Fighting Collusion in Auctions: An Experimental Investigation[*]

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June 8, 2009

Abstract

The danger of collusion presents a serious challenge for auctioneers. In this paper, we compare the collusive properties of two standard auctions, the English auction and the first-price sealed-bid auction, and a lesser-known format, the Amsterdam (second-price) auction. In the Amsterdam auction, the highest losing bidder earns a premium for stirring up the price. We study two settings: in one, all bidders can collude, and in another, only a subset is eligible. The experiments show that the Amsterdam auction triggers less collusion than the standard auctions. We compare experimental results to theoretical predictions, and provide an explanation where they differ.

Keywords and Phrases: Auctions; Collusion; Laboratory Experiment.

JEL Classification Numbers: C91, D44, L41

[*]The research of Theo Offerman has been made possible by a fellowship of the Royal Netherlands Academy of Arts and Sciences. Financial support from the Dutch National Science Foundation (NWO-VICI 453-03-606) is gratefully acknowledged. We are grateful to Jos Theelen for programming the experiment. This paper benefited from the comments of the editor (Bradley Ruffle) and two anonymous referees.

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1 Introduction

Fighting collusion is a primary concern for auctioneers because bidders who manage to form a cartel can seriously harm the seller's revenue. Klemperer (2002) argues that collusion and other competition policy related issues like predation and entry deterrence are more relevant for practical auction design than risk-aversion, affiliation, and budget-constraints that play a prominent role in mainstream auction theory. Case law shows that collusion in auctions is not just a theoretical possibility: Krishna (2004) reports that in the 1980s, 75% of the US cartel cases were related to auctions. Apparently, competition law enforcement does not sufficiently deter bidders to collude. In fact, Motta (2004) argues that "[i]t is better to try to create an environment that discourages collusion in the first place than trying to prove unlawful behavior afterwards."

The literature provides several ways for auctioneers to implement auction rules that discourage bidders to collude. It is well known that the auctioneer may impose a reserve price to do so (Graham and Marshall, 1987). Recent papers show that collusion-proof mechanisms exist under fairly general circumstances. These mechanisms raise as much revenue as a revenue-maximizing mechanism in the absence of collusion (Laffont and Martimort, 1997, 2000, Jeon and Menicucci, 2005, and Che and Kim, 2006, 2008).

These theoretical solutions have several practical limitations. The optimal reserve price and the collusion-proof mechanism require the auctioneer to know the distribution functions from which bidders draw their values. In addition, the auctioneer needs to know which bidders belong to which cartel. In practice, such information is difficult, if not impossible, to acquire.[1] For practical mechanism design, Wilson (1987) strongly advocates the implementation of "detail-free" auctions, i.e., auctions of which the rules do not depend on the above mentioned peculiarities of the environment.

Therefore, we will focus on a more practical solution and search for an existing "detail-free" auction format that prevents collusion as much as possible. Among the existing auctions, the

[1] Other limitations of proposed collusion-proof mechanisms are the following. Both Laffont and Martimort (1997, 2000) and Jeon and Menicucci (2005) require a risk-neutral, "benevolent" third-party to coordinate the side-payments for the coalition to function. Che and Kim's (2006) collusion-proof model does not rely on the special structures or bidder-types like the previous work. However, selling to the coalition is often not feasible in practice.

literature suggests using the first-price sealed-bid auction (FP) instead of the English auction (EN) (Robinson, 1985, and Marshall and Marx, 2007). The reason is that a cartel agreement is stable in EN, where no bidder has an incentive to deviate from the cartel agreement because the cartel will continue bidding up to the highest value of its members. In contrast, a cartel in FP has to shade its bid below the highest value in the group to make a profit, which gives individual cartel-members an incentive to cheat on the agreement and submit a higher bid than the cartel.

Still, there have been many FP auctions where bidders colluded, for instance by submitting identical bids (Scherer, 1980; McAfee and McMillan, 1992). Recent examples of collusion in FP include infrastructure procurement (Porter and Zona, 1993, and Boone et al., 2009) and school milk tenders (Porter and Zona, 1999, and Pesendorfer, 2000). Apparently, many cartels have been able to overcome the free-rider incentives in FP, possibly because repeated interaction renders collusion stable in FP (Blume and Heidhues, 2008, Abdulkadiroğlu and Chung, 2003, Aoyagi, 2003, 2007, and Skrzypacz and Hopenhayn, 2004). Motivated by these examples, we focus on the toughest possible case for auctioneers, the one where cartel members do not have to fear that there will be defection from within the cartel and where side-payments are possible between cartel members (a "strong cartel" in McAfee and McMillan's (1992) terminology, and a "bid submission mechanism" in Marshall and Marx's (2007)). Our choice to focus on strong cartels is also supported by experimental evidence. Phillips, Menkhaus and Coatney (2003) show that even groups of 6 bidders who interact repeatedly are able to form stable coalitions when communication is allowed. In their communication treatment, Hamaguchi, Ishikawa, Ishimoto, Kimura and Tanno (2007) find that in procurement auctions subjects do not cheat on the agreement reached in the communication phase.

In this paper, we compare how effective FP, EN, and a lesser known format based on a premium auction are in deterring collusion. In a premium auction, the auctioneer pays the runner-up a premium for driving up the price paid by the winner. In situations where the auctioneer fears collusion, a premium auction may make collusion less attractive because it encourages bidders outside of the cartel to compete for the premium.[2] In Europe, premium

[2] The literature identifies other situations where premium auctions may perform well relative to standard auction formats such as FP and EN. Goeree and Offerman (2004) show, both theoretically and in an experiment, that premium auctions may generate more revenue than standard auctions when bidders are asymmetric.

auctions are used to sell houses, land, boats, machinery and equipment. There are many variants of premium auctions, that differ in institutional details. In fact, in the Netherlands and Belgium, many of the larger cities have their own variant that they claim to be unique in the world.

Here, we consider a premium auction investigated in Goeree and Offerman (2004), the Amsterdam second-price auction (AMSA). This auction is one of the simpler formats and it has the advantage that its equilibrium is analytically tractable. AMSA consists of two phases. In the first phase, the auctioneer raises the price successively while bidders decide whether or not to drop from the auction. This process continues until two bidders remain. The price at which the last bidder dropped out defines the endogenous reserve price or bottom price for the second phase. In this phase, both remaining bidders independently submit sealed bids, which must be at least as high as the bottom price. The highest bidder wins and pays a price equal to the second highest bid. Both bidders of the second phase receive a premium, which is a fraction $0 < \alpha < 0.5$ of the difference between the second highest bid and the bottom price.

Notice that there are some similarities between the use of premium auctions and shill bidding. With shill bidding, the seller invents fake bids or asks a confederate to submit fake bids to stir up the bidding. In contrast to the use of a premium in auctions, shill bidding is usually explicitly forbidden. For instance, eBay unambiguously prohibits shill bidding. The rationale provided by eBay is that family members, roommates and employees of the seller have a level of access to information on the good for sale that is not available to other bidders. This is an important difference with a premium auction, where the bidders who pursue the premium are not better informed than the bidders who are genuinely interested in the good. In addition, an important difference is that all the bidders who participate in a premium auction are exactly informed about the rules of the game, while in shill auctions the genuine bidders are not informed of the presence of a shill bidder. For such reasons premium auctions are legally more acceptable than shill bidding, even though they both intend to stir up the bidding.

In most countries collusion is forbidden, and, if it is detected, cartel-members receive a fine. In addition, players incur costs when they decide to set up a cartel. Instead of closely modeling such processes, we simply introduce a cost that bidders have to pay when they decide to collude.

Milgrom (2004) argues that the prospect of receiving a premium may attract “weak” bidders to a premium auction who would not have entered in a standard auction where they have no hope to beat the strong bidder.

