for bidding one's valuation in a second-price auctions with private values. Bidding above this value results in the potential for winning auctions at a price above valuation if another bidder bids between one's own valuation for the item and one's own bid. This intervening bid may come from the other strong bidder or the weak bidder, with the probability of each event a function of the distributions of the weak bidder's value and the other strong bidder's composite signal. Bidding below one's value risks missing out on profitable opportunities to win the auction at prices below one's valuation, if another bidder bids between one's valuation for the item and one's own bid. Here, analogously, bidding greater than $b_i^*(x_i, y_i)$ results in the possibility of paying more than the expected value of the item, and bidding below $b_i^*(x_i, y_i)$ risks missing out on profitable purchases. The proof that the strategy profile described in (2) is part of an equilibrium to the subgame is given in Appendix A.

2.2.2 The main auction with collusion

We now analyze the subgame in which the main auction takes place after the formation of a cartel. Assume that bidder i has won the knockout auction and is the designated bidder. She is then in a two-player auction facing the weak bidder, who has a dominant strategy to bid c. The information she has available is (x_i, y_i) and the knockout bid of the other ring member k_j. In equilibrium, bidder i updates her belief about the type of j, and in turn her own valuation. Her optimal strategy is to bid her expected valuation, conditional on what she has learned about y_j in the knockout auction. Her equilibrium bid in the auction equals:

$$d_i^*(x_i, y_i) = x_i + \frac{y_i}{2} + \frac{1}{2}\mathbb{E}\left(y_j|k_j\right) = s_i + \frac{1}{2}\mathbb{E}\left(y_j|k_j\right). \tag{3}$$

2.2.3 Knockout auction

We now turn to the knockout auction in Stage 3. To derive the equilibrium knockout bids of the subgame with collusion, note that they are determined by the expected payoff that the agent can earn if she is the designated bidder in the subsequent main auction. A bidder would rather lose the knockout auction if she receives at least as much in a side payment as her expected payoff in the main auction, and would like to win the knockout auction if she can do so at a price less than her expected payoff in the main auction. Thus, her optimal bid in the knockout auction is a function of her expected payoff given her composite signal, and conditional on winning the knockout auction. Given the strictly monotonic relationship between the composite signal and the knockout bid, the designated bidder learns the composite signal of the other strong bidder after the knockout auction is completed.

We denote the expected payoff of i in the main auction as $\bar{\Pi}\left(s_i, s_j\right)$, where the first argument denotes the surplus of the bidder and the second one refers to the other ring member's surplus. This expected payoff corresponds to a case where i faces only the weak bidder. Following Kittsteiner (2003), bidder i bids according to

$$k_i^*(s_i) = \frac{1}{2}\left(\bar{\Pi}\left(s_i, s_i\right) + \frac{\int_{s=s_i}^{x_H+\frac{y_H}{2}} \frac{\partial\bar{\Pi}(s,s)}{\partial s}(1-H(s))^2\, ds}{(1-H(s_i))^2}\right), \tag{4}$$

where $H(s_i)$ refers to the *ex ante* distribution of the composite signal. Unlike in the standard second-price auction, the loser receives her own bid. That is, in equilibrium, conditional on facing an identical opposing bid, the bidder must be indifferent between (a) being the winner of the knockout auction and continuing on to the main auction, and (b) receiving the side payment. This point of indifference determines equation (4). For notational simplicity, we write $k_i^*(\cdot) = k_j^*(\cdot) = k^*(\cdot)$.

2.2.4 The collusion decision

We now consider the decision of a bidder, taken in Stage 2, regarding whether or not to collude. This binary decision is denoted by $e \in \{0, 1\}$, where 1 refers to joining the ring. By definition, $e = 1$ for each type if and only if the collusive mechanism is *interim* individually rational.[11] The expected payoff of a bidder engaging in collusion is

$$\int_{s_j=x_L+\frac{y_L}{2}}^{s_i} \left(\bar{\Pi}\left(s_i, s_j\right) - k^*\left(s_j\right)\right) \, d\,H\left(s_j\right) + \int_{s_j=s_i}^{x_H+\frac{y_H}{2}} k^*(s_i) \, d\,H\left(s_j\right) \qquad (5)$$

conditional on all bidder types joining the ring. The term on the left describes the payoff in the event of winning the knockout auction, as $\bar{\Pi}(s_i, s_j)$ is the expected payoff to the designated bidder in the main auction. The term on the right corresponds to losing the knockout auction and receiving the side payment. Rearranging, we obtain

$$\int_{s_j=x_L+\frac{y_L}{2}}^{s_i} \left(\bar{\Pi}\left(s_i, s_j\right) - \frac{1}{2}\bar{\Pi}\left(s_j, s_j\right)\right) \, d\,H\left(s_j\right)$$

$$+ \int_{s_j=s_i}^{x_H+\frac{y_H}{2}} k^*(s_i) dH\left(s_j\right) - \int_{s_j=x_L+\frac{y_L}{2}}^{s_i} \frac{\int_{s=s_i}^{x_H+\frac{y_H}{2}} \frac{\partial \bar{\Pi}(s,s)}{\partial s} (1 - H(s))^2 \, ds}{(1 - H(s_i))^2} dH\left(s_j\right)$$

$$\geq \frac{1}{2} \int_{s_j=x_L+\frac{y_L}{2}}^{s_i} \bar{\Pi}\left(s_i, s_j\right) \, d\,H\left(s_j\right) \qquad (6)$$

[11] Our collusion mechanism is equivalent to a dissolution game, in which a partnership is dissolved with one party buying out the share of the other. Kittsteiner (2003) has shown that a dissolution game can be modeled as a k-double auction game with $k = 1$, where the winning bidder pays an amount equal to the other player's bid to buy out her share. Under the assumption of *interim* individual rationality, the unique symmetric equilibrium is given by an expression corresponding precisely to (4). As the equilibrium strategy is monotonic in type, the mechanism also satisfies *interim* efficiency. The 1-double auction satisfies *ex post* budget balance.

The individual rationality condition is satisfied if the right-hand side of (6) is larger than the expected payoff of bidder type s_i in a competitive auction. We denote this competitive expected payoff as $\widehat{\Pi}(s_i)$. The resulting individual rationality constraint is given in (7).

$$\frac{1}{2}\int_{s_j=x_L+\frac{y_L}{2}}^{s_i} \bar{\Pi}\left(s_i, s_j\right)\ d\,H\left(s_j\right) \geq \widehat{\Pi}(s_i) \tag{7}$$

Our findings regarding participation in the cartel are summarized in Proposition 1.[12,13]

Proposition 1. *All bidder types join the ring, $e^*(s_i) = 1$, if Condition (7) holds for all $x_L + \frac{y_L}{2} \leq s_i \leq x_H + \frac{y_H}{2}$.*

That is, all bidder types participate if competition can be successfully suppressed. The expected payoff of all bidder types is higher with a bidding ring than in a competitive auction in all treatments of our experiment in which collusion is permitted.[14]

The arguments presented in these last four subsections show that there exists an equilibrium with the following structure.[15]

[12] Expressed in terms of exogenous parameters, the expected payoff from joining the ring, net of the side-payment, is $s_i + \int_{s_j=x_L+\frac{y_L}{2}}^{s_i} \mathbb{E}(y_j|s_j)dH\left(s_j\right) - \frac{c_L+c_H}{2}$ if $s_i + \frac{1}{2}\mathbb{E}\left(y_j|k_j\right) \geq c_H$, and $\int_{c=c_L}^{s_i}\int_{s_j=x_L+\frac{y_L}{2}}^{s_i}\left(s_i + \mathbb{E}(y_j|s_j) - c\right)dH\left(s_j\right)\,dc$ if $s_i + \frac{1}{2}\mathbb{E}\left(y_j|k_j\right) < c_H$. The first expression corresponds to the case where i's expected value for the item is greater than the highest possible value of the weak bidder, and the second expression is the case where i has some probability of losing to the weak bidder. On the other hand, a bidder in a competitive auction faces two bidders and gets $H(s_i)\int_{c=c_L}^{c_H}\int_{s_j=x_L+\frac{y_L}{2}}^{s_i} s_i + \mathbb{E}(y_j|s_j) - max\left\{b_j^*(s_j), c\right\}\,dH\left(s_j\right)\,dc$ if $b_i^*(s_i) \geq c_H$, and $H(s_i)\frac{b^*(s_i)-c_L}{c_H-c_L}\int_{c=c_L}^{b_i^*(s_i)}\int_{s_j=x_L+\frac{y_L}{2}}^{s_i} s_i + \mathbb{E}(y_j|s_j) - max\left\{b_j^*(s_j), c\right\}\,dH\left(s_j\right)\,dc$ if $b_i^*(s_i) < c_H$. All bidders join the ring if the payoff from joining a cartel is greater than that in a competitive auction for all types s_i.

[13] Making the third bidder weak ensures that strong bidders generally have strong incentives to collude. This does not necessarily mean that the higher valuations imply a greater willingness to collude, given that one is already a strong bidder. While collusion between the two strongest bidders is expected to be more likely if they get stronger compared to the third bidder, it is not necessarily the case that the stronger among them would be more likely to seek to collude. Our model predicts that in our experiment all strong bidders seek to collude, regardless of their type.

[14] A figure that compares the predicted expected payoffs under collusion and competition for all types in all treatments can be found in Appendix B.

[15] There is clearly a multiplicity of equilibria in this game. Consider for instance the same strategy profile as that given in (8) - (12), with one modification. Bidder i, conditional on reaching the main auction as a designated bidder, can submit any arbitrarily high bid if $s_i > c_H$. However, equilibria of this type lead to the same outcomes and payoffs as the one we have derived, in that a cartel is always formed, the bidder with the highest valuation

$$e_i^*(s_i) = 1 \tag{8}$$
$$d_i^*(s_i) = s_i + \frac{1}{2}\mathbb{E}\left(y_j|k_j\right) \tag{9}$$
$$k^*(s_i) = \frac{1}{2}\left(\bar{\Pi}\left(s_i, s_i\right) + \frac{\int_{s=s_i}^{x_H+\frac{y_H}{2}} \bar{\Pi}(s,s)((1-H(s_i))^2)}{(1-H(s_i))^2}\right) \tag{10}$$
$$b_i^*(s_i) = s_i + \frac{1}{2}(t \cdot E[y_j|s_i = s_j] + (1-t)E[y_j|s_i \geq s_j]) \tag{11}$$
$$b_l^*(c) = d_l^*(c) = c \tag{12}$$

with bidder j employing the same strategy as i.

2.2.5 Theoretical results regarding efficiency

Ex post efficiency is guaranteed in a pure common value auction, since valuations are identical. In a symmetric pure private value auction, equilibrium bids increase in valuation, and this guarantees that the efficient buyer obtains the commodity. Inefficiencies might appear if both types of information asymmetry are present, as Goeree and Offerman (2003) argue.

A bidder with high PV and low CV might bid lower in equilibrium than an opponent with low PV and high CV. For example, consider two strong bidders, with types ($x_i = 800, y_i = 0$) and ($x_j = 700, y_j = 400$), where the supports of PV and CV signals are $[0, 800]$ and $[0, 400]$, respectively. The weak bidder bids $c = 500$. In equilibrium, player i submits $b_i^* = 900$, whereas $b_j^* = 1050$. Bidder j wins the auction, while her opponent has higher PV, resulting in an efficiency loss of $x_i - x_j = 800 - 700 = 100$.

The ranking of knockout bids and competitive auction bids of the strong bidders coincide, since bids are monotonic in composite signals in both the competitive and the knockout auctions. However, the information contained in the knockout bids help the designated bidder to improve her beliefs regarding the CV signal of the other ring member, as we have also seen above, bidding $s_i + \frac{\mathbb{E}(y_j|k_j)}{2}$. This bid equals the expected valuation of the bidder, where the distribution of beliefs second-order stochastically dominates that of the competitive bidder. This means that the probability of winning, conditional on having a valuation greater than that of the weak bidder, is also greater than in the competitive auction. These arguments are summarized in Proposition 2.

is always the designated bidder, and the prices in the knockout and main auctions, as well as the final allocation, are the same.

Proposition 2. *Collusion has no effect on the allocation of the good between the strong players. The overall probability of an efficient allocation is higher if a bidding ring is formed.*

Proof. The first part of the proposition is a consequence of the monotonicity of bids in composite signals in the competitive auction, and the fact that the bidder with the highest composite signal within a cartel is always the designated bidder. To prove the second part of the proposition, one has to compare the probability of producing an inefficient allocation between the weak bidder and the strong bidder with the higher composite signal s_1 under collusion and under competition. The ranking of these bids in the main auction is different between collusion and competition if and only if

$$b_1^*(s_1) > c > s_1 + \frac{1}{2}\mathbb{E}\left(y_2|k_2\right) \tag{13}$$

is satisfied, that a strong bidder who would bid higher than the weak bidder does so under competition but not under collusion. If the condition in (13) applies, inefficiency occurs under collusion but not competition if $s_1+y_2 > c$. Similarly, inefficiency occurs under competition but not collusion if $c \geq s_1 + y_2$. The condition is not vacuous since $b_1^*(s_1) > s_1 + \mathbb{E}\left(y_2|k_2\right)$. That is, winning the knockout auction causes bidder 1 to revise her beliefs about y_2 downward.

The probability of $s_1 + y_2 > c$ is $\frac{1}{2}$, if $c = s_1 + \frac{1}{2}\mathbb{E}\left(y_2|k_2\right)$. This follows from the fact that for any s_1, the conditional probability of $y_1 \geq \mathbb{E}\left(y_2|k_2\right)$ is exactly $\frac{1}{2}$. Also, $Pr\left[s_1 + y_2 > c\right] < \frac{1}{2}$, if $c > s_1 + \frac{1}{2}\mathbb{E}\left(y_2|k_2\right)$. Therefore, the probability of efficiency loss under collusion compared to under competitive bidding is strictly smaller than $\frac{1}{2}$ and the probability of efficient allocation is greater under collusion. □

The next result concerns the effect of a mean preserving spread on the common value of strong bidders. Milgrom and Weber (1982) show that the effect of disclosing any relevant private information the seller has, which has the effect of reducing the variance of the common value distribution, is to make bidders with low private values bid less. Proposition 3 is similar in spirit in that it shows that an decrease in spread has a similar effect on the behavior of our strong bidders.

Proposition 3. *A mean-preserving spread of the common value distribution increases the probability of an inefficient choice of designated bidder. It also increases the probability of an inefficient ranking of composite signals, That is, it increases the probability of $s_i > s_j$ while $x_j > x_i$.*

Proof. As we argued above, collusion does not alter the ranking of bids among strong bidders. Therefore, the subject of our interest is the sum of the probabilities of two cases: (i) $s_i > s_j$ if $x_j > x_i$ and (ii) $s_j > s_i$ if $x_i > x_j$.[16] We prove monotonicity of the probability of event (i) in the spread of the common value distribution. The result for (ii) is analogous. First, observe that

$$s_i > s_j \iff x_i + \frac{y_i}{2} > x_j + \frac{y_j}{2} \iff \frac{y_i}{2} - \frac{y_j}{2} > x_j - x_i \tag{14}$$

All signals are independently drawn, so the distribution of $\frac{y_i}{2} - \frac{y_j}{2}$ equals

$$f(\frac{y_i}{2} - \frac{y_j}{2}) = \begin{cases} \frac{2}{y_H - y_L} + \frac{2(\frac{y_i}{2} - \frac{y_j}{2})}{(y_H - y_L)^2} & (y_L - y_H)/2 \leq \frac{y_i}{2} - \frac{y_j}{2} \leq 0 \\ \frac{2}{y_H - y_L} - \frac{2(\frac{y_i}{2} - \frac{y_j}{2})}{(y_H - y_L)^2} & 0 \leq \frac{y_i}{2} - \frac{y_j}{2} \leq (y_H - y_L)/2 \end{cases} \tag{15}$$

and zero otherwise, for all $x_j > x_i$. Thus, letting $F(\cdot)$ denote the cumulative distribution function,

$$\begin{aligned} Pr(\frac{y_i}{2} - \frac{y_j}{2} \geq x_j - x_i) = 1 - F(x_j - x_i) = \\ \frac{1}{2}(\frac{2}{y_H - y_L} - \frac{2(x_j - x_i)}{(y_H - y_L)^2})(\frac{y_H - y_L}{2} - x_j - x_i) = \\ \frac{1}{2}((1 - \frac{2(x_j - x_i)}{y_H - y_L})^2 - \frac{2(x_j - x_i)}{y_H - y_L}) \end{aligned} \tag{16}$$

if $x_j - x_i \leq (y_H - y_L)/2$ and zero otherwise. The last expression of (16) is an increasing function of $(y_H - y_L)$ for any x_j, x_i with $x_j > x_i$. □

Since the actual common value term of these bidders is identical, efficient allocation is solely based on private values. However, Proposition 3 demonstrates that greater variance of the common value signal implies that it becomes more likely that the common value signals determine the ranking of strong bidders.

3 General procedures and treatments

The experiment was conducted between October 2014 and March 2016, at the CentERlab experimental facility at Tilburg University. We ran nine ses-

[16] This result for competitive auctions is similar to part (iii) of Proposition 2 of Goeree and Offerman (2003).

Treatment	PV	CV	Weak Bidder	Collusion	Sessions	N
LoVar	$[200, 600]$	$[0, 400]$	$[0, 500]$	Allowed	3	54
HiVar	$[200, 600]$	$[0, 800]$	$[0, 500]$	Allowed	2	40
PVOnly	$[400, 800]$	$[0, 0]$	$[0, 500]$	Allowed	2	32
NoColl	$[200, 600]$	$[0, 800]$	$[0, 500]$	Precluded	2	40

Table 1: Summary of the differences between treatments

sions with 166 subjects. In each session, an even number of subjects, numbering between 16 and 22, participated. The average length of a session was 105 minutes. Subjects were recruited online from a pool of undergraduate students at Tilburg University, most of whom were majoring in economics or business. The experiment was conducted in English, with which our participants have a high degree of fluency, and which is the language of instruction for most programs at the university. The average total earnings per subject amounted to 14.15 EUR (1 EUR = 1.13 USD at the time the last session was conducted). Participants' valuations and earnings were expressed in terms of an experimental currency, called *Coin*, which was exchanged for Euro at the end of the session at a rate of 100 Coins for 1 Euro.

There were four treatments, called LoVar, HiVar, PVOnly and NoColl. Each session only had one treatment in effect so that all treatment comparisons in the study are between-subject. LoVar, HiVar and PVOnly were treatments in which bidding rings were allowed. In NoColl, collusion was precluded. LoVar and HiVar refer to the variance of the common value signals. In PVOnly, there was no common value component to subjects' valuations, which were fully determined by their private values. In NoColl, the common value variance was identical to HiVar, and thus the only difference between these two treatments was that collusion was not allowed in NoColl. Table 1 summarizes the differences between the four treatments. The intervals indicate the supports of the private value (PV) and common value (CV) distributions of the strong bidders, as well as the PV distribution of the weak bidder. Subjects assumed the role of the strong bidders whereas the weak bidder was computerized.[17]

In order to guarantee non-negative payoffs in any period, two specific parameter choices were made. The first was to give each bidder a constant endowment of 800 Coin per period, in addition to the amount they earned in the auction. The second was to place an upper limit on the bids that

[17]Using computerized bidders is a standard tool in auction experiments and allows us to eliminate the complicating effect of the beliefs of ring members about the weak bidder's strategy (Kagel and Levin, 2002).

an individual could submit; an individual's bids in the knockout and main auctions could not total more than 1400, in the LoVar, HiVar and NoColl treatments. In the PVOnly treatment, a total above 1000 was not permitted. Because payoffs were never below 0 for bids at these maximum levels (including the additional payment of 800), the bidding caps ensured non-negative payoffs.[18] Furthermore, the caps were set high enough that they were very rarely, if ever, binding.[19] The bidding caps were not expected to influence observed efficiency and the likelihood of cartel formation. This is because the predicted bids of the model are well inside the feasible region for all possible private values and common value signals. Furthermore, the efficiency of the allocation is determined by the identity of the designated bidder in the cartel and whether the cartel outbids the weak bidder. These two variables are unlikely to be affected by a high limit on bid levels.[20]

The weak bidder was computerized and did not interact with the cartel. While the valuations of the strong bidders ranged from 200 to 1400, depending on the treatment, the weak bidder always submitted a bid between 0 and 500 Coins, following a uniform distribution. The reason behind the choice to make the computerized bidder weak was to reflect the fact that in general bidding rings are formed among strong bidders (Hu, Offerman, and Onderstal, 2011). In a second-price auction, a ring can only reach a positive collusive gain in equilibrium if the bidders with the two highest equilibrium bids are members. A low distribution of valuations for the weak bidder guaranteed that there was a high probability that the two potential cartel members had the two highest valuations.

3.1 Timing within a session

The experiment consisted of two parts. Both parts were fully computerized and programmed in z-Tree (Fischbacher, 2007). The first part is of primary interest, and consisted of 11 periods of the auction game. The first period was played for practice and the remaining 10 periods could count toward subjects' earnings. At the end of the session, one period was randomly chosen to count. Pairs of subjects were randomly rematched anonymously in each period. In the second part of the experiment, subjects completed

[18]The lowest observed payoff a bidder received in any single period was 301, including the 800 endowment.

[19]In only six instances did a bidder bid the maximum permitted. Five of the six cases were in the PVOnly treatment.

[20]The distribution of valuations in LoVar form a mean-preserving spread of valuations in PVOnly. On the other hand, distribution of valuations in HiVar is 100 lower than mean-preserving spread of the latter two in order to avoid negative payoffs.

the Holt and Laury (2002) protocol to measure their risk preferences. The activity within each period is described in Section 3.2.

As the instructions were read out, subjects followed along on their own printed copies. After subjects were read the instructions for the auction, they completed a number of control questions to ensure their understanding of the rules. The instructions and the control questions can be found in Appendix C and D.[21]

3.2 Events within an auction period

The sequence of events within a period of the auction game is summarized below. The stages that appear only when players choose to form a ring are noted. Since Treatment NoColl precluded collusion, it only included Stages 1, 6 and 7.

1. Subjects learn their private values x_i and x_j, (as well as their common value signals y_i and y_j in the LoVar, HiVar, and PVOnly treatments).

2. Participants answer a yes/no question regarding whether or not they would like to participate in a prospective bidding ring. The ring is formed if both strong bidders reply *yes*. If one or both answer *no*, no ring is formed and the game skips to Stage 6.

3. If a ring is formed, the ring members have an opportunity to chat by computer.[22] Players automatically leave the chat by submitting a bid in the knockout (KO) auction described below. After 90 seconds, they receive a warning on their screens asking them to submit their bid. They must submit a knockout bid to continue to the next stage.[23]

[21]The instructions and control questions were identical for all treatments. The exceptions were the following. (i) The indication of the distribution of types of the strong bidders was tailored to the actual distributions in effect. (ii) The description of the collusion process was omitted in NoColl. (iii) The common value was not described in the PVOnly treatment. (iv) The quadratic scoring rule used different parameters in different treatments. However, the payoff for an exactly correct guess of the other strong bidder's CV was the same in all treatments permitting collusion. The Appendix contains the materials for the LoVar Treatment.

[22]The chat data was coded by three individuals who did not participate in any of the sessions, and who were paid a fixed fee of 70 EUR. The instructions to the coders can be found in Appendix F. If at least two of the three coders interpreted a statement in the same way, it was entered in the dataset that we used for our analysis.

[23]The experimental design deviates from the model in Section 2 in that it includes an additional stage with the opportunity to communicate. However, this does not affect the equilibrium predictions. A bidder could in principle benefit by strategically sending a

4. There is an incentivized elicitation of bidders' beliefs about the PV and CV signals of the other strong bidder. The belief elicitation is conducted regardless of whether or not a cartel is formed.

5. If a ring is formed, members are informed of the winner and both knockout bids. Side payments are transferred.

6. The main auction takes place.

7. Players receive feedback about the outcome of the main auction. They are informed of all bids submitted and their payoff for the period, except for their earnings from the belief elicitation, which they are not informed of until the entire experiment has ended.

Bidders' private value and common value signals were drawn independently from each other, and were also independent between one period and the next. They were drawn from uniform distributions with ranges as indicated in Table 1, which summarizes the parameters in effect in each treatment. Subjects knew their own values and the distributions from which all subjects' private information was drawn.

In Stage 3 above, subjects who had agreed to join a bidding ring could communicate with each other in an unrestricted manner, except that they were not allowed to signal their identity, they could only send messages phrased in English, and they could only interact through the computer. When a player no longer wished to communicate, she entered a bid in the knockout auction. If at least one prospective cartel member declined to join the cartel, there was no chat stage.[24]

The knockout auction in Stage 3 proceeded as follows. Each member of the cartel submitted a sealed bid. The higher bidder won the knockout auction and thus earned the right to bid in the main auction. The winning bidder in the knockout auction then transferred an amount of money, equal to the losing bid, to the other strong bidder.

In Stage 4, after bids were submitted in the knockout auction, but before the results from the auction were displayed, we elicited player's beliefs

message that minimizes the other ring member's beliefs about their joint common value signal, if the other strong bidder believes it. However, in equilibrium, such messages are not believed and no belief updating occurs. The assignment of designated bidder is unaffected. Moreover, the model guarantees an *interim* efficient allocation of the designated bidder's role, regardless of whether or not communication is possible.