If the eligible bidders agree to form a cartel, they determine in a pre-auction knockout who will proceed to the auction and how much she has to pay to compensate the other members for not participating.

We examine two settings in which bidders can collude. In the symmetric setting, all bidders can collude, and in the asymmetric setting, only a subset can do so. In the symmetric environment, all bidders draw their values from the same distribution function. In the asymmetric one, we distinguish between "weak" and "strong" bidders. A strong bidder always has a higher value than a weak bidder. This form of asymmetry characterizes many situations in practice, where serious, genuinely interested bidders compete with fortune-hunters out for a bargain. Maskin and Riley (2000) motivated this setup with a reference to the "Getty effect", after the wealthy museum known for consistently outbidding the competition. Only strong bidders have the opportunity to collude. The rationale for this choice is that in practice there is basically an infinite supply of bidders with a weak preference for the good, so it is prohibitively costly to try and include all of them in a cartel. On the other hand, there is usually only a limited number of seriously interested bidders, and for them it may be very interesting to prevent competition from each other.

The theoretical properties of this model are the following. In the symmetric case, collusion is equally likely in the three auctions, i.e., it is equally like that bidders form a cartel. In the asymmetric case, collusion occurs more often in EN than in FP despite the assumption that the cartel, if formed, is also stable in FP. In the stage game where the designated bidder of a cartel faces weak bidders, AMSA turns out to have multiple equilibria, which mainly depend on how aggressively weak bidders bid. If they remain "passive" and bid up to value, AMSA and EN are equally conducive to collusion, and both mechanisms are dominated by FP. However, in an "aggressive equilibrium", AMSA outperforms both FP and EN in terms of fighting collusion.

Which equilibrium of AMSA is the most likely to be played remains an open question, which we address using a laboratory experiment. Another reason for using a laboratory experiment to empirically test our theoretical findings is that field data on cartels are difficult to obtain by its illegal nature. In the experiment, we compare AMSA with FP and EN. We observe the following results. In the symmetric setting, EN and AMSA are equally successful in fighting collusion. Both mechanisms outperform FP. In the asymmetric setting, AMSA triggers less collusion than the other two auctions, which perform equally poorly. Overall, our experiments suggest that AMSA is the superior choice to fight collusion. To the extent that the experimental results deviate from the theoretical predictions, we provide a coherent explanation for why they differ.

In single-unit auctions, collusion does not arise under standard experimental procedures.[3] The exception is provided in Lind and Plott (1991), who report attempts at collusion in one of their five common value auction sessions. There is surprisingly little experimental work that allows subjects to explicitly collude in single-unit auctions. The main exception is Isaac and Walker (1985) who gave bidders the opportunity to talk before they submitted their sealed bids in a first-price private value auction. In four out of their six series where a single unit was put up for sale, the four bidders managed to collude.[4] Kagel (1995) discusses two unpublished studies that also study collusion in single-unit auctions. In one study, Dyer investigated tacit collusion in first-price private value auctions by comparing bidding in fixed groups and known identities with bidding in groups that were randomly rematched between auctions. His results were inconclusive. In the other study, Kagel, Van Winkle, Rondelez and Zander let subjects communicate prior to bidding in a first-price common value auction. When the reserve price was announced, subjects used a rotation rule and almost always submitted bids at the reserve price. With a secret reserve price, bidders were less successful in colluding and earned somewhat less than half the amount they made when the reserve price was announced and the amount that they made when there was no communication. More recently, Hamaguchi et al. (2007) study collusion in procument auctions and the effectiveness of leniency programs. As in Isaac and Walker (1985), bidders could talk before submitting bids. They observe that virtually all bids are at the monopoly price, so that bidders clearly manage to collude. Our experiment goes a step further than the previous literature by examining how successful bidders are in forming cartels under different auction formats, and by studying the role of bidders outside the cartel who may render a cartel unattractive if they bid aggressively.[5]

[3] See Kagel (1995) for an overview of experimental single unit auctions.

[4] More recently, Hamaguchi et al. (2007) study collusion in procument auctions. As in Isaac and Walker (1985), bidders could talk before submitting bids. They observe that virtually all bids are at the monopoly price, so that bidders clearly manage to collude.

[5] In contrast, there is a vast experimental literature on collusion in multi-unit auctions. This literature includes Goswami, Noe, and Rebello (1996), Shertsyuk (1999, 2002), Kwasnica (2000), Kagel and Levin (2001, 2005), Phillips, Menkhaus and Coatney (2003), Sade, Schnitzlein and Zender (2006), Kwasnica and Sherstyuk

The remainder of this paper is organized as follows. In Section 2, we describe the theoretical background of our experiments. Section 3 includes our experimental design. In Section 4, we present our experimental findings and section 5 concludes. Proofs of Propositions 1, 3, and 4 are relegated to the appendix.

2 Theory

A seller offers one indivisible object in FP, EN, or AMSA to $n \geq 2$ risk neutral bidders, $s \geq 2$ strong ones and $w \equiv n - s \geq 0$ weak ones. Bidders who are active in the second phase of AMSA obtain a premium equal to a fraction $\alpha \in (0, 1/2)$ of the difference between the second highest bid and the reserve price. Weak bidders draw their value from the uniform distribution on the interval $[0, 1]$, while strong bidders' values are uniformly distributed on $[L, H]$, $H > L \geq 0$. All values are drawn independently. We let $v^{[2]}$ denote the second order statistic of s draws from the uniform distribution on $[L, H]$.

Bidders interact in a three-stage game. In the first stage, strong bidders vote for or against forming a cartel. A cartel forms if and only if all strong bidders vote "yes". All bidders in the cartel incur a commonly known exogenous cost $c > 0$ if and only if the cartel is actually formed. If a cartel forms, in stage two, the strong bidders interact in a pre-auction knockout mechanism like the one described in McAfee and McMillan (1992). In this knock-out auction, all bidders independently submit a sealed bid. The highest bidder wins, she pays a fraction $1/(s-1)$ of her bid to each of the other $s - 1$ strong bidders, and proceeds to stage three. In the third stage, in the case of a cartel, the designated strong bidder interacts in the auction (AMSA, EN, or FP) with the weak bidders.[6] The designated bidder can submit shill bids on behalf of the other cartel-members. This realistic feature helps to conceal the fact that the strong bidders collude. When bidders do not form a cartel, stage two is skipped and all bidders compete in the auction in stage three. As solution concept, we use the perfect Bayesian equilibrium.[7]

In the first stage, a strong bidder will vote for collusion if and only if the (expected) benefits of collusion outweigh its costs c. Let us assume that the strong bidder with the highest value

(2007).

[6] Boone et al. (2009) describe how members of a Dutch construction cartel used a similar mechanism to determine the designated winner and his side-payments to the other cartel members.

[7] When we speak about the equilibrium of an auction, we refer to the Bayesian equilibrium of the last subgame in which $w + 1$ $[w + s]$ bidders participate if a cartel is [not] formed.

always wins, with or without collusion. Let P denote the price the designated strong bidder expects to pay in the actual auction. The following proposition characterizes when strong bidders will vote for collusion in stage one.

Proposition 1 *Suppose that the subgame after the voting stage has an equilibrium in which the auction always allocates the object to the strong bidder with the highest value (in both the collusive and the non-collusive case) and that the strong bidders' lowest type expects zero profit in the non-collusive case. Then, in the equilibrium of the entire game, a strong bidder, regardless of her value, votes in favor of the cartel if and only if*

$$c \leq \frac{1}{s}\left[E\left\{v^{[2]}\right\} - P\right]. \tag{1}$$

Note the expected benefits of collusion for the strong bidders is the difference between the expected (net) payments without collusion (which is the expectation of the second highest value) and the price the designated winner expects to pay with collusion (which is P). This additional pie will be divided equally among the s strong bidders, which explains the expected benefits on the right-hand side of (1). The result that the willingness-to-pay for forming a cartel does not depend on a bidder's value follows from Myerson's (1981) revenue equivalence theorem. Given that two auctions always assign the object to the bidder with the highest value, the difference in expected utility for a bidder is determined only by the difference in expected utility for the bidder with the lowest value L. The following corollary follows from Proposition 1.