[24]This setting corresponds to actual industrial cartels, in which cartel members typically have at least some private information that is not verifiable (Marshall and Marx, 2012). For an example, see Asker (2010).

about the private value and common value signal of the other strong bidder.[25] This was required of all subjects, regardless of whether a ring was formed or not. The payoff was calculated by a simple quadratic scoring rule, with a payoff of 200 Coins for a perfect guess.[26] That is, the payoff was determined by function $\max\left\{0, (10000 - (x_{guess} - x_j)^2)/(50)\right\}$ in PVOnly, and $\max\left\{0, (20000 - (x_{guess} - x_j)^2 - (y_{guess} - y_j)^2)/(100)\right\}$ in LoVar and HiVar, where x_{guess} and y_{guess} denote the elicited beliefs.[27]

In Stage 5, cartel members received information about the knockout auction. The knockout bids, the side payment, and the identity of the designated bidder, were displayed on the screen.

The game then proceeded to the main auction in Stage 6. If a cartel was formed in the period, the designated bidder submitted a bid. The computerized weak bidder also submitted a bid equal to her private value. In the final Stage 7, own submitted bids and own payoff for the auction game, except for the payoff of the belief elicitation, were displayed on subjects' screens. That is, at the end of the period, players were informed of (a) their payoff in the main auction if no ring was formed; and (b) their total payoff in the main auction and in the knockout auction if they engaged in collusion.

Subjects' risk aversion was measured using the Holt and Laury (2002) protocol.[28] Subjects made 10 choices between a low-variance and a high-variance lottery. The choices took the form of $p \cdot l_1 + (1-p) \cdot l_2$ vs. $p \cdot h_1 + (1-p) \cdot h_2$, where $h_2 > l_2 > l_1 > h_1$, and where p varied between 0.1 and 1 with 0.1 increments. Values were set at $h_1 = 25$ Coins, $l_1 = 400$ Coins, $l_2 = 500$ Coins and $h_2 = 960$ Coins. The full set of 10 choic es were presented on the same screen and subjects could revise their choices before submitting them. One of the choices was randomly selected to count for the earnings in this task. The number of safe choices of $p \cdot l_1 + (1-p) \cdot l_2$ was

[25]We could have alternatively elicited beliefs after the knockout auction. This would allow us to measure whether correct inferences have been drawn after observing the other bidder's behavior. However, we were more interested in the beliefs about the other player that went into the formation of the knockout auction bids. We were particularly interested in the process of assignment of the designated bidder because of its centrality in determining the efficiency of the outcome. Thus, we sought to focus on the determinants of bids in the knockout auction rather than its implications for subsequent behavior in the main auction.

[26]The exact function did not appear on subjects' instruction sheets, but the functional forms were explained to subjects if they requested that we do so.

[27]Quadratic scoring rules are widely used in experimental economics to incentivize belief elicitation. Brier (1950) shows that they are incentive compatible. See also Selten (1998) as well as Sonnemans and Offerman (2001). Proper Scoring Rules (PSR) have been studied extensively. For an overview, see Armantier and Treich (2013).

[28]The instructions for this task can be found in Appendix E.

taken as our measure of the risk aversion of the individual.

4 Hypotheses

The hypotheses that are evaluated in the experiment are general patterns that are implied by the model in Section 2. The model also makes precise point predictions about bids in both the knockout and main auctions, and by implication the winning bidders and efficiency levels. However, to expect the point predictions from a multi-stage game to accurately characterize behavior of inexperienced bidders in our view is a very demanding standard. The experiment was designed with the intent of evaluating a number of qualitative patterns that emerge from the model. The first prediction of the model is that efficiency is increased on average by the formation of a bidding ring.

Hypothesis 1. *Forming a bidding ring increases the probability of an efficient allocation.*

Hypothesis 1 can be evaluated in two ways. The first is to compare periods in which cartels were formed and not formed with regard to the percentage of periods resulting in an inefficient outcome. This comparison can be conducted for the LoVar and HiVar treatments separately. The second way to evaluate Hypothesis 1 is to compare behavior in periods with a cartel in the HiVar treatment with the NoColl treatment, in which bidding rings were not permitted. While the model predicts greater efficiency under collusion, it must be recognized that a cartel allows an additional potential source of inefficiency, potential misallocation during the knockout auction of the right to bid in the main auction. This can occur if bidders employ heterogeneous bidding strategies in the knockout auction. Furthermore, knockout auction bids might be influenced by misrepresentation of private information during the communication stage, if reported common value signals are believed by other cartel members.

Hypothesis 2 concerns the effect of the spread in the common value signals. In our model, we have shown that the correlation between common value uncertainty and the probability of inefficiency appears when a cartel is present. Because greater common value variance increases the likelihood of an inefficient ordering of composite signals, we also hypothesize that it lowers the efficiency of auctions when no cartel forms as well.

Hypothesis 2. *Greater common value variance has a negative effect on allocative efficiency, both in the presence and the absence of collusion.*

The third pattern derives from Proposition 1 of the model, which states that for any private value or common value signal, a bidder finds it advantageous to join the bidding ring. While the model predicts that all players join a cartel whenever possible, there can be strategic uncertainty about the behavior of the other ring member during the knockout auction or as a designated bidder in the main auction. In light of this uncertainty, some players may prefer to guarantee their ability to bid freely in the main auction by not joining a ring.

Hypothesis 3. *All bidder types join the ring.*

Hypothesis 3 is a stringent prediction and we will say it is supported if a large majority of individuals join the cartel, the likelihood of joining is independent of one's type, and individuals are increasingly likely to join as the game is repeated.

5 Results

The reporting of the results is organized in the following manner. We first, in Subsection 5.1, consider how collusion and the variance of the common value signals influence efficiency, revenue and bid levels. In Subsection 5.2, we examine the decision to join a cartel. Some additional patterns in the communication content, beliefs, knockout bids, and behavior in non-collusive auctions are discussed in Subsection 5.3.

5.1 The effect of collusion on efficiency

Figure 1 shows the average actual and predicted payoffs of the strong and weak bidders, the revenue to the seller, and the efficiency loss relative to the maximum possible level.[29] These variables are expressed in percentages of the maximum possible total surplus. Each of the treatments is displayed separately, and periods in which collusion did and did not occur are also distinguished for the treatments that allow for collusion. The panels on the left illustrate the observed level of these variables and the right side shows the model's predictions.[30]

[29]The measure of efficiency loss in Figure 1 is expressed by $\frac{v_{max}-v_{winner}}{v_{max}}$, where v_{max} corresponds to the valuation of the efficient bidder and v_{winner} is the valuation of the winner of the auction.

[30]In the panels on the right side of Figure 1, the averages are taken over the same periods as those depicted in the corresponding panel on the left of the Figure. Therefore, comparisons of predicted and actual values of the variables control for the different PV and CV signal draws in the different periods.

Figure 1 reveals a number of patterns. The first is that the efficiency loss is greater than in equilibrium under both collusion and competition. The second is that efficiency loss is greater in collusive than in competitive periods in both the LoVar and HiVar treatments. The corresponding t-tests show that in both treatments the difference is significant at the $p < .01$ level. Furthermore, over all periods, mean efficiency loss under HiVar is greater than in the directly comparable NoColl treatment, in which collusion is precluded. The difference is significant at $p < .001$. These patterns indicate a lack of support for Hypothesis 1. In PVOnly, the efficiency loss is also significantly higher ($p < .01$) in the presence of a cartel than in its absence.

The payoffs to the ring are considerably lower than in equilibrium. Payoffs to strong bidders are higher when a cartel forms than when it does not. The ring is able to extract a larger percentage of total surplus in HiVar than in LoVar. Seller revenue, as might be expected, follows the opposite pattern. The seller receives much less if a cartel is formed, and receives higher revenue under LoVar than HiVar. Interestingly, seller revenue is higher and cartel surplus lower when collusion is interdicted than when it is permitted but players choose to bid competitively.

The descriptive analysis does not confirm a negative effect of CV variance on efficiency. Comparing efficiency between periods of HiVar and LoVar, for periods with and without collusion separately, in t-tests, shows no significant difference in efficiency loss at a $p < .05$ significance level. This suggests that support for Hypothesis 2 may not be very strong.

Table 2 contains estimates of the effect of collusion on revenue, cartel payoffs and efficiency loss, controlling for a number of other variables. The observed efficiency level is measured in two different ways. The dependent variable *Efficiency Loss*, or E.L., is the magnitude of the difference between the maximum possible and actual observed welfare. *Efficient* takes value 1 if the winner of the auction is the bidder with the highest valuation and 0 otherwise. The models are applied to Treatments HiVar and NoColl, which have identical parameters.

The first two columns of the table show that revenue is increasing in both the private values and the common value signals of the strong bidders. Permitting collusion lowers revenue, and revenue tends to increase over time. Revenue is also greater, the higher the value of the weak bidder. Columns (3) and (4) indicate the determinants of a bidder i's payoff. A bidder's profit is increasing in her own private value as well as in her own common value signals. The coefficient of the other cartel member's common value

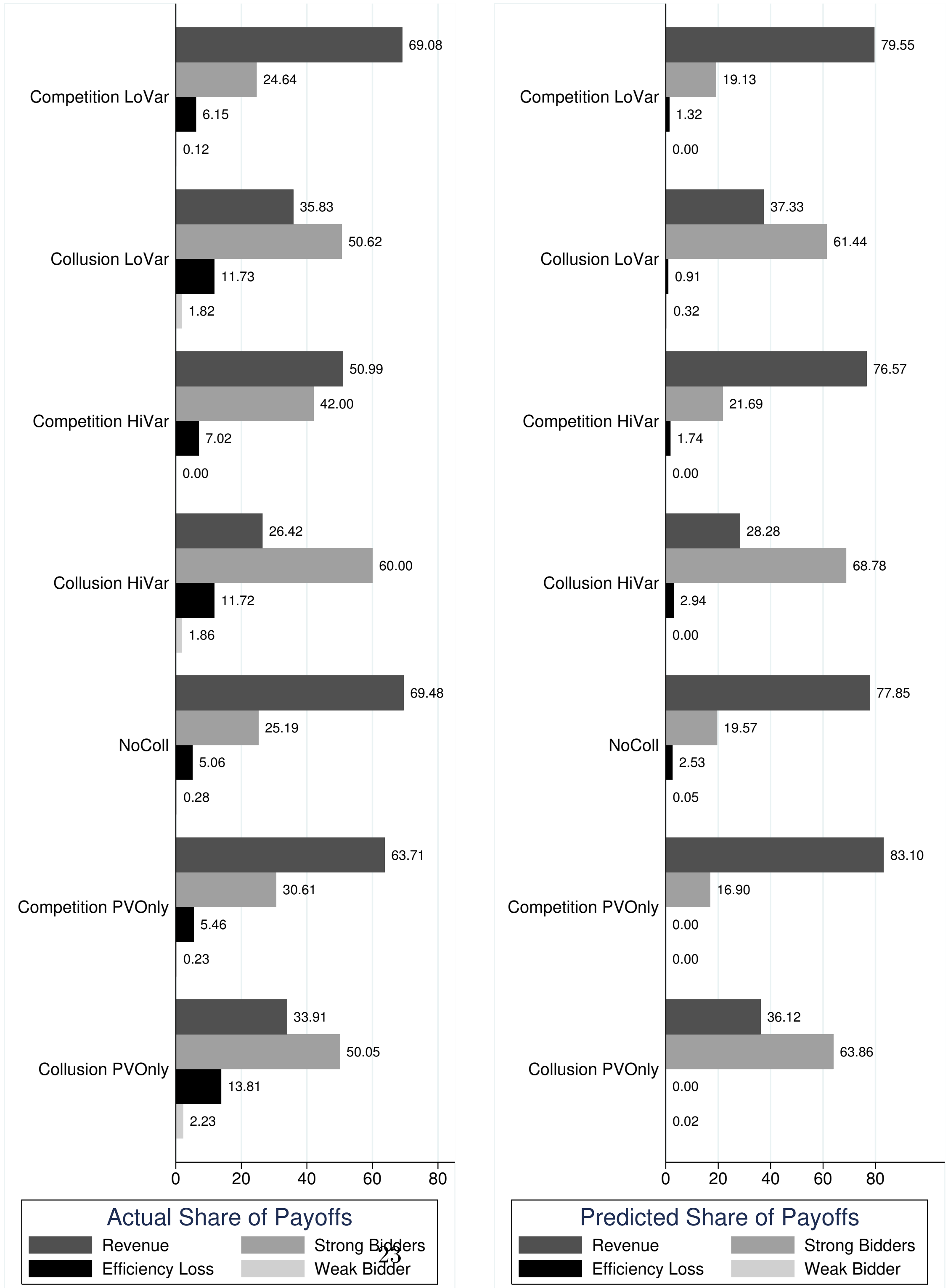

Figure 1: Actual and Predicted Average Revenue, Strong and Weak Bidder Payoff, and Efficiency Loss in each Treatment

signal is positive, but not significant. These three values constitute the three components of her valuation, so the positive coefficients are in line with the predictions. A bidder's payoff is decreasing in the private value of the other string bidder, as well as in the valuation of the weak bidder, two measures of the competitiveness of other bidders. Permitting collusion increases a strong bidder's earnings. The last four columns of the table reveal that on average, permitting collusion decreases efficiency, confirming the impression from Figure 1 and showing a lack of support for Hypothesis 1.

Hypothesis 2 is a claim that the effect of CV uncertainty on efficiency is negative. This is a consequence of our model that arises with or without a bidding ring. Our estimates in Table 3 allow us to evaluate the Hypothesis, while controlling for key variables. The dependent variables are our efficiency measures. The first independent variable $y_H - y_L$ is the range of possible common value signals, which differ between the LoVar and HiVar treatments. The effect on the ranking of subjects' bids is not significant according to columns (1) and (2). Taking a closer look, a greater range significantly increases the probability of an inefficient allocation (columns (3) and (4)) and it reduces efficiency in two relevant specifications (columns (5) and (6)). Other influences on efficiency are the difference between the two private values and the valuation of the weak bidder.

Overall, the evidence weakly supports Hypothesis 2. We find that a larger range of possible common value signals reduces overall efficiency, given that a cartel is formed. Under competition a larger range lowers the probability of an efficient allocation as well as the average level of efficiency. We also observe that a larger absolute difference in the private values of the two bidders leads to a greater likelihood of an efficient designated bidder assignment and final allocation, but a greater average efficiency loss. With a large difference, misassignment of designated bidder or misallocation of the item is less likely, but more costly when it occurs.

5.2 The collusion decision

The next prediction of our model, stated as Hypothesis 3, is that all subjects choose to collude. This implies that the decision to agree to join a ring is independent of private values, common value signals, and other variables. In our experiment, collusion was indeed chosen in the vast majority of cases, 78.21 percent of the time in the LoVar treatment, and 82.1 in HiVar.[31]

Table 4 contains random-effects probit estimates of the determinants of

[31] In PVOnly, 70% chose to collude.

Table 2: Determinants of Revenue, Individual Payoff, and Efficiency, Pooled Data from the HighVar and NoColl Treatments

	(1) Rev.	(2) Rev.	(3) Π_i	(4) Π_i	(5) E.L.	(6) E.L.	(7) Eff.	(8) Eff.
x_i	0.199***	0.205***	0.619***	0.606***	-0.00591	0.0104	0.000407	0.000338
	(0.0535)	(0.0467)	(0.0617)	(0.0596)	(0.0395)	(0.0385)	(0.000411)	(0.000414)
y_i	0.0983***	0.102***	0.312***	0.306***	0.0211	0.0252	-0.0000728	-0.0000914
	(0.0241)	(0.0225)	(0.0280)	(0.0283)	(0.0183)	(0.0182)	(0.000205)	(0.000206)
x_j	0.194***	0.202***	-0.304***	-0.321***	-0.00591	0.0112	0.000421	0.000342
	(0.0481)	(0.0421)	(0.0679)	(0.0640)	(0.0364)	(0.0352)	(0.000411)	(0.000414)
y_j	0.101***	0.108***	0.0688	0.0624	0.0211	0.0252	-0.0000588	-0.0000830
	(0.0258)	(0.0235)	(0.0366)	(0.0344)	(0.0183)	(0.0177)	(0.000206)	(0.000207)
Collusion Allowed	-295.9***	-294.1***	120.9***	120.0***	45.70***	47.35***	-0.369***	-0.362***
	(16.21)	(14.45)	(14.89)	(14.85)	(7.109)	(7.318)	(0.102)	(0.105)
Period		14.86***		-6.459**		-1.421		0.0126
		(1.794)		(2.233)		(1.348)		(0.0161)
c		0.285***		-0.272***		0.182***		-0.000931**
		(0.0471)		(0.0585)		(0.0389)		(0.000328)
Risk Aversion		3.167		-3.893		1.383		-0.0282
		(6.134)		(4.401)		(2.531)		(0.0299)
Constant	349.3***	175.0***	639.7***	774.1***	29.90	-28.96	0.0648	0.414
	(36.08)	(44.73)	(42.06)	(50.25)	(22.19)	(29.34)	(0.269)	(0.317)
Observations	780	780	780	780	780	780	780	780

Panel estimates with subject random effects in (1)-(6). Random effect probit estimates in (7) and (8). R.= Revenue. Π_i = Payoff of bidder i. E.L. = Efficiency Loss relative to optimum. Eff. = Efficiency, dummy variable takes value 1 if allocation is efficient. Robust standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 3: The effect of common value uncertainty on efficiency, pooled data from the LoVar and HiVar treatments

	(1) E.A.S.	(2) E.A.S.	(3) Eff.	(4) Eff.	(5) E.L.	(6) E.L.
$y_H - y_L$	-0.00078	0.000218	-0.00101*	0.000186	0.0473*	0.0784**
	(0.00042)	(0.000268)	(0.00042)	(0.000270)	(0.0239)	(0.0269)
$\lvert x_i - x_j \rvert$	0.00176*	0.0023***	0.00185*	0.00233***	0.216***	0.296***
	(0.0008)	(0.00058)	(0.00081)	(0.000578)	(0.0428)	(0.0570)
Period	-0.0203	0.0148	-0.0388	0.00149	0.732	0.334
	(0.0238)	(0.0186)	(0.0240)	(0.0188)	(1.303)	(1.867)
Risk	0.00760	0.0281	0.00961	0.00728	-1.344	2.498
Aversion	(0.0408)	(0.0381)	(0.0412)	(0.0385)	(2.411)	(3.816)
c	-0.00005	-0.00078*	-0.00022	-0.00174***	0.0536	0.264***
	(0.0005)	(0.00037)	(0.00051)	(0.00038)	(0.0274)	(0.0372)
Constant	0.494	-0.392	0.763*	-0.115	-16.55	-74.02**
	(0.317)	(0.276)	(0.323)	(0.278)	(17.65)	(27.85)
Collusion	No	Yes	No	Yes	No	Yes
Obs.	354	586	354	586	354	586

Random effect probit estimates in (1)-(4). Random effect panel estimates by subject in (5) and (6). E.A.S.: Efficient ranking of bids or efficient choice of the designated bidder between strong players. Eff.: Efficiency, dummy, takes 1 if allocation is efficient. E. L: Efficiency Loss relative to optimum. Robust standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

the decision to collude. The coefficient of composite signal is significant at at least the 5 percent level and negative in all specifications, indicating that higher types are less inclined to join a ring. The coefficients on x_i and y_i reveal that this relationship is true for both the private and common value components of the composite signal. Higher types exhibit a lower willingness-to-collude. Risk aversion has an inconsistent effect. Subjects are less inclined to join in later periods, but the coefficient is significant at the 5 percent level, only in HiVar. Thus, while the model correctly predicts widespread collusion, it exhibits inaccuracies in that cartel participation actually declines over time, and is correlated with values and signals.

5.3 Other patterns in the data

In this subsection we investigate four aspects of the data. Subsection 5.3.1 reports on bidding behavior in auctions in which collusion does not occur. Subsection 5.3.2 concerns communication and truthfulness of information exchanged between cartel members. The effect of the communication on beliefs is studied in Subsection 5.3.3. Finally, Subsection 5.3.4 analyzes knockout bidding strategies.

5.3.1 Bidding behavior when no cartel forms

The regressions reported in Table 5 reveal some determinants of bids in the main auction when no cartel forms. The estimates confirm that own private value and common value signal are significant correlates of bids. Prior participation in cartels lowers bids in subsequent competitive auctions, perhaps because of a carry-over of low bidding from the cartel periods. The variable *Collusion Percentage* is the fraction of the preceding periods in which the subject was a cartel member. The coefficient estimate for this variable is negative and significant at the 5 percent level for all treatments. That is, exposure to collusion makes subjects bid less aggressively in competitive auctions.

Table 5 also shows that bids increase over time in competitive periods as individuals presumably learn that competitive periods are different from those in which a cartel forms, and necessitate higher bidding. Learning to bid higher over time is more rapid in NoColl, in which individuals have more exposure to competitive auctions. The coefficients on the private value and the common value signal are greater in NoColl than in the HiVar treatment. Overall, as illustrated in Figure 1, revenue, bidder surplus, and allocative

Table 4: Determinants of the Willingness-to-Collude

	(1) LoVar	(2) HiVar	(3) LoVar	(4) HiVar	(5) PVOnly
Collusion Decision in period $t-1$	0.359 (0.222)	0.0892 (0.332)	0.354 (0.224)	0.115 (0.335)	0.0410 (0.273)
s_i	-0.00235*** (0.000669)	-0.00151* (0.000709)			-0.00325*** (0.000852)
Risk Aversion	0.339** (0.109)	-0.299* (0.132)	0.352** (0.116)	-0.291* (0.132)	-0.00183 (0.131)
Period	-0.0199 (0.0303)	-0.103* (0.0420)	-0.0222 (0.0310)	-0.105* (0.0424)	-0.0323 (0.0365)
x_i			-0.00153* (0.000741)	-0.00290** (0.00103)	
y_i			-0.00307*** (0.000791)	-0.0000602 (0.000503)	
Constant	0.807 (0.600)	4.316*** (1.020)	0.870 (0.628)	4.569*** (1.040)	2.785** (0.882)
Observations	504	342	504	342	288

Robust standard errors in parentheses. Composite value equals x_i in PVOnly Treatment.
Random effects probit estimates.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 5: Influences on bids in periods with no cartel

Treatment	(1) LowVar	(2) HighVar	(3) NoColl	(4) PVOnly
x_i	0.605***	0.315	0.494***	0.721***
	(0.132)	(0.172)	(0.0796)	(0.0677)
y_i	0.279**	0.236*	0.318***	
	(0.105)	(0.106)	(0.0467)	
Risk Aversion	-6.935	-9.464	-0.920	-31.24
	(10.40)	(15.79)	(8.325)	(20.16)
Period	12.41**	17.71**	20.87***	10.83**
	(4.575)	(6.532)	(2.489)	(3.786)
Collusion Percentage	-166.6***	-210.8*		-161.8**
	(43.19)	(92.23)		(55.49)
Constant	290.0**	377.3*	239.9***	210.1
	(97.30)	(182.8)	(68.48)	(112.1)
Observations	210	116	400	152

Random effects panel estimates on competitive bids. Collusion Percentage: Share of previous periods in which i was ring member. Robust standard errors are in parentheses.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

efficiency in NoColl are close to those predicted in our model.[32]

5.3.2 The content of communication

If the strong bidders have agreed to form a cartel, they have the opportunity to chat. This chat can be used in a cooperative manner to ensure that the more advantaged bidder wins the knockout auction at an appropriate price. It can also be used strategically to attempt to convince the other bidder to bid lower in the subsequent knockout auction. This can be done by attempting to mislead the other bidder into thinking that one's common value signal is lower that it really is, so that the other bidder has more pessimistic beliefs about her own valuation. The content of communication

[32]The predicted private value coefficients in our theoretical model are 1.1996 in LoVar and 1.5042 in HiVar. The predicted common value signal coefficients are 0.6633 and 0.7523, respectively. Thus, the sensitivity of bids to private values and common value signals is less than predicted by the model.

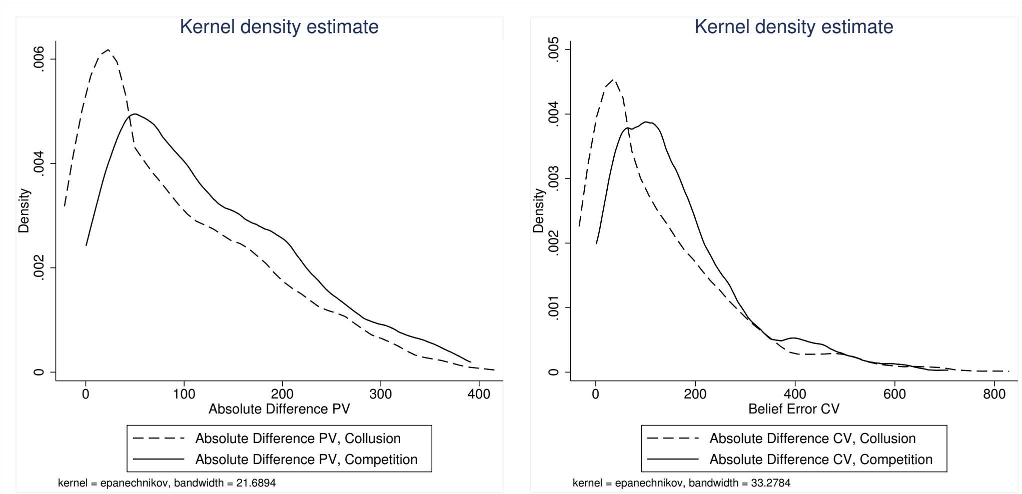

Figure 2: Belief updating and its effects

in this phase is not verifiable, since at no time do bidders ever learn the private information of the other cartel member.