Corollary 1 *If two auctions always allocate the object to the bidder with the highest value in equilibrium (both in the collusive and the non-collusive case) and the lowest type expects zero profit in the non-collusive case, then the auction with the lower P is more conducive to collusion.*

Corollary 1 shows that we only have to compare the expected price the designated winner has to pay in FP, EN, and AMSA to predict which of the three auction formats is less prone to collusion.

We consider a symmetric and an asymmetric setting. In the symmetric one, $w = 0$ (there are no weak bidders), $H = 1$, and $L = 0$. The following proposition immediately follows from Corollary 1, because the three auctions are efficient (with and without collusion), the lowest type expects zero profit in the absence of collusion, and in all three auctions, the designated winner pays zero for the object in the case of a cartel.[8]

Proposition 2 *If $w = 0$, $H = 1$, and $L = 0$, collusion is equally likely in equilibrium in FP, EN, and AMSA.*

In the asymmetric case, $w \geq 1$ (there is at least one weak bidder) and $H > L \geq 1$ (a strong bidder's value is always higher than a weak bidder's). We will establish how the auctions rank in terms of incentives to collude on the basis of the equilibria of the subgame played in stage three. For FP, let $B^{FP}(v)$ $[b^{FP}(v)]$ be a strong [weak] bidder's bid if her value is v. Using Maskin and Riley's (2003) uniqueness result, it follows that all non-collusive equilibria of FP in non-dominated strategies are characterized by

$$\begin{aligned} B^{FP}(v) &= v - \frac{v-L}{s}; \\ b^{FP}(v) &\in [0, v]. \end{aligned}$$

The following proposition describes collusive equilibria for FP for sufficiently high L.

Proposition 3 *Suppose that strong bidders form a cartel. If $w \geq 1$ and $L \geq \frac{w+1}{w}$, then in any equilibrium of FP in non-dominated strategies, the designated strong bidder bids $B^{FP}(v) = 1$ and always wins the auction.*

So, if $L \geq \frac{w+1}{w}$, the expected payment by the designated winner equals

$$P^{FP} = 1.$$

For EN it is always a weakly dominant strategy to bid value. So, in the case of collusion, the designated winner expects to pay the highest value among the weak bidders:

$$P^{EN} = \frac{w}{w+1}.$$

The following proposition establishes an equilibrium for AMSA in the absence of collusion.[9]

[8] In the unique equilibrium of FP, a bidder with value v bids $B^{FP}(v) = v - v/n$, while EN has an equilibrium in weakly dominant strategies in which each bidder bids value. Goeree and Offerman (2004) establish that AMSA has an equilibrium in which a bidder with value v bids $\frac{v+\alpha}{1+\alpha}$ in both stages.

[9] For weak bidders the strategy to bid value weakly dominates bidding below value.

Proposition 4 *Let $w \geq 1$ and $L \geq 1$. Suppose that the strong bidders do not form a cartel. The following bidding strategies constitute an equilibrium outcome of AMSA in non-dominated strategies. In the first phase, a strong bidder with value v remains in the auction up to $\frac{v+\alpha H}{1+\alpha}$. The weak bidders all drop out at any price between their value and L. In the second phase, a strong bidder with value v bids $\frac{v+\alpha H}{1+\alpha}$.*

As we discussed before, the designated bidder can submit bids on behalf of the other strong bidders. In FP and EN, these shill bids do not affect the equilibrium outcome. In AMSA, however, the designated bidder may discourage weak bidders from pursuing the premium by keeping at least one of the shill bidders in the auction as long as weak bidders continue bidding. The possibility of shill bids makes it harder for AMSA to outperform the standard auctions. The following proposition shows that the AMSA may have several equilibria, which depend on how "aggressively" weak bidders bid.

Proposition 5 *Let $w \geq 1$ and $L \geq 1$. Suppose that the strong bidders form a cartel. The following bidding strategies constitute an equilibrium outcome of AMSA in non-dominated strategies. In the first phase, the strong bidder and her shill bidder remain in the auction up to her value. The weak bidders all drop out at any price between their value and L. In the second phase, the strong bidder bids value and the shill bidder bids the bottom price.*

The above proposition holds true because a weak bidder has no incentive to bid more than L, the lowest bid submitted by a strong bidder. If she does, she will outbid some types of strong bidders and end up paying more for the object than her value. It is easy to see that the strong bidder has no reason do deviate either. We say that weak bidders bid aggressively [passively] if they bid up to L [value] in the first phase, which is the highest [lowest] bid which is consistent with Propositions 4 and 5. Let P_{agr}^{AMSA} [P_{pas}^{AMSA}] denote the designated winner's expected payment in the aggressive [passive] equilibrium in the case of a cartel. Then:

$$P_{agr}^{AMSA} = L$$

and

$$P_{pas}^{AMSA} = \frac{w}{w+1}.$$

Table 1 ranks the three auctions in terms of likelihood of collusion for the two equilibrium extremes of AMSA. Corollary 1 and the expected equilibrium payments in FP, EN, and AMSA imply that in equilibrium, collusion is (weakly) less likely in AMSA than in EN. If $L \geq \frac{w+1}{w}$, collusion is more likely in EN than in FP, while the ranking of AMSA relative to FP depends on which of the equilibria in AMSA is played in the case of collusion. If the passive [aggressive] equilibrium is played, collusion is more [less] likely in AMSA than in FP.

[Table 1 here]

3 Experimental Design and Procedure

The computerized experiment was conducted at the Center for Experimental Economics and political Decision making (CREED) of the University of Amsterdam. A total of 180 students from the undergraduate population of the University were recruited by public announcement and participated in 9 sessions. Subjects earned points in the experiment, that were exchanged in euros at a rate of 5 points for €1. On average subjects made €25.70 with a standard deviation of €7.45 in sessions that lasted between 100 and 140 minutes.[10] Subjects read the computerized instructions at their own pace. Before they could proceed to the experiment, they had to correctly answer some questions testing their understanding of the rules. Before the experiment started, subjects received a handout with a summary of the instructions.[11]

We employed a between-subjects design, in which subjects participated in one of three treatments only, FP, EN, or AMSA. The treatments only differed in the auction rules. In FP, subjects simultaneously submitted sealed bids for the good for sale. The highest bidder bought the good for sale and paid a price equal to the own bid (in all auctions, tied bids were randomly resolved by the computer). In EN, a thermometer showing the current price started rising from 0. Bidders decided whether or not to quit at the current price. When all but one bidder had pushed the quit button, the thermometer stopped rising and the remaining bidder bought the good at the current price. In AMSA, the auction process consisted of two phases. In the first

[10] At the end of the first session, we found out that subjects earned less than we had expected. Therefore, we provided them with an unannounced gift of €5 that was added to the total that they had made in the experiment. We kept the same procedure in the other sessions.

[11] The instructions of one of the treatments is available at http://www1.fee.uva.nl/creed/people/offerman/index.shtml.

phase, a thermometer started rising from 0. The thermometer stopped rising when all but two bidders had pushed the quit button. This price was called the bottom price for phase two. The two remaining bidders proceeded to the second phase where they simultaneously submitted sealed bids at least as high as the bottom price. The highest bidder bought the good for sale at a price equal to the second highest sealed bid.

In all auctions, the winner earned a payoff equal to the own value minus the price paid. In addition, in AMSA the two bidders of the second phase each earned a premium equal to 30% of the difference between the lowest bid in the second phase and the bottom price. We now describe the features that were the same in each treatment.