Among groups forming a cartel, 90 percent make an explicit attempt to communicate during the chat stage, in the sense that at least one cartel member makes a claim about either their private value or common value signal, or initiates an attempt at an explicit agreement. Among those who make an attempt to communicate, 62.5 percent manage to reach an agreement or to share private information.

Most ring members make claims about their types in their chat. There are 457 instances in which a player reports a private value to the other party and 393 instances of a common value signal report. The influences on these claims are reported in Table 6. All specifications include the LoVar and HiVar treatments.

The coefficients of common value signals are highly significant determinants of the reports of these variables. The other variables in the regression are not significant, with the exception of risk aversion and one's own earnings in the preceding period. Estimates on the constant term and on y_i show that subjects underreport their CV signals. This is consistent with strategic communication, since beliefs about the other bidder's common value signals are a component of their beliefs about their own valuation. A lower assessment of the other bidder's common value signal would prompt a bidder to bid lower. Risk aversion and earnings in the previous period are also signif-

Table 6: Claimed private and common values, pooled data from treatments LoVar and HiVar

	(1)	(2)	(3)	(4)
	Claim x_i	Claim x_i	Claim y_i	Claim y_i
x_i	0.0679	0.0785		
	(0.0436)	(0.0444)		
y_i			0.574***	0.529***
			(0.0654)	(0.0727)
Period	2.788	3.553	4.200	3.651
	(2.129)	(2.400)	(2.474)	(2.772)
Risk Aversion	0.0728	-0.300	12.15*	15.02*
	(3.960)	(3.999)	(6.083)	(6.724)
Π_{t-1}		-0.00765		0.112**
		(0.0346)		(0.0393)
Collusion		-16.86		7.219
in $t-1$		(14.97)		(13.47)
Constant	325.8***	338.0***	32.41	-80.94
	(26.90)	(45.77)	(28.73)	(45.69)
Observations	380	360	393	371

Random effect panel estimates by subject. Robust standard errors in parentheses.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

icant factors, but the estimated effects associated with these variables are small.

The coefficients of the private value are positive but low, and they are only significant at 10 percent level. Furthermore, the intercept is substantially above 0. This lack of truthful reporting of private values may reflect attempts to behave strategically in the belief that keeping one's private value information to oneself can be beneficial.

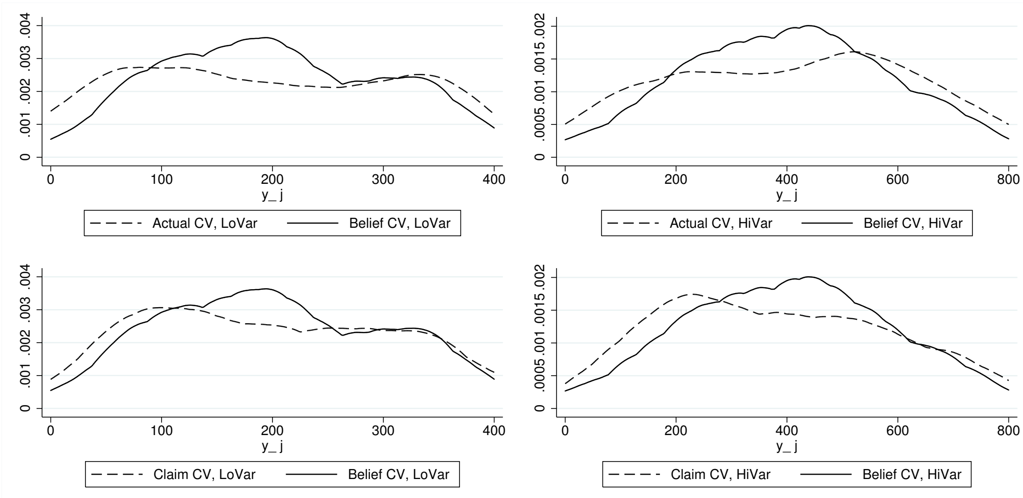

Figure 3: Claims, beliefs, and the true distribution of common value signals, kernel density estimates

5.3.3 Beliefs

As we have seen, there is widespread misreporting of both private values and common value signals during the communication stage. The subsequent belief elicitation stage allows us to measure whether these reports were believed.

The two graphs in Figure 2 show Epanechnikov kernel density estimates of the distribution of the reported and actual distributions of the PV and CV signals, in both collusive and competitive periods, for the pooled data from the LoVar and HiVar treatments. The left graph depicts the private value, while the right one depicts common value beliefs. The distributions illustrate the absolute differences between elicited beliefs and the corresponding actual values. The mean difference between actual values and elicited beliefs is 125.4 and 93.4 under competition and collusion for the PV, and 157.7 vs 125.7 for the CV signal. The Kolmogorov-Smirnov test rejects that the distributions are identical at significance level 0.1 percent. That is, the performance of subjects in the belief elicitation stage is improved if they engage in collusion and explicitly communicate, indicating that there is a leakage of private information during the communication stage.[33]

[33]The payoffs in the belief elicitation stage also indicate that collusion improved the accuracy of beliefs. The mean payoff in the belief elicitation stage was 44.91 under com-

The improvement likely stems from the fact that subjects take the claims of others into account when formulating their own beliefs. However, we have seen in Subsection 5.3.2 that claims in the communication stage tend to be highly strategic. Figure 3 shows that these claims are only partially believed. The upper panels in the Figure compare the submitted beliefs about the other cartel member's CV signal to the objective distribution. The panel on the left contains the data from the LoVar treatment and the one on the right displays the data from HiVar. They show that the beliefs are on average unbiased, though beliefs are more concentrated toward the center of the distribution than they should be. The bottom panels illustrate the contrast between the claims and the beliefs. The Figure reveals that there is a tendency for low reports to be disbelieved, as the density of reported low signals tends to be greater than the density of beliefs.

Table 7 reports estimates of the determinants of beliefs.[34] Coefficients on x_j or y_j would equal zero if the claims of bidder j were not believed at all, and would equal 1 if all claims are accepted literally. Clearly, the coefficients of the communicated private values and common value signals on beliefs about these variables are significant at conventional levels for all treatments. This shows that claims are at least partially believed. However, the coefficients are also all significantly less than one, which means that they are not taken at face value.

5.3.4 The knockout auction

Our model makes predictions of the bids in the knockout auction and we compare the observed data to these predictions. Correlates of knockout bids are identified in the random effects regressions reported in Table 8. The estimates show that knockout bids are increasing in one's own private value, which is predicted in our model and associated with greater efficiency. However, the value of the constant is positive, and the coefficients on PV and CV signal are significantly lower than the model's prediction. This means that the bidding function is flatter in its key arguments than predicted.[35] Beliefs

petition and 88.37 under collusion.

[34]The individuals coding the chat data were instructed to identify certain additional variables. These included (a) groups in which explicit agreement or disagreement occurred, (b) claims about one's own private value or common value signal, (c) suggestions about one's own knockout bid or the other cartel member's knockout bid. The most common of these events are reports about one's own PV or CV signals.

[35]We have run alternative specifications including own private and common values as regressors. The estimates are not significant except for the coefficient of y_i on the beliefs about y_j, and only in LoVar. The estimated coefficient is low, 0.16.

Table 7: Belief updating and its effect

	(1) Belief x_j	(2) Belief y_j	(3) Belief x_j	(4) Belief y_j	(5) Belief x_j
Treatment	LoVar	LoVar	HiVar	HiVar	PVOnly
Claim x_j	0.780***		0.605***		0.656***
	(0.0683)		(0.0675)		(0.173)
Claim y_j		0.771***		0.649***	
		(0.0425)		(0.0875)	
Period	1.685	0.393	-5.019	-2.154	-8.835**
	(1.970)	(1.566)	(2.939)	(4.333)	(2.732)
Risk Aversion	1.464	-2.556	5.315	11.86	5.186
	(1.982)	(3.285)	(6.976)	(11.74)	(4.698)
Constant	63.04	55.80**	148.9***	104.8**	234.4*
	(33.58)	(18.81)	(34.67)	(36.62)	(93.26)
Observations	240	238	139	143	60

Random effect panel estimates by subject. Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

about the other cartel member's common value signal are also correlated with higher bids, as the model predicts.[36]

Coefficients of own type and beliefs about the type of the other subject are significant and consistent with the model. The insignificant effect of the belief about the PV of the other bidder is also consistent with the model since this variable does not affect a bidder's own valuation. The marginal effect of the private value is lower than 0.2 in all specifications, significantly lower than in equilibrium.The time trend is significant at the 1 and 5 percent levels, respectively in the two specifications. In model (4), this corresponds to an estimated overall increase of 65.1 of the knockout bid on average from the first to the last period of a session.

The distribution of payoffs between strong bidders is a motivating factor behind the decision to join the ring. Table 9 contains the average payoffs of designated and non-designated bidders in the relevant treatments, compared to the predicted levels. High-type bidders have a greater chance to win the knockout and become designated bidder. The non-designated bid-

[36]The predicted coefficients for own private value are 0.4568 in LowVar and 0.5488 in HiVar. The predicted coefficients of the common value signal are 0.2284 and 0.2744 in the same treatments.

Table 8: The effect of private information and beliefs on knockout bids

	(1) LoVar	(2) HiVar	(3) PVOnly
x_i	0.166*	0.169**	0.269*
	(0.0721)	(0.0593)	(0.112)
y_i	0.0801	0.0462	
	(0.0465)	(0.0275)	
Belief	0.0658	0.0503	-0.0119
x_j	(0.0565)	(0.0899)	(0.138)
Belief	0.174**	0.0445	
y_j	(0.0647)	(0.0479)	
Period	2.507	12.64***	0.630
	(3.258)	(2.937)	(4.494)
Risk Aversion	-6.037	4.563	9.033
	(7.762)	(8.046)	(18.61)
Constant	114.0	77.88	86.79
	(59.57)	(52.64)	(166.9)
Observations	332	254	156

Random effect panel estimates by subject.
Standard errors in parentheses.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 9: Mean payoffs of the designated and non-designated bidders within the bidding rings

	Designated Bidder		Non-designated Bidder	
	Actual	Prediction	Actual	Prediction
PVOnly	119.43	240.25	204.12	177.48
LoVar	168.72	242.01	180.16	177.72
HiVar	294.13	310.31	229.65	291.63

der receives the side payment. In the periods in which a ring is formed, the averages reported in Table 9 show that the designated bidder receives less than in equilibrium. The opposite is true for the non-designated bidder, except under HiVar. Comparing the realized payoff of the two ring members, the designated bidder receives significantly less in PVOnly, marginally less in LoVar and more in HiVar. The lower than predicted earnings of the designated bidders may account for the relatively high likelihood that bidders with high values abstain from collusion, since these bidders are likely to become designated bidders.

6 Conclusion

Many goods that are sold by auction have a value to bidders that is determined by both their individual tastes and a component that is only partially known at the time of bidding. Information that others have about this second component is helpful to a bidder in formulating more accurate estimates about the good's final value. Under such conditions, inefficiency may arise because the bidder with the highest valuation may receive a relatively low common value signal and fail to win the auction. It is well-known that under such conditions, reducing the uncertainty about the common value component increases the average efficiency of the allocation.

One way to decrease the uncertainty about the common value component is to let bidders collude. Information can be exchanged, bidders can transfer side payments to each other, and a designated bidder can be chosen in a manner that increases efficiency. The theoretical model that we propose describes how this would work. The model describes a situation in which two bidders have an opportunity to form a cartel and jointly bid against a weak bidder. A knockout auction determines which bidder is designated to bid and the side payment the other bidder receives.

Our model makes three main predictions. The first is that efficiency increases in the presence of a cartel. The second is that an increase in common value uncertainty decreases the efficiency of the final allocation under a cartel. The third is that all potential bidders join the cartel, regardless of their private information.

We report an experiment designed to test the three predictions. We find that a large majority of individuals do choose to join a cartel. The principal inaccuracy of our model is a tendency for bidders with higher valuations to sometimes forego cartel participation, and it appears rational to do so in light of the relatively small empirical payoffs of designated cartel bidders. Comparison of the LoVar and HiVar treatments yields some evidence that inefficiency is greater in HiVar, where the common value signal variance is greater, than in LoVar. However, we observe that the level of inefficiency is actually greater when a cartel forms than when it does not, indicating that this prediction of the model is not borne out. It appears that frictions in the collusion process, which involves more stages in which inefficiency can potentially appear, account for this pattern.

An additional treatment, NoColl, is identical to HiVar except that collusion is not permitted. The NoColl treatment generates higher prices than the HiVar treatment, even in those trials of HiVar when a cartel was not formed. This pattern suggests that prior experience with the low prices in a cartel has a carryover effect that leads to less aggressive bidding and higher payoffs to bidders in subsequent competitive auctions.

The PVOnly treatment, in which bidder valuations have only a private value component, leads to less cartel formation than the LoVar and HiVar treatments. This may reflect a recognition on the part of bidders that a cartel can be helpful to members in learning about their own valuations, a motivation that does not exist in PVOnly. Indeed, in PVOnly, collusion lowers efficiency quite substantially.[37]

The experiment also identifies a number of consistent behavioral patterns beyond our model's predictions. Communication between colluding bidders tends to be strategic, and bidders underreport their common value signals. These reports tend to be greeted with skepticism and only partially believed. Nevertheless, reported private values and signals are increasing in their true values, resulting in a significant improvement of beliefs under collusion. In the knockout auction, there is some heterogeneity in behavior among bidders, perhaps reflecting a preference of some bidders to be desig-

[37]While the PVOnly treatment can be viewed as a special case in which our model can be applied, it is a setting in which a key element of the model, the common value component, does not exist.

nated bidders in the main auction and a preference of some others to leave the bidding to the other party. Thus, while it is possible that efficiency is increased by the information exchange within the cartel, it is offset by inefficiencies created by the system of allocation of the role of designated bidder for the main auction, and of the side payment to the other cartel member. Our design has features that would enhance the efficiency of the cartel. In particular, the designated bidder was allocated endogenously and communication allowed for pooling of private information. Despite this, we found that collusion lowered efficiency. Allowing collusion hurts sellers, by depressing bids and revenue, even in auctions where a cartel does not actually form. While bidders gain additional surplus, this remains below predicted levels.

Our findings have practical relevance. Sharing sensitive information between competitors is generally seen as an indicator of anticompetitive behavior and a red flag. As such, it is subject of scientific and policy debate whether evidence of direct communication between firms can be identified as a good reason for starting a costly investigation. Bidding markets have the special characteristic that output is preset by a decision maker and the efficiency of the game's outcome is determined by an allocation mechanism. Our theoretical model shows that in such a setting, information sharing with a cartel actually improves equilibrium welfare compared to the competitive outcome. This result is in line with the Dutch construction cartel's testimonial in 2002 in which they claimed that their communication was welfare-enhancing (Boone, Chen, Goeree, and Polydoro, 2009).

Using unrestricted communication and a collusive mechanism mimicking actual cartels, we apply a fairly realistic and flexible design to test our theoretical predictions. However, the laboratory data shows that the hypothesis of a positive effect of collusion on efficiency can be soundly rejected. Hence, the policy implication of our paper is that there is no strong argument in favor of allowing free communication between bidders in auction markets. We find no compelling evidence in favor of permitting bidders to collude on efficiency grounds.

In this study, we have only investigated cartels with two members. One important extension would be to consider cartels with more than two bidders. As the number of bidders grows, it becomes more important to suppress competition and information sharing becomes more valuable. However, one would expect the knockout auction to function less effectively. This means that bidders with high signals might be more likely to opt out of collusion. Our argument is supported by the results of Kwasnica and Sherstyuk (2007) who find that a greater number of bidders significantly limits the probability of cartel formation. The knockout auction would need to be modified to allow for more than two bidders (Seres, 2017).

It is important to note that our model does not cover all possible types of collusion. In the environment we have studied, collusion improves the bidders' prospects through both information sharing and the fact that it enhances the market power of the cartel. The information sharing allows individuals to more effectively designate the appropriate bidder, and the withdrawal of one bidder lowers the price that can be obtained by the designated bidder. Some potential alternative cartel mechanisms might conceivably make use of only one of the two benefits. A system whereby the designated bidder was chosen randomly among cartel members would be able to increase market power, and might be effective if the item sold has a common value to all bidders. However, in our environment, it may inefficiently appoint a designated bidder with a relatively low composite signal. We are unaware of any cartel that has employed such a rule. On the other hand, information sharing followed by a competitive bidding process might increase efficiency in that it makes it more likely that the bidder with the higher composite signal would win the auction, but, if anything, it would increase the price paid and damage the cartel. Most actual bidding rings do engage in some form of communication (Marshall and Marx, 2012).

Online Supplemental Material

There are six appendices. The first appendix is a proof of the claim that equation (2) is part of a Bayesian equilibrium strategy profile of the subgame in which there is no collusion. The second contains a graphical illustration of the fact that collusion is optimal for all strong bidder types (Appendix B). The third consists of the instructions for the experiment (Appendix C). The fourth contains the control questionnaire (Appendix D). Appendix E reproduces the instructions for the second part of the experiment, in which risk preferences were elicited. The instructions for the individuals coding the chat data are given in Appendix F.

Appendix A Proof to Accompany Equation (2)

Suppose that j and the weak bidder follow $b^*(\cdot)$ and i bids $b > b^*(s_i)$. We show that this is not a profitable deviation. Compared to $b_i^*(s_i)$, this only changes the payoff if the higher of $b_j^*(s_j)$ and c fall between b and $b_i^*(s_i)$. That is, the difference between the expected payoff under the deviation and under $b_i^*(s_i)$ equals:

$$\pi(b) - \pi(b_i^*(s_i)) = \int_{s_j=s_i}^{b_j^{*-1}(b)} \int_{c=c_L}^{b_j^*(s_j)} s_i + \frac{1}{2}E[y_j|s_j] - b_j^*(s_j)\, dc\, dH(s_j) + \int_{s_j=x_L+\frac{y_L}{2}}^{b_j^{*-1}(c)} \int_{c=b_j^*(s_j)}^{b} s_i + \frac{1}{2}E[y_j|s_j] - c\, dc\, dH(s_j) \tag{17}$$

The first term in (17) corresponds to the case where $b_j^*(s_j)$ is greater than both $b_i^*(s_i)$ and c but less than b. In this case bidder i has bid higher than $b_i^*(s_i)$ and pays an amount, $b_j^*(s_j)$, exceeding her expected valuation. The second term refers to the situation where the weak bidder has bid more than both $b_i^*(s_i)$ and $b_j^*(s_j)$ but less than b, another case in which bidder i pays c, which is in this instance more than her expected valuation. We now show that $\pi(b) - \pi(b_i^*(s_i))$ is always non-positive, and thus that there is no incentive to deviate from $b_i^*(s_i)$ by bidding higher.

Define $m = \max\{b_j^*(s_j), c\}$ and rewrite (17) as

$$\pi(b) - \pi(b_i^*(s_i)) = \iint\limits_{b_i^*(s_i)<m<b} s_i + \frac{1}{2}E[y_j|m] - m\, dc\, dH(s_j) \tag{18}$$

First, let us note that $E[y_j|m]$ may come from $m = b_j^*(s_j)$ or $m = c$. Second, the conditional probability of observing $m = b_j^*(s_j)$ is $t(s_j) = t(b_j^{*-1}(m))$. From this, (18) becomes

$$\iint\limits_{b_i^*(s_i)<m<b} s_i + \frac{1}{2}(t(b_j^{*-1}(m))E[y_j|s_j = b_j^{*-1}(m)]$$

$$+(1-t(b_j^{*-1}(m)))E[y_j|s_j < b_j^{*-1}(m)]) - m\,dc\,dH\,(s_j) \qquad (19)$$

Substituting the equilibrium bidding function of the other strong bidder j into (19) yields

$$\iint\limits_{b_i^*(s_i)<m<b} s_i + \frac{1}{2}(t(b_j^{*-1}(m))E[y_j|s_j = b_j^{*-1}(m)]$$

$$+(1-t(b_j^{*-1}(m)))E[y_j|s_j < b_j^{*-1}(m)]) - b_j^*(b_j^{*-1}(m))dcdH(s_j)$$

$$= \iint\limits_{b_i^*(s_i)<m<b} s_i + \frac{1}{2}(t(b_j^{*-1}(m))E[y_j|s_j = b_j^{*-1}(m)] + (1-t(b_j^{*-1}(m)))E[y_j|s_j < b_j^{*-1}(m)])$$

$$-b_j^{*-1}(m) - \frac{1}{2}(t(b_j^{*-1}(m))E[y_i|s_i = b_j^{*-1}(m)] + (1-t(b_j^{*-1}(m)))E[y_i|s_i < b_j^{*-1}(m)])\,dc\,dH\,(s_j)$$

$$= \iint\limits_{b_i^*(s_i)<m<b} s_i + \frac{1}{2}(t(b_j^{*-1}(m))E[y_j|s_J = b_j^{*-1}(m)] + (1-t(b_j^{*-1}(m)))E[y_j|s_j < b_j^{*-1}(m)])$$

$$-b_j^{*-1}(m) - \frac{1}{2}(t(b_j^{*-1}(m))E[y_j|s_j = b_j^{*-1}(m)] + (1-t(b_j^{*-1}(m)))E[y_j|s_j < b_j^{*-1}(m)])\,dc\,dH\,(s_j)$$

$$= \iint\limits_{b_i^*(s_i)<m<b} s_i - b_j^{*-1}(m)\,dc\,dH\,(s_j) \leq 0 \qquad (20)$$

The weak inequality holds since in the situation described in (17), in which $b \geq \max\{b_j^*(s_j), c\} > b_i^*(s_i)$, that at least one of the two following inequalities must hold (a) $s_i < s_j < b_j^*(s_j)$ or (b) $s_i < b_i^*(s_i) < c$.

We have shown that no deviation b, where $b > b_i^*(s_i)$, is profitable. We now argue that any deviation $b < b_i^*(s_i)$ is also not profitable. The logic is similar to the case of $b > b_i^*(s_i)$. If $b < b_i^*(s_i)$, the payoff of i only changes from that under $b_i^*(s_i)$ if the larger of $b_j^*(s_j)$ and c is smaller than $b_i^*(s_i)$, but larger than b. Conditional on being type s_i, the difference between the expected payoff from bidding b and the expected equilibrium payoff is

$$\pi(b) - \pi(b_i^*(s_i)) = -\int_{s_j=b_j^{*-1}(b)}^{b_i^*(s_i)} \int_{c=c_L}^{b_j^*(s_j)} s_i + \frac{1}{2}E[y_j|s_i = s_j] - b_j^*(s_j)\, dc\, dH\,(s_j)$$
$$- \int_{s_j=x_L+\frac{y_L}{2}}^{b_j^{*-1}(c)} \int_{c=b}^{b_i^*(s_i)} s_i + \frac{1}{2}E[y_j|s_i = s_j] - c\, dc\, dH\,(s_j)\,. \quad (21)$$

Again, using $m = \max\{b_j^*(s_j), c\}$, (21) becomes

$$- \iint_{b<m<b_i^*(s_i)} s_i + \frac{1}{2}E[y_j|m] - m\, dc\, dH\,(s_j)$$

$$= - \iint_{b<m<b_i^*(s_i)} s_i + \frac{1}{2}(t(b_j^{*-1}(m))E[y_j|s_j = b_j^{*-1}(m)] + (1-t(b_j^{*-1}(m)))E[y_j|s_j < b_j^{*-1}(m)])$$

$$-b_j^{*-1}(m) - \frac{1}{2}(t(b_j^{*-1}(m))E[y_j|s_j = b_j^{*-1}(m)] + (1-t(b_j^{*-1}(m)))E[y_j|s_j < b_j^{*-1}(m)])\, dc\, dH\,(s_j)$$

$$= - \iint_{b<m<b_i^*(s_i)} s_i - b_j^{*-1}(m)\, dc\, dH\,(s_j) \leq 0. \quad (22)$$

The expression in equation (22) is negative since the integrand is positive. This can be seen since in the region considered $s_i > s_j = b_j^{*-1}(m)$.

Appendix B Expected Payoff in Collusive and Competitive Auctions

A bidder's *interim* expected payoff is higher when a ring is formed than when it is not, if

$$\int_{s_j=x_L+\frac{y_L}{2}}^{s_i} \left(\bar{\Pi}\,(s_i, s_j) - k^*\,(s_j)\right)\, d\,H\,(s_j) + \int_{s_j=s_i}^{x_H+\frac{y_H}{2}} k^*(s_i)\, d\,H\,(s_j) \geq \widehat{\Pi}(s_i).$$

When this condition holds, all bidder types join the ring in equilibrium. The condition is satisfied in all of our treatments in which collusion is possible. This result is illustrated in Figure 4, which depicts the *interim* expected payoff under collusion (solid line) and under competition (dashed line), as a function of composite signal (surplus).