The experiment consisted of three subsequent parts: a symmetric environment without collusion, a symmetric environment with collusion, and an asymmetric environment with collusion. The three parts consisted of 6 periods, 8 periods and 10 periods, respectively. Subjects received the instructions of a subsequent part only after the previous part had been completed. In each period, subjects were assigned to groups of 6. We randomly rematched subjects between periods within a matching-group of 12 subjects. In each session, we ran two independent matching-groups simultaneously, unless we did not have sufficient subjects in which case we ran one group. In each treatment, we obtained data on 5 independent matching-groups of 12 subjects each.

We started part one without collusion because we wanted the subjects to gain experience with the auction rules before they proceeded to the more complicated game where they were allowed to collude. At the outset of part one, subjects received a starting capital of 50 points. In addition, they earned and sometimes lost points with their decisions. In each period, a good was sold in each group of subjects. We communicated to the subjects that each subject received a private value for the good for sale, which was a draw from a U[0,50] distribution. Draws were independent across subjects and periods. Subjects were only informed of their own value. We kept draws constant across treatments for the sake of comparability of the results.

In part two, subjects were allowed to collude. In each period, subjects were first informed of the costs of cooperating, which were the same for all subjects.[12] Then subjects simultaneously voted whether or not to cooperate. Only if all 6 players voted for cooperation, the group

[12] In the instructions we avoided the word collusion, because many subjects are unfamiliar with its meaning.

actually cooperated. When a group cooperated, each bidder paid a cost of cooperation. This cost varied across periods, but it was constant across treatments to make results comparable. Group-members were informed of the total number of votes for cooperation in their group. If the group cooperated, all 6 bidders simultaneously submitted sealed bids in a knock-out auction for the right to be the designated bidder. The highest bidder became the designated bidder and automatically bought the good for zero in the auction. The designated bidder paid her bid in the knock-out auction, which was equally shared by the 5 other bidders. If the group did not cooperate, subjects did not incur the costs of collusion and the good was sold with the same auction rules as in part one.

Part three introduced asymmetry between bidders. In each period, three out of six bidders in a group were assigned the role of weak bidder and the three others the role of strong bidder. Weak bidders received a value from U[0,50], while strong bidders received a value from U[70,120]. Roles and values were assigned privately and independently across subjects and periods. In part three, only strong bidders had the possibility to collude. At the outset of the period, all bidders were informed of the costs that strong bidders would incur if they actually cooperated. A period started with strong bidders voting to cooperate or not. If all three strong bidders voted for cooperation, strong bidders did cooperate. Only strong bidders were informed of the outcome of the voting process. Therefore, weak bidders were not sure whether or not they faced a cartel. When strong bidders cooperated, they paid the cost of cooperating and proceeded to a knock-out auction, where they submitted sealed bids for the right to be designated bidder. The highest bidder won and paid a price equal to the own bid. This price was equally shared by the other two strong bidders. Then the designated bidder proceeded with the weak bidders to the main auction to bid for the good for sale. In the main auction, the designated bidder submitted shill bids on behalf of the other strong bidders and serious bids on the own behalf. Designated bidders did not share the profits (and premiums) that they made in the main auction. In case the strong bidders did not collude, all bidders immediately proceeded to the main auction with the same auction rules as in the previous parts.

During EN and the first phase of AMSA, other bidders in the group were immediately informed when one of their rivals had dropped out and, in part three, whether this bidder was weak or strong. At the end of a period, all bidders were informed of all bids in the group, and, when applicable, the strength of the bidder making the bid. Table 2 summarizes our experimental design.

[Table 2 here]

We deliberately chose to build up the strategic complexity throughout the experiment. In the first part, subjects became familiar with the auction rules. In the second part, they were introduced to the possibility of collusion. By varying the costs of collusion, we encouraged them to vote for collusion when costs were low and to vote against collusion when costs were high. This way they rapidly gained experience with how profitable collusive bidding is compared to competitive bidding. Finally, in part three we introduced asymmetry between the bidders after they had become familiar with the auction rules and the possibility of collusion. To some extent our design mimics a natural process where bidders are engaged in a new series of auctions and then start spotting opportunities for collusion after time progresses. The main difference between our design and a natural process outside the lab is that we force our subjects to think about the possibility of collusion. However, we do not think that our designs triggers too much or too little collusion compared to a more natural process. Because subjects experience collusive auctions as well as competitive auctions, they can make well informed choices after a limited amount of time. Our design choices make it easier for subjects to learn. The enhanced possibilities for learning may compensate for the lack of experience that our subjects have in participating in auctions.

In any case, the most important goal of our experiment is to compare behavior between treatments. Since the sequencing is the same for any treatment, there is no reason to expect a bias in the comparison of the auction formats.

4 Results

We present the results in three parts. Before we start we want to make the caveat that all our results depend on the particular parameters that we employ in our experiments. However, there is no reason to expect that our parameter choices bias the qualitative comparison between the auctions. In section 4.1, we compare the three auction formats at the aggregate level. In section 4.2, we take a closer look at individual bidding behavior and in section 4.3 we provide a coherent explanation of the main results.

4.1 Between auction comparisons

We evaluated the three auction formats on the basis of how they scored with respect to deterring collusion, raising revenue, and pursuing efficient outcomes. Table 3 presents the percentages of bidders who voted in favor of collusion together with the theoretical predictions that depend on the costs of collusion. In part two, where all bidders were symmetric, theory predicts that the auctions are equally vulnerable to collusion. The data show that the votes on collusion were very close to Nash in EN and AMSA. In FP, we observed moderately more votes for collusion than predicted. Notice that the proportions of cases where groups actually colluded were substantially smaller than the theoretically predicted ones. This is due to the fact that subjects did not exactly follow the theoretical threshold rule. Combined with the unanimity rule for collusion, this led to much fewer occasions where the groups actually colluded.

[Table 3 here]

In part three with asymmetric bidders, AMSA triggered considerably fewer votes for collusion than FP and EN did. The proportion of votes for collusion in AMSA was about halfway the level predicted by the aggressive and the one predicted by the passive equilibrium. Remarkably, EN and FP performed about equally poorly in preventing collusion, while theory predicted that FP should trigger less collusion. We will come back to these results in section 4.3 after we have dealt with individual behavior.

In part three, theoretical predictions on when bidders collude vary with the treatments. The EN auction and the passive equilibrium of AMSA predict that collusion is only prevented for a cost of 20. In FP, players should not collude for costs higher than or equal to 16, and in the aggressive equilibrium of AMSA, players should not collude for costs of 10 and higher. Therefore, for a cost level of 20 and cost levels below 10 the predictions were the same for all treatments. Table 3 pools across all levels of costs of collusion, also the ones for which the theoretical predictions are the same. Figure 1 provides an view on the relationship between costs of collusion and votes for collusion. It is striking that in part three votes for collusion were very similar across treatments for cost levels below 10 and at 20, as theory predicts. The difference in votes was indeed produced in the theoretically relevant cost set {10, 12, ..., 18}.

[Figure 1 here]

We now investigate to what extent these qualitative results were statistically significant. To take account of the panel data structure of our experiment, we estimated the following logit model with random effects. Let $y_{i,t}$ represent the vote of individual i in period t; $y_{i,t} = 1$ if i voted for collusion in period t and $y_{i,t} = 0$ if i voted against. We introduce the underlying latent variable $y^*_{i,t}$:

$$y^*_{i,t} = \gamma + \beta_{cost} * cost_t + \beta_{value} * value_{i,t} + \beta_{dumam} * dumam_i + \beta_{dumfp} * dumfp_i + \alpha_i + \varepsilon_{i,t}$$

$$y_{i,t} = 1 \quad if \;\; y^*_{i,t} > 0$$

$$y_{i,t} = 0 \quad if \;\; y^*_{i,t} \leq 0$$

Here, γ represents the constant; $cost_t$ refers to the costs of collusion in period t; $value_{i,t}$ to the value of i in period t; $dumam_i$ is a dummy that equals 1 if i participated in AMSA and 0 elsewhere, and $dumfp_i$ is the corresponding dummy for FP. In addition, we included "group dummies" in the regressions to correct for matching-group specific effects (not reported) and "period dummies" to correct for timing effects. Table 4 reports the treatment effects compared to the omitted treatment EN.