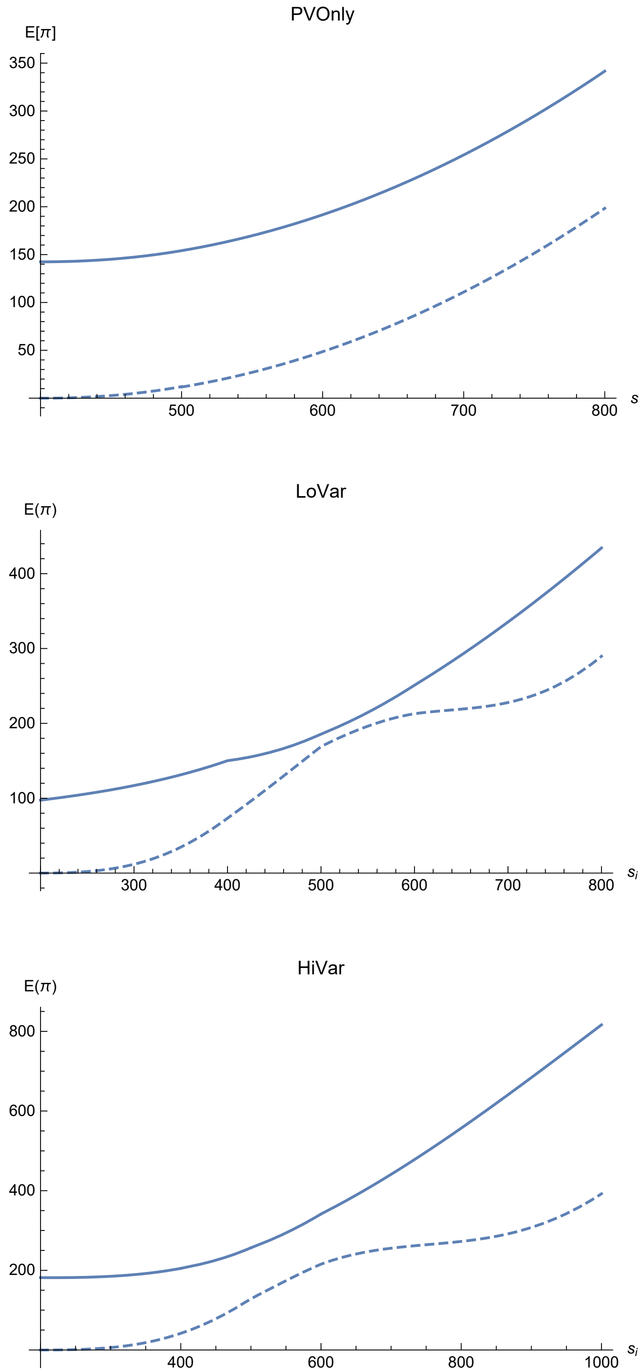

Figure 4: Predicted Expected Payoff in PVOnly, LoVar and HiVar under Collusion (Solid Line) and Competition (Dashed Line) as a Function of Composite Signal (Surplus)

Appendix C Instructions for the Experiment

The following session is an experiment in decision-making. The instructions are written here and read out loud before we start. If you follow them and depending on your decisions, you can earn a considerable amount of money, which will be transferred to you after the end of the experiment. The amount of payment you receive depends on your decisions, on the decisions of others, and on chance. Your ID number for the experiment is the computer ID you can find next to you. The entire experiment is anonymous, so we will use this ID to call you when the payments are paid out at the end.

The currency used in the experiment is *Coin*. All amounts will be expressed in terms of Coin. The cash payment at the end of the experiment will be given to you in Euro. The conversion rate is 100 Coins to 1 Euro. Once the experiment has started, no one is allowed to talk to anybody other than the experimenter. If you have a question please raise your hand and we will go to your place. During the entire experiment, please remain seated.

The experiment consists of two parts. Your final payment will be the sum of your payments for these two parts. In the following you will learn the details of the first part.

Auction experiment

The experiment will consist of a sequence of 11 rounds in which you participate in an auction where you can bid for an object X. Of these 11 rounds, the first one will be for practice and the other 10 might count towards your payment. At the beginning of each round, you will begin with an endowment of 800 Coins. A round's outcome is independent from other rounds. So, your payment in any given round will not be affected by your or others' decisions in other rounds.

In each round, you are randomly paired with an anonymous other participant in the room. That is, we will never tell you the identity of the participant you are paired with. Neither will we tell the other participant your identity. When a new round starts, new pairs are formed, and everyone in the room has equal chance to be paired up with you.

Before the auction takes place, you are allowed to communicate with the other bidder in your group and to make an agreement. The following list summarizes the timing of each round; you can read the details below.

1. *Redemption value*: In the first stage you learn values A_{you} and B_{you} affecting your *redemption value*. If you acquire a unit of X, you can

redeem it for Coin. The amount of Coins that a unit of X gives you is called your *redemption value*.

2. *Decision*: You are asked about your willingness to cooperate with the other bidder in your group. If you both reply 'Yes', you continue with the *Chat stage*. In other words, no agreement is made unless both of you wants to make one.

3. *Chat*: If you and the other bidder decide to cooperate, you can chat and make an agreement.

4. *Guessing game*: You are asked to guess the redemption value of the other bidder in the group.

5. *Agreement*: If you and the other bidder decide to cooperate, and make an agreement, you can read the details of this agreement on your screen.

6. *Auction*: The auction takes place.

7. *Results*: You can read the final results of the round.

Redemption value

In the auction you are bidding for a good called X with the other bidder and a computerized bidder.

If you acquire the good in the auction, you redeem it for your *redemption value*. The *redemption value* can be different for bidders in the same auction. Your redemption value will be denoted by R_{you}. Now we explain how is it calculated.

You and the other human bidder are given two random numbers privately, denoted by A and B. A is between 200 and 600 Coins, B is between 0 and 400 Coins. Your and the other bidder‘s numbers are denoted by A_{you}, A_{other}, B_{you} and B_{other}. These numbers are integers, and all possible numbers have an equal chance of being drawn. All numbers are independently drawn.

Your *redemption value* is calculated from these numbers. Before the auction, you only know A_{you} and B_{you} but you do not know A_{other} and B_{other}. Similarly, the other player knows A_{other} and B_{other}, but does not know $A_{you}$and B_{you}.

Your redemption value is calculated from A_{you}, B_{you} and B_{other} as:

$$R_{you} = A_{you} + \frac{B_{you} + B_{other}}{2}$$

Similarly redemption value of the other human bidder is:

$$R_{other} = A_{other} + \frac{B_{you} + B_{other}}{2}$$

That is, the first component is different for you and the other human bidder. The second one, $\frac{B_{you}+B_{other}}{2}$ is the same, and determined by B_{you}, which only you can see, and B_{other}, which only the other bidder can see.

Decision

Before the *auction* takes place, you are allowed to chat with the other human player, and you can make an agreement. Participation at the *decision* stage depends on your and the other player's decision. A question appears in each round and your answer only affects that particular round.

The following question appears on your screen. 'Do you wish to cooperate with the other bidder in your group?' If you both reply 'Yes', you continue with the *chat* stage. If at least one of you replies 'No', you proceed to the *guessing game* and to the *auction*. In other words, no agreement is made unless both of you wants to make one.

Chat

If you both replied 'Yes' at the *decision* stage, a chat box and a proposal box appear. In the chat box you send a message by pressing the [Enter] button on your keyboard. You have 90 seconds available for chat. During that time, you are allowed to talk about the numbers you observed (A_{you}, B_{you}) and you can agree on a strategy for the remainder of the round. The other player in your group is able to see the message that you send, but nothing more. So he or she cannot see on the screen whether you write the truth.

You are free to discuss whatever you like except: Do not use any words or phrase which helps to identify you. Only communicate in English. In case you violate these rules, you must leave the experiment and you receive no payment.

You leave the chat by making a proposal to other player in your group next to the text 'Please, make your proposal!'. By clicking OK, you leave the chat. The purpose of this part of the round is to decide who will participate in the auction and how much compensation the other participant should get for not participating.

In the bracket 'Make your proposal', you are allowed to type a number, which is not bigger than your endowment. The one making the higher proposal has to pay *the lower of the two amounts* (in other words, the second highest proposal) to the other player, which is deducted from her endowment. If the numbers are equal, one of you is chosen with equal chance to do so. If you receive a payment, you do not participate in the auction, and your bid will be automatically 0. The payoff of this round is:

$$\text{payoff} = \text{endowment} + \text{smaller proposal}$$

The other player participates in the auction with the computerized bidder with:

$$\text{balance} = \text{endowment} - \text{smaller proposal}$$

The proposal part can make two things possible for your group. First, you can share information during chat. Second, you can decide who should participate in the auction. If an agreement is made, one of you who pays can have only one opposing bidder, the computer.

Guessing game

The next stage is a guessing game in which everyone participates, even the pairs who decided not to cooperate. On your screen you can see two questions and two brackets in which you are asked to write numbers. These are 'How much do you think A_{other} is?' and 'How much do you think B_{other} is?'

In the brackets, you are asked to guess the numbers of the other player in your group. The available information to you is what you can have read in the instructions and what the other player writes to you during the chat. There is an extra payment for guessing right. The closer your guesses are to the actual number, the more you earn. This amount is not added to your balance in this round, but it is counted at the end of the experiment if the round is the one that counts. The maximum you can earn with guessing is 200 Coins, with a perfect guess.

For example, if $A_{other} = 550$, $B_{other} = 200$ and your guesses are 550 and 200, your payoff is 200 Coins for the guessing game. Your payoff is determined using the difference between A_{other}, B_{other} and your guesses. Suppose your guesses are 630 and 280 it means your guess was more far away from A_{other}, you get 72 Coins. The least you can earn is 0 Coin.

Agreement

Before the auction, a new stage appears, which provides you information about the outcome of the proposals. This can only be seen by pairs who decided to cooperate. You can see your new balance and whether you are allowed to participate in the auction.

Auction

The auction has two or three participants, depending on whether you and the other player in your group made an agreement. The auction has similar rules as the proposal part. That is, you are required to make your bids at the same time. The winner of the auction is the one making the highest bid. In case of a tie, the winner is chosen randomly among the ones with the highest bids. The amount paid is the *second highest bid* submitted. In the auction stage, you are allowed to submit an integer number in the bracket 'Please, make your bid', that is at least 0.

The computer submits a number, that is between 0 and 500 Coins.

The highest bidder receives the unit of X being sold and earns his or her *redemption value* for it. If you win, your redemption value equals R_{you}. Other participants, who do not win any X, do not pay any Coin and do not receive any X, so their earnings for the period equal their balance. Thus, if you win, your payoff is:

$$yourpayoff = yourbalance - \text{second highest bid} + R_{you}$$
$$= yourbalance - \text{second highest bid} + A_{you} + \frac{B_{you} + B_{other}}{2}$$

Let us see an example. Suppose you have cooperated with the other player in your group and you have given 150 Coins. Your new balance is $800 - 150 = 650$ Coins. Suppose your values are $A_{you} = 500$ and $B_{you} = 100$. You decide to bid 650. The computer bids 200. The other bidder does not participate, so the second highest bid is 200 Coins. You win the auction, pay 200 Coins, and receive your *redemption value.* In order to calculate your redemption value, you also need to know B_{other}. The only way you can learn it before the auction is by participating in the Chat round. Even in that case, you can only see what the other human bidder writes, we do not show you the actual B_{other}.

Suppose $B_{other} = 300$. So, you redemption value is $R_{you} = 500 + \frac{300+100}{2} = 500 + 200 = 700$. So, your payoff of this round is $650 + 700 - 200 = 1150$ Coins. If someone does not win the auction, his resulting payoff is payoff = balance. So, the other player receives 800 + 150 = 950 Coins, the sum of the endowment and the amount he or she has received by the agreement.

Results

After all bidders have submitted their bids, the outcome of the auction is announced. You can read whether you have won, all the submitted bids and your earnings for the round. You can see this screen even if you did not participate in the auction. The process is repeated 11 times. The first round is only practice, whereas one of the remaining 10 counts towards your payment. At the beginning of the first round which could count, we ask you to type in your seat number. You can find this number on the separating wall, and it is between 1-24. We need this in order to make the payments at the end of the session.

Your payoff and end of session

After the second part of the experiment, you will receive your payments in cash. The amount you receive for the first part of the experiment is your payoff from a random round, including the payment of the guessing game of the same random round. After the 11 rounds of the auction game, you will participate in a second part of the experiment. Your earnings in the second part will be added to your final payment.

After the two parts, payments are made anonymously and individually. Please remain seated until we call you.

Appendix D Control questions

Please make a choice for each question by encircling (a), (b) or (c).

1. In a round you learn that your numbers are $A_{you} = 500$ and $B_{you} = 200$. In the previous round, your number was $A_{you} = 400$ and $B_{you} = 100$. In this round
   (a) My *redemption value* is 700, it does not depend on the previous round.
   (b) My *redemption value* is 500.
   (c) I do not know my own *redemption value* with certainty.

2. Before the chat part, to the question 'Do you wish to cooperate with the other player in the auction?', you reply 'Yes' and the other player replies 'No'. What does happen next?
   (a) We proceed to the auction, since we both need to reply 'yes' in order to start the chat and make an agreement.
   (b) We proceed to the chat, since I replied 'yes'.

3. At the proposal for making an agreement, you offer 150 Coins, whereas the other player offers 100 Coins. What does happen next?
   (a) We can both participate in the auction and we keep our endowments.
   (b) I can participate in the auction but the other player cannot. I pay 100 Coins to the other player, so my new balance is 700 Coins, my endowment minus what I paid out.
   (c) I can participate in the auction, but the other player cannot. I pay 150 Coins to the other player, so my new balance is 650 Coins, my endowment minus what I paid out.

4. In the auction
   (a) there are always three bidders.
   (b) there are two or three bidders, but I always participate.
   (c) there are two or three bidders, and I do not participate if we cooperated and I received an amount for my proposal.

5. You are the winner of the auction and you are required to pay 300 Coins. Previously, you have made an agreement, and paid 100 Coins to the other player. Your numbers are $A_{you} = 500$ and $B_{you} = 200$. Your payoff for this round

   (a) is $800 - 100 + 500 + 200 - 300 = 1100$ Coins.

   (b) is $800 - 100 - 300 = 400$ Coins.

   (c) you do not know with certainty.

Appendix E Instructions for the Holt-Laury protocol

In this part of the experiment you will be making choices between two lotteries, such as those represented as "Option A" and "Option B" below. The money prizes are determined by the computer equivalent of throwing a ten-sided die. Each outcome, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, is equally likely. If you choose Option A in the decision shown below, you will have a 1 in 10 chance of earning 500 Coins and a 9 in 10 chance of earning 400 Coins. Similarly, Option B offers a 1 in 10 chance of earning 960 Coins and a 9 in 10 chance of earning 25 Coins.

Decision 1:

Option A: 500 Coins if the die is 1 and 400 Coins if the die is 2 - 10.

Option B: 960 Coins if the die is 1 and 25 Coins if the die is 2 - 10.

Each box of the decision table contains a pair of choices between Option A and Option B. You make your choice by clicking on the "A" or "B" buttons on the bottom. Only one option in each box can be selected, and you may change your decision as you wish before you submit it.

Even though you will make ten decisions, only one of these will end up being used. The selection of the one to be used depends on the "throw of the die", that is, it is determined by the computer's random number generator. No decision is any more likely to be used than any other, and you will not know in advance which one will be selected, so please think about each one carefully.

For example, suppose that you make all ten decisions and the roll of the die is 9, then your choice, A or B, for decision 9 would be used and the other decisions would not be used.

After the random die throw determines the decision box that will be used, a second random number is drawn that determines the earnings for the option you chose for that box. In Decision 9 below, for example, a throw of 1, 2, 3, 4, 5, 6, 7, 8, or 9 will result in the higher payoff for the option you chose, and a throw of 10 will result in the lower payoff.

Decision 9:

Option A: 500 Coins if the die is 1-9 and 400 Coins if the die is 10

Option B: 960 Coins if the die is 1-9 and 25 Coins if the die is 10

For decision 10, the random die throw will not be needed, since the choice is between amounts of money that are fixed: 500 Coins for Option A and 960 Coins for Option B.

Your earnings in this part of the experiment will be added to your final payoff.

Appendix F Instructions to Chat Coders

The following task is part of an experiment in decision-making. The instructions are written here. If you follow them, you can earn a considerable amount of money, which will be transferred to you after completion of the task. The amount of payment is fixed, 70 EUR. The content of all attached files is confidential. You are not allowed to share it with anybody other than the experimenter. If you have a question, please contact us.

The instructions for the coding follow. Attached you can find a MS Excel file with two spreadsheets, *chat* and *data*. Your task is to read the content of *chat* and fill in the content of *data*. You can do this job anytime before the deadline of December 17, at 17:00. At that point, the spreadsheet must be complete. After delivering the completed file, you will receive your payment by bank transfer, which will be sent to your account.

Chat

Spreadsheet *chat* contains observations from an anonymous economic experiment. The entries are chat messages and identification values. The meaning of each column is explained below. This database records the chat messages of participants in experimental sessions.

- Period: This refers to the round in which the chat has taken place. There were 11 rounds, numbered between 0 and 10. Note that not every participant had a chat in every round.
- Text: This is a chat message.
- Group: Code number of the group. A group consists of two participants in a *Period*.
- Time: The time the message was sent.
- ID: identification number of the participant used (only) in the experiment.

In spreadsheet *chat*, the entries are ordered such that you can read a conversation between two participants easily. For example, rows 2, 3 and 4 contain a conversation between subjects 102 and 105 in round 0, with chat messages in chronological order. Note that not all participants participated in chat for all periods. In all chats there were exactly two participants, but it is possible that only one of them has chat entries.

Data

The second spreadsheet must be filled in using the *Chat* spreadsheet. Each row corresponds to a participant with identification *ID* in a certain *Period*. These two variables are already filled in, please do not modify them or change their order.

There are three cases. A participant with *ID* in a *Period*

- has no chat entry in a period. In this case, leave that row empty. Never delete entries for *ID* and *Period*.
- has chat entry, but he or she was the only one communicating. Please write 1 in the row *onesided*. In any other case, leave this variable empty.
- has participated in a chat with two-sided communication. That is, both participants of the group have sent at least one line.

If a participant has chat entries (case 2 and 3), you need to fill in the remaining cells. The conversation is about a proposal. After this chat, both participants in the group made a proposal, which was always a number. They can refer to this as *offer*, *proposal*, *payment* or *bid*. This is a decision made by the participants *after* the chat.

Furthermore, they mention *values*, which they refer to as A or B. If in a conversation they mention only one value without explicitly saying A or B, you should assume they talk about value A. All participants knew their own values *before* the chat.

In the chat, participants mainly talked about these numbers. It is possible, that a chat contains no mention of some or all of them. You need to fill in the following. As a general rule, do not write anything in a cell if the respective information cannot be found in the chat. In each case, the prefix *own* refers to chat messages of the participant *ID*, this is the information the participant provided. The prefix *other* always refers to the other participant in the same group. This is the information the participant received. As a general rule, if there are multiple numbers for one entry, please type in only the last one.

- *ownproposal*: If *ID* in *Period* mentions a *offer*, *proposal*, *payment* or *bid* with a specific number, please write that number here.
- *otherproposal*: If the participant receives an offer, please write it here. Similarly, if there are multiple numbers, write the last one here.

- *ownproposaltoother*: If the participant suggests a number what the other participant should propose, please write it here.
- *otherproposaltoown*: If the participant is suggested a number, please write it here.
- *ownavalue*: Claim about value A.
- *otheravalue*: Received claim about A.
- *ownbvalue*: Claim about value B.
- *otherbvalue*: Received claim about B.
- *agreement*: Please fill in 1, if an agreement has been reached in the conversation.
- *disagreement*: Please fill in 1, if there was a disagreement at the end of the conversation, and 0 otherwise. Do not fill it in if there is no chat entry.
- *noresponse*: Please fill in 1, if there was an attempt to make an agreement, but the conversation ended without explicit agreement or disagreement.

It is possible that there was only a hint about a certain value, but no precise number. In that case, write down your best guess in that cell, i.e. the midpoint of an interval, do not leave it empty.

Good luck with finishing the task. If you have any questions, please write an email to g.seres@tilburguniversity.edu. It is important that you only send inquiries to this email address, *do not discuss* any part of this task with other participants.

References

AGRANOV, M., AND L. YARIV (2016): "Collusion through Communication in Auctions," *California Institute of Technology.*

APESTEGUIA, J., M. DUFWENBERG, AND R. SELTEN (2007): "Blowing the whistle," *Economic Theory*, 31(1), 143–166.

ARMANTIER, O., C. A. HOLT, AND C. R. PLOTT (2013): "A Procurement Auction for Toxic Assets with Asymmetric Information," *American Economic Journal: Microeconomics*, 5(4), 142–162.

ARMANTIER, O., AND N. TREICH (2013): "Eliciting beliefs: Proper scoring rules, incentives, stakes and hedging," *European Economic Review*, 62, 17–40.

ASKER, J. (2010): "A study of the internal organization of a bidding cartel," *The American Economic Review*, 100(3), 724–762.

BIGONI, M., S.-O. FRIDOLFSSON, C. LE COQ, AND G. SPAGNOLO (2015): "Trust, leniency, and deterrence," *Journal of Law, Economics, and Organization*, 31(4), 663–689.

BOONE, J., R. CHEN, J. K. GOEREE, AND A. POLYDORO (2009): "Risky procurement with an insider bidder," *Experimental Economics*, 12(4), 417–436.

BRIER, G. W. (1950): "Verification of forecasts expressed in terms of probability," *Monthly Weather Review*, 78(1), 1–3.

BROWN, A. L., C. R. PLOTT, AND H. J. SULLIVAN (2009): "Collusion facilitating and collusion breaking power of simultaneous ascending and descending price auctions," *Economic Inquiry*, 47(3), 395–424.

FISCHBACHER, U. (2007): "z-Tree: Zurich toolbox for ready-made economic experiments," *Experimental Economics*, 10(2), 171–178.

GOEREE, J., AND T. OFFERMAN (2002): "Efficiency in auctions with private and common values: An experimental study," *American Economic Review*, 92(3), 625–643.

——— (2003): "Competitive bidding in auctions with private and common values," *Economic Journal*, 113(489), 598–613.

Groenewegen, J. (1994): "About double organized markets: issues of competition and cooperation. The Dutch construction cartel: an illustration," *Journal of Economic Issues*, 28(3), 901–908.

Hinloopen, J., and S. Onderstal (2014): "Going once, going twice, reported! Cartel activity and the effectiveness of antitrust policies in experimental auctions," *European Economic Review*, 70, 317–336.

Hinloopen, J., and A. R. Soetevent (2014): "Exploitation and induced tacit collusion: a classroom experiment of corporate leniency programs," in *The Analysis of Competition Policy and Sectoral Regulation*, pp. 193–212.

Holt, C. A., and S. K. Laury (2002): "Risk aversion and incentive effects," *American Economic Review*, 92(5), 1644–1655.

Hu, A., T. Offerman, and S. Onderstal (2011): "Fighting collusion in auctions: an experimental investigation," *International Journal of Industrial Organization*, 29(1), 84–96.

Jackson, M. O., and J. M. Swinkels (2005): "Existence of Equilibrium in Single and Double Private Value Auctions1," *Econometrica*, 73(1), 93–139.

Jehiel, P., and B. Moldovanu (2001): "Efficient design with interdependent valuations," *Econometrica*, 69(5), 1237–1259.

Kagel, J. H., and D. Levin (2002): "Bidding in common-value auctions: A survey of experimental research," *Common value auctions and the winner's curse*, 1, 1–84.

Kittsteiner, T. (2003): "Partnerships and double auctions with interdependent valuations," *Games and Economic Behavior*, 44(1), 54–76.

Kwasnica, A. M., and K. Sherstyuk (2007): "Collusion and equilibrium selection in auctions," *The Economic Journal*, 117(516), 120–145.

Llorente-Saguer, A., and R. Zultan (2014): "Auction mechanisms and bidder collusion: Bribes, signals and selection," *Working Paper, Max Planck Institute for Research on Collective Goods.*

Mailath, G. J., and P. Zemsky (1991): "Collusion in second price auctions with heterogeneous bidders," *Games and Economic Behavior*, 3(4), 467–486.

Marshall, R. C., and L. M. Marx (2007): "Bidder collusion," *Journal of Economic Theory*, 133(1), 374–402.

——— (2012): *The economics of collusion: Cartels and bidding rings*. Mit Press.

McAfee, R. P., and J. McMillan (1987): "Auctions and bidding," *Journal of Economic Literature*, 25(2), 699–738.

Milgrom, P. R., and R. J. Weber (1982): "A Theory of Auctions and Competitive Bidding," *Econometrica*, 50(5), 1089–1122.

Parlementaire Enquêtecommissie Bouwnijverheid (2003): "Enquête bouwnijverheid," *Tweede Kamer der Staten-Generaal*.

Phillips, O. R., D. J. Menkhaus, and K. T. Coatney (2003): "Collusive practices in repeated English auctions: Experimental evidence on bidding rings," *American Economic Review*, pp. 965–979.

Selten, R. (1998): "Axiomatic characterization of the quadratic scoring rule," *Experimental Economics*, 1(1), 43–62.

Seres, G. (2017): "Auction cartels and the absence of efficient communication," *International Journal of Industrial Organization*, 52, 282–306.

Sherstyuk, K. (1999): "Collusion without conspiracy: An experimental study of one-sided auctions," *Experimental Economics*, 2(1), 59–75.

——— (2002): "Collusion in private value ascending price auctions," *Journal of economic behavior & organization*, 48(2), 177–195.

Sonnemans, J., and T. Offerman (2001): "Is the Quadratic Scoring Rule really incentive compatible?," *Working paper CREED, University of Amsterdam*.

Vickrey, W. (1961): "Counterspeculation, auctions, and competitive sealed tenders," *The Journal of Finance*, 16(1), 8–37.