[Table 4 here]

It turns out that in part two (the symmetric case), FP attracted significantly more votes for collusion than EN ($p = 0.01$) and AMSA ($p = 0.00$, Wald test). EN raised slightly more votes for collusion than AMSA did, and the difference is significant at $p = 0.05$. In part three (the asymmetric case), we observe less collusive votes in AMSA than in FP ($p = 0.01$, Wald test) and EN ($p = 0.00$), whereas there is no statistical difference between FP and EN ($p = 0.30$). As expected, there was a clear significant negative effect of the cost of collusion on the inclination to vote for collusion in both regressions reported.

A remarkable result is that in part two the period dummies are always positive and significantly so in 4 of 6 cases. This suggests that subjects learned in the sense that they more easily voted for collusion after they obtained some experience with the game. In contrast, there does not seem to be a systematic pattern in the period dummies in part three. Interestingly, the coefficient for value is significantly negative in part two. There, subjects were more inclined to vote for collusion when they received lower values. This is in contrast to theory, which indicates that the decision to vote for collusion does not depend on value. Possibly, subjects with low values realized that they would not have a fair chance in a competitive auction, which made them more inclined to vote for collusion. The coefficient for value ceases to be significant in part three, though, which may be a sign that subjects learned across the two parts.

We now turn to the comparison of revenues between the treatments. Figure 2 shows revenue histograms for parts one, two and three. In part one, revenue was on average somewhat higher and less dispersed in FP than in EN and AMSA. The histogram of revenues in AMSA was almost identical to the one in EN. In agreement with the finding that subjects colluded more often in part two of FP, the upper-right panel shows a larger spike at 0 in FP than the other two formats. Thus in the symmetric setup, the possibility to collude counteracted the usual revenue dominance of FP over EN found in previous experimental auctions.[13] The lower-left panel shows that the largest differences in revenues were observed for asymmetric bidders. Here, a bimodal distribution resulted in FP, with the largest number of outcome close to 50 and most of the other outcomes close to 100. In contrast, the revenue histograms for EN and AMSA were much more spread out. EN was the most vulnerable auction in terms of raising very low revenues.

[Figure 2 here]

Table 5 reports the average revenues in the experiment in comparison with the theoretical revenues given the values and collusion costs employed in the experiment. In part one, FP generated the highest revenue, followed by AMSA and EN. The differences were small, though, and all quite close to the theoretically expected levels. The second part reveals that in the case of symmetric bidders and potential cartel formation, EN and AMSA both raised higher

[13] See Kagel (1995).

revenues than FP. In all treatments, revenues were much higher than the theoretical predictions. Because unanimity was required for a cartel to form, the number of actual cartels was much lower than predicted by theory, and, as a consequence, actual revenue was higher. In the third part, AMSA performed best while EN and FP raised similar revenues. Here, EN performed much better than theoretically predicted. The revenue of AMSA was closer to the revenue expected in the aggressive equilibrium than the revenue in the passive equilibrium.

[Table 5 here]

To investigate the significance of the revenue comparisons, we estimated a random effects model that took the interaction in the experiment into account. Let $r_{i,j,t}$ represent the revenue of group i ($i = 1$ or $i = 2$) in matching-group j in period t:

$$r_{i,,j,t} = \gamma + \beta_{cost} * cost_t + \beta_{dumam} * dumam_j + \beta_{dumfp} * dumfp_j + \alpha_j + \varepsilon_{i,j,t}$$

Here, γ denotes the constant; $cost_t$ represents the costs of collusion in period t; $dumam_j$ ($dumfp_j$) is a dummy that equals 1 if the matching-group j was run in AMSA (FP) and 0 elsewhere. Table 6 reports the results compared to the omited treatment EN.

[Table 6 here]

In part one, only the difference in revenue between FP and EN is significant at p=0.08. In part two there are no significant differences between the treatments. In the asymmetric situation of part three, it becomes attractive for sellers to employ the AMSA format, as it raised roughly 10% more revenue than FP and EN. The difference in revenue between AMSA and FP is significant at p=0.08 (Wald test) and the difference in revenue between AMSA and EN is significant at p=0.04. The difference between FP and EN is not significant (p=0.50). In both regressions there is a significant effect of costs of collusion. With higher costs of collusion, groups colluded less and more revenue was raised.

Table 7 presents revenue in parts two and three conditional on whether a cartel was established. In part two, conditional on a cartel not being formed, the results were very similar as the ones for part one. Thus, the different revenue results in parts one and two are mainly attributed to the differences in votes for collusion between the treatments. In part three, both in the cases where collusion occurred and the cases where collusion did not occur, actual revenues were very close to the theoretical predicted outcomes in EN and FP. The result that, pooled across all cases, revenue in EN was much higher than theoretically expected must thus be attributed to the fact that this auction was much less conducive to collusion than predicted. Overall, revenue in AMSA was higher than the other two formats despite the fact that AMSA realized less revenue in the absence of collusion. Conditional on collusion, AMSA dominated EN, but raised similar revenues as FP did. Therefore, the results that AMSA revenue dominated FP and EN must be attributed to bidders being less inclined to vote for collusion. Note that the observations are closer to the Nash predictions than in Table 5, with AMSA in part three being closer to the "passive" equilibrium than the "aggressive" one.

[Table 7 here]

Finally, we point the spotlight on efficiency. Table 8 includes the average efficiency of the auctions in each part.[14] Theory predicts that all auctions are 100% efficient because in equilibrium, the bidder with the highest value always wins the object. In all three parts, EN was more efficient than FP, and AMSA was less efficient than FP and EN. The efficiency differences were substantial in parts one and three. Running similar regressions as the ones reported for revenue, we find that the differences in efficiency in part one between FP and AMSA and EN and AMSA are both significant at the 5% level. In part three, the differences between EN and AMSA and FP and EN are significant at the 10% level. All other differences in efficiency are not significant at conventional levels. So while AMSA tends to outperform FP and EN in terms of cartel formation and revenue, the auctioneer may still prefer EN if efficiency is considered the important criterion.

[Table 8 here]

4.2 Individual bidding behavior

In this section, we take a close look at subjects' bidding behavior before we turn to an explanation of the main results. First, we deal with how subjects behaved in the knock-out auctions

[14] We define efficiency as $(v_{\text{winner}} - v_{\min})/(v_{\max} - v_{\min})$, where v_{winner}, $v_{\min}$, and $v_{\max}$ represent the value of the winner, the lowest value among the bidders and the highest value among the bidders, respectively.

once they had decided to collude. Figure 3 shows average bids conditional on value in parts two and three. In part 2, the Nash predictions trace average bids in FP very well, as can be observed in the upper-left panel. In EN, submitted bids fall below the Nash prediction while in AMSA bidders tended to overshoot compared to Nash. Nevertheless, deviations from Nash were rather small when symmetric bidders bid in the knock-out auction.

[Figure 3 here]

The other panels of Figure 3 display how strong bidders bid after they voted to collude in part three, where the theoretical predictions depended on the employed auction format. Like in part two, actual average bids in FP were very close to the theoretical prediction. In contrast, in EN strong bidders submitted substantially lower bids than predicted. It was as if bidders preferred to leave the task to exploit the right to be designated bidder to others in this treatment. In section 4.3, we will provide an explanation of this remarkable result. In AMSA, average knock-out bids were above the amounts that were predicted by the aggressive equilibrium but below the amounts of the passive equilibrium.

We now turn to the bids submitted in the main auction. For EN, the left-panel of Figure 4 provides the histograms for the deviations of bids from value in all three parts. Most submitted bids were equal to value, and only few deviated more than two points from value. Only in part three a small minority of bids deviated substantially from value. Most of these deviating bids were submitted by weak bidders, who either gave up from the start or who chose to drive up the price for the strong bidders.

[Figure 4 here]

In the first two parts of FP, bidders' behavior agreed with the general picture coming from symmetric private value auctions. Bidders submitted bids that were on average slightly higher than Nash. The right-panel of Figure 4 shows average bids together with theoretical predictions for the much less investigated asymmetric case. Average bids were remarkably close to the theoretically predicted ones, both for weak and for strong bidders.

Figure 5 tells a somewhat different story for the first two parts of AMSA. In the first phase of these auctions, bidders on average exited a bit sooner than predicted by Nash, while the subjects that went on to the second phase with low values submitted higher sealed bids than expected (upper-left panel). A similar pattern was observed in Goeree and Offerman (2004). One possible explanation is that subjects differ in their risk-attitudes. The AMSA format automatically selects the risk-averse types to drop in the first phase while the risk seeking ones tend to continue to the second phase. Alternatively, low-valued subjects who proceeded to the second phase may have decided to submit high bids to rationalize their risky bidding in the first phase. Occasionally, low-valued bidders thus became the winner of the auction, which agrees with the poor efficiency performance of this format. A similar picture emerged in part three of AMSA. Again, in the first phase weak bidders behaved rather cautiously, on average exiting only somewhat higher than their value (lower-left panel). Those weak bidders that continued to the second phase tended to take high risks (lower-right panel).

[Figure 5 here]

Conditional on collusion, bidders faced a coordination problem in part three of the AMSA auction. In the experiment, the passive equilibrium, predicting that weak bidders bid up to value, and the aggressive equilibrium, predicting that weak bidders submitted bids equal to 70, attracted bidders' attention. To classify the collusive cases, we divided the interval between the prediction of the passive equilibrium (i.e., the highest value of the weak bidders) and the prediction of the aggressive equilibrium (i.e., 70) in three equal parts. If the realized revenue was to the left of the middle interval, it was classified as being close to the passive equilibrium and if it was to the right of the middle interval, it was classified as being close to the aggressive equilibrium. A substantial part of 50% of the colluding groups ended up being close to the passive equilibrium, while 25% finished close to the aggressive equilibrium. The remaining 25% of the collusive cases was in between the passive and the aggressive equilibrium.

According to both equilibria, the designated bidder should be tough and keep the shill bidders in the auction as long as the weak bidders had not yet exited. Only if a designated bidder plays tough, the bottom price is not determined by weak bidders. In agreement with this feature of the equilibria, designated bidders played tough in 72.5% of the cases and received higher profits if they did so. That is, the designated bidder's profit on the transaction equalled 48.9 (at an s.e. of 25.3) for tough play and it equalled 35.7 (at an s.e. of 28.3) when they let their shill bidders drop before the weak bidders did.[15]

4.3 Explanation of the main results

In this section, we provide an explanation for the main results on collusion. In part two, theory predicted that the auctions were revenue equivalent and that, as a consequence, the auctions would be equally conducive for collusion. Instead, we observed that FP triggered significantly more votes than the other two formats.[16] We think that the key to explaining these differences is given by the revenues actually raised in part one. There, bidding was most competitive in FP, while AMSA and EN raised similar profits. FP-bidders experienced that the main auction was not so profitable, which made collusion more attractive compared to the other two formats. In fact, when revenue equivalence breaks down in the way it did in part one, the theoretical predictions on collusion change in the direction that we actually observed.

The main results in part three were that AMSA proved less conducive to collusion than the other auctions, and that, rather unexpectedly, FP performed equally unsuccessful in fighting collusion as EN did. Table 9 presents some statistics that provide an explanation for these results. The table lists for each auction how much profit the designated bidder actually made on the transaction in the main auction, at which price the designated bidder bought the good for sale, and what the probability was that the designated bidder actually bought the good in the main auction.[17] On all these criteria, AMSA offered the worst prospects for the designated bidder. Given that collusion was most unattractive in AMSA, it makes sense that bidders voted more often against collusion in this format.

[Table 9 here]

What remains puzzling though was that FP did not attract less collusive votes than EN did, even though the statistics in Table 9 show that the prospects for the designated bidder

[15] In AMSA, the profit on the transaction equals the own value minus price paid plus premium in case the bidder bought the good and it equalled the premium or 0 in case the bidder did not buy the good.

[16] In addition, EN was significantly more conducive to collusion than AMSA, but the difference in collusive votes between these two auctions was rather small.

[17] For AMSA, the profit on the transaction was defined in the previous footnote. In EN, it was equal to the own value minus the price paid in the main auction if the designated bidder won the auction and 0 otherwise; in FP, it was equal to value minus own bid in case of winning and 0 otherwise.

were worse in FP. We think that two features may have contributed to this result. The first one is that, even though the designated bidder made on average a higher profit in EN than in FP, this occurred at a higher variance. Subjects who disliked risk may have been more reluctant to become designated bidder in EN. This was also reflected in the knock-out bids shown in Figure 3. Bids in the knock-out auction were close to the theoretically predicted ones in FP, while they were considerably below the theoretical bids in EN. We think that perhaps an even stronger force behind this result may have been designated bidders' lack of control in the EN auction. In the FP auction, it was easy for a bidder to predict how much profit was available in the main auction. Bidders knew that a bid of 50 or 51 would win the main auction almost surely. Therefore, a colluding strong bidder could easily anticipate the profit to be made in FP, which may have led to more confident bidding in the knock-out auction and more confident voting for collusion in the voting stage. In contrast, in EN the price that the designated bidder was going to pay completely depended on the behavior of weak bidders. As Figure 6 shows, this price was much more volatile in EN than in FP. The extra ambiguity in EN that designated bidders faced in the main auction may have discouraged voting for collusion.[18]

[Figure 6 here]

It is important to remember that in our experiment the cartel was stable by design in all auctions. This feature of our experiment diminishes the relevance of our results for one-shot auctions. When some bidder cheats on the cartel agreement, bidders may retaliate within a one-shot EN auction but not within a one-shot FP auction. Therefore, when bidders do not have the possilibilty to retaliate in the future, EN auctions may be more prone to collusion than FP auctions (Robinson, 1985; Marshall and Marx, 2007). Instead, our results are relevant to situations where bidders interact repeatedly as in bidding for projects in the construction industry. In such situations, there is ample evidence that even in FP auctions bidders refrain from cheating on the cartel, presumably out of fear for future retaliation (Scherer, 1980; McAfee and McMillan, 1992; Porter and Zona, 1993; Porter and Zona, 1999; Pesendorfer, 2000; Boone et al., 2009).

[18] Notice that in AMSA designated bidders were faced with a similar lack of control as in EN, so this factor also worked against collusion in AMSA.

5 Conclusion

In this paper, we studied the collusive properties of EN, FP and AMSA using a laboratory experiment. We did so in two settings. In the first one, bidders were symmetric and all could participate in the cartel. Here we observed that FP triggers more collusive votes than the other formats. This result is consistent with the finding that without collusion, the FP auction was the most competitive one. Therefore, the incentive to collude was highest in this format. Interestingly, with the possibility to collude, the revenue dominance of FP over EN usually reported in experimental private value auctions completely disappears.

In the second setting, both strong and weak bidders competed for the good for sale. Only strong bidders were eligible for collusion. In theory, FP should outperform EN in preventing collusion, because in the former a designated bidder could not afford to bid below the higher end of the support of the weak bidders, which makes collusion relatively less attractive. In contrast to this prediction, we observed that EN triggered about as much collusion as FP did. We think that there are two reasons behind this result. First, the designated bidder ran a higher risk in EN when she had to beat the weak bidders in the auction. Second, the designated bidder faced less ambiguity in FP than in EN. That is, in FP the designated bidder could easily anticipate the amount of profit that she would almost surely make in the main auction, whereas in EN the actual price paid in the main auction varied substantially. Consistent with these explanations is our finding that in EN strong bidders tended to submit low bids in the knock-out auction, as if they preferred to leave the right to be designated bidder to others.

According to theory, AMSA is less conducive to collusion than the other formats only if weak bidders bid sufficiently aggressively in the case of collusion. In the experiment, bidders focussed sufficiently on the aggressive equilibrium to make collusion unattractive. AMSA triggered less collusion than the other auctions did.

6 Appendix

Proof of Proposition 1. We let $F^{[1]}$ $[F^{[2]}]$ denote the distribution function of the first [second] order statistic of s draws from the uniform distribution on the interval $[L, H]$. Myerson

(1981) shows that a strong bidder's expected pay-off from an auction can be expressed as

$$\pi(v) = \underline{\pi} + \int_L^v Q(x)dx$$

where $\underline{\pi}$ denotes the expected pay-off for the strong bidder's lowest type and $Q(x)$ the probability that a strong bidder with value x wins. Let $\underline{\Pi}$ be the expected pay-off for the strong bidder's lowest type in the case of collusion. Because the auction always allocates the object to the bidder with the highest value (both in the collusive and the non-collusive case) and the strong bidders' lowest type expects zero profit in the non-collusive case, a strong bidder with value v is willing to join the cartel if and only if $c \leq \underline{\Pi}$. McAfee and McMillan (1992) show that in the knock-out auction, the following bidding function constitutes a symmetric Bayesian Nash equilibrium:

$$B(v) = \frac{s-1}{s} F^{[1]}(v)^{-1} \int_L^v (x-P)\, dF^{[1]}(x).$$

Given this equilibrium, $\underline{\Pi}$ can be expressed as

$$\begin{aligned}
\underline{\Pi} &= \frac{1}{s-1} \int_L^H B(v) dF(v)^{s-1} \\
&= \frac{1}{s} \int_L^H F(v)^{-s} \int_L^v (x-P)\, dF(x)^s dF(v)^{s-1} \\
&= \frac{1}{s} \int_L^H (x-P) \int_x^H F(v)^{-s} dF(v)^{s-1} dF(x)^s \\
&= \frac{1}{s} \int_L^H (x-P)\, s\,(s-1)\,[1-F(x)]\, F(x)^{s-2} dF(x) \\
&= \frac{1}{s} \int_L^H (x-P)\, dF^{[2]}(x) \\
&= \frac{1}{s} \left(E\left\{ v^{[2]} \right\} - P \right),
\end{aligned}$$

where F denotes the value distribution function of a strong bidders. The third equality follows by changing the order of integration. The other steps are straightforward.

PROOF OF PROPOSITION 3. For weak bidders, bids above their value are weakly dominated. Therefore, none of the weak bidders bids more than 1 in equilibrium so neither does the designated strong bidder. Therefore, the proof is established if we show that the designated strong bidder will never bid less than 1 in equilibrium. Now, suppose her lowest equilibrium bid equals $b < 1$. Then a weak bidder with value $v_w \in (b, 1]$ best responds by submitting a bid in the interval (b, v_w), while those with a value below b bid less than b. Therefore, the designated winner's expected profit given her value v equals $U(b,v) = (v-b)\, b^w$ if she bids b and $v-1$ if she bids 1. Note that, for all $v \in [L, H]$, $\frac{\partial U(b,v)}{\partial b} = b^{w-1}(wv - (w+1)\, b) > 0$ if $L \geq \frac{w+1}{w}$ so that $(v-b)\, b^w < v - 1$. A contradiction is established because bidding $b < 1$ is not a best response for the designated winner. An equilibrium in which $B^{FP}(v) = 1$ can be readily constructed by letting all weak bidders bid value.

Proof of Proposition 4. We begin by solving the second phase given the strategies in the first phase. If $s > 2$, let v_3 denote the value of a strong bidder whose bid in phase one equals the bottom price $X = B_1(v_3)$. Otherwise, $v_3 = L$. Moreover, v_2 denotes the other strong bidder's value. The second phase expected payoff of a strong bidder with value v who bids $B_2(\hat{v}) \geq X$ can be expressed as:

$$\pi(\hat{v}|v) = \frac{1}{H - v_3}\left(\int_{v_3}^{\hat{v}}(v - B_2(v_2))dv_2 + \alpha\int_{v_3}^{\hat{v}}(B_2(v_2) - X)dv_2 + \alpha(B_2(\hat{v}) - X)(H - \hat{v})\right).$$

The first (second) [third] term on the RHS refers to the bidder's value minus her payment if she wins (the premium if she wins) [the premium if she loses]. The FOC is:

$$\left.\frac{\partial \pi(\hat{v}|v)}{\partial \hat{v}}\right|_{\hat{v}=v} = \frac{1}{H - v_3}\left[v - B_2^a(v) + \alpha(B_2^a(v) - X) + \alpha B_2^{a\prime}(v)(H - v) - \alpha(B_2^a(v) - X)\right] = 0$$

from which we obtain the optimal bidding strategy for strong bidders. It is readily verified that the SOC $sign\left(\frac{\partial \pi(\hat{v}|v)}{\partial \hat{v}}\right) = sign\,(v - \hat{v})$ is satisfied. Because a strong bidder with value L has not reason to bid more than $\frac{L+\alpha H}{1+\alpha}$, a weak bidder surely has no reason to do so. Therefore, she has no reason to deviate from the above bids.

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Table 1
Ranking of auctions w.r.t. likelihood of collusion: the asymmetric case

		Expected (net) payment	
Ranking	Auction	No collusion	collusion
1	AMSA: passive equilibrium	$E\{v^{[2]}\}$	$w/(w+1)$
1	EN	$E\{v^{[2]}\}$	$w/(w+1)$
2	FP	$E\{v^{[2]}\}$	1
3	AMSA: aggressive equilibrium	$E\{v^{[2]}\}$	L

Notes: This is the ranking for $w \geq 1$ and $L \geq (w+1)/w$. A higher ranking (=lower number) refers to a higher likelihood of collusion in the sense that there is a larger range of cartel costs c for which collusion is profitable in equilibrium.

Table 2
Experimental design

characteristics treatments					
treatment	price paid by winner	premium?	group-size	matching-group size	# matching-groups
FP	b_1	no	6	12	5
EN	b_2	no	6	12	5
AMSA	b_2	$0.3*(b_2-b_3)$	6	12	5
other features that were the same in all treatments					
part	collusion? who?	bidders' types	valuations	# periods	cost collusion
1	no	6 symmetric	U[0,50]	6	no
2	yes, all	6 symmetric	U[0,50]	8	0,5,2,3,7,6,4,1
3	yes, only strong	3 weak and 3 strong	weak: U[0,50] strong: U[70,120]	10	2,20,12,16,14, 6,10,8,18,4

Notes: b_i refers to the i-th highest bid. The column cost collusion reports the costs per period, from the first period to the last one.

Table 3
Collusion

		part 2		part 3	
		group colludes	votes collusion	group colludes	strong bidders' votes collusion
FP	realized	42.5%	81.9%	56.0%	79.3%
	Nash	75.0%	75.0%	70.0%	70.0%
EN	realized	26.3%	75.8%	53.0%	81.0%
	Nash	75.0%	75.0%	90.0%	90.0%
AMSA	realized	30.0%	75.0%	40.0%	68.7%
	Nash	75.0%	75.0%	--	--
	Nash passive	--	--	90.0%	90.0%
	Nash aggressive	--	--	40.0%	40.0%

Table 4
Random effects logit model on vote for collusion

	part 2	part 3
	estimate (s.e.)	estimate (s.e.)
dumam	-1.12 (0.57)**	-2.61 (0.71)**
dumfp	2.00 (0.73)**	-0.76 (0.73)
cost	-0.41 (0.05)**	-0.17 (0.03)**
value	-0.03 (0.01)**	-0.01 (0.01)
dump1	0.64 (0.25)**	-0.21 (0.38)
dump2	0.98 (0.38)**	-0.20 (0.34)
dump3	0.53 (0.29)*	-0.15 (0.36)
dump4	0.04 (0.23)	0.89 (0.62)
dump5	0.89 (0.29)**	1.06 (0.54)**
dump6	0.16 (0.34)	0.28 (0.48)
dump7		-0.25 (0.34)
dump8		-0.38 (0.54)
constant	3.71 (0.54)**	5.45 (1.08)**
Wald-test		
dumam−dumfp=0	-3.12 (1.01)**	-1.85 (0.67)**
-logL	602.21	393.45

Notes: standard errors in parentheses. ** (*) denotes significance at 5% (10%) level; the omitted treatment is EN; dumam equals 1 for AMSA and 0 otherwise; dumfp equals 1 for FP and 0 otherwise; for part 2, dump1, …, dump6 equal 1 for periods 8, …, 14, respectively, and 0 otherwise; for part 3, dump1, …, dump8 equal 1 for periods 17, …, 24, respectively, and 0 otherwise.

Table 5
Revenue

		part 1	part 2	part 3
FP	realized	35.7 (5.7)	21.3 (18.8)	70.9 (25.2)
	Nash	34.9 (6.1)	9.5 (16.6)	63.7 (21.4)
EN	realized	33.5 (8.1)	26.4 (17.7)	68.0 (33.8)
	Nash	35.8 (7.5)	9.8 (17.3)	45.2 (20.5)
AMSA	realized	34.3 (8.0)	24.9 (17.5)	76.8 (25.3)
	Nash	35.7 (5.5)	9.6 (16.8)	--
	Nash passive	--	--	45.0 (19.4)
	Nash aggressive	--	--	86.1 (14.5)

Notes: standard errors in parentheses.

Table 6
Random effects model on revenue

	part 1	part 2	part 3
	estimate (s.e.)	estimate (s.e.)	estimate (s.e.)
dumam	0.80 (1.34)	-1.49 (4.34)	8.76 (4.35)**
dumfp	2.12 (1.20)*	-5.15 (4.36)	2.90 (4.30)
cost		2.31 (0.79)**	1.39 (0.35)**
dump1	-5.88 (2.07)**	-10.07 (3.20)**	0.09 (6.08)
dump2	2.92 (0.97)**	3.66 (4.11)	6.98 (5.46)
dump3	-1.17 (1.34)	3.72 (4.19)	4.68 (6.42)
dump4	-4.75 (1.20)**	6.15 (3.36)*	-9.25 (5.40)*
dump5	-3.93 (1.73)**	-9.73 (3.53)**	-17.23 (4.56)**
dump6		9.44 (4.30)**	-4.37 (5.97)
dump7			6.53 (5.69)
dump8			3.54 (7.44)
constant	35.67 (1.16)**	17.95 (4.34)**	53.65 (6.22)**
Wald-test dumfp−dumam=0	1.32 (1.16)	-3.66 (4.33)	-5.86 (3.37)*
R^2 within	0.18	0.28	0.20
R^2 between	0.44	0.11	0.29
R^2 overall	0.18	0.26	0.21

Notes: (robust) standard errors in parentheses. ** (*) denotes significance at 5% (10%) level; the omitted treatment is EN; dumam equals 1 for AMSA and 0 otherwise; dumfp equals 1 for FP and 0 otherwise; for part 1, dump1, …, dump5 equal 1 for periods 2, …, 6, respectively, and 0 otherwise; for part 2, dump1, …, dump6 equal 1 for periods 8, …, 14, respectively, and 0 otherwise; for part 3, dump1, …, dump8 equal 1 for periods 17, …, 24, respectively, and 0 otherwise.

Table 7
Revenue conditional on (no) collusion

		part 2	part 3	
		no collusion	no collusion	collusion
FP	realized	37.0 (5.2)	97.8 (9.6)	49.8 (5.8)
	Nash	36.1 (5.3)	96.7 (5.6)	50.0 (0.0)
EN	realized	35.8 (9.2)	99.0 (12.7)	40.5 (19.9)
	Nash	36.7 (9.1)	101.3 (11.9)	39.2 (8.6)
AMSA	realized	35.6 (7.2)	93.8 (10.5)	51.3 (18.6)
	Nash	37.3 (6.7)	98.6 (7.8)	--
	Nash passive	--	--	38.8 (7.5)
	Nash aggressive	--	--	70.0 (0.0)

Notes: in part 2 realized and theoretical revenues in case of collusion equal 0 by definition; the Nash predictions are computed on the basis of the actual voting behavior. Standard errors in parentheses.

Table 8
Efficiency in %

	part 1	part 2	part 3
FP	95.4 (13.9)	96.0 (12.6)	92.7 (15.3)
EN	95.4 (16.0)	97.0 (13.1)	96.1 (11.9)
AMSA	86.7 (27.1)	94.4 (18.3)	90.9 (21.5)

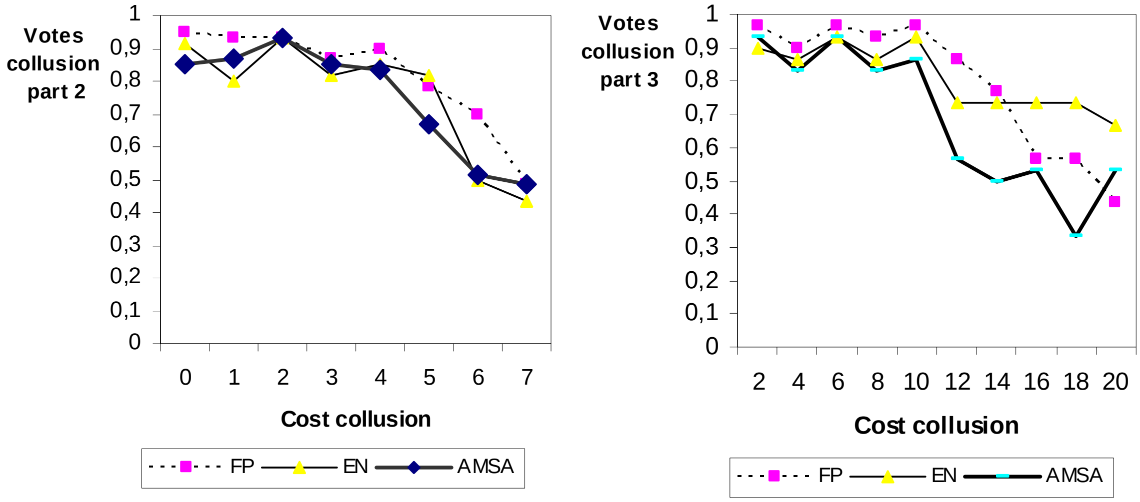
Notes: standard errors in parentheses.

Table 9
Prospects for designated bidder part 3

Part 3	profit transaction winner collusion	price paid by designated bidder	% cases designated bidder buys product
FP	49.6 (19.3) n=56	50.3 (5.6) n=52	92.9%; n=56
EN	61.8 (26.5) n=53	40.9 (19.6) n=33	96.2%; n=53
AMSA	42.3 (26.1) n=40	51.6 (17.9) n=33	82.5%; n=40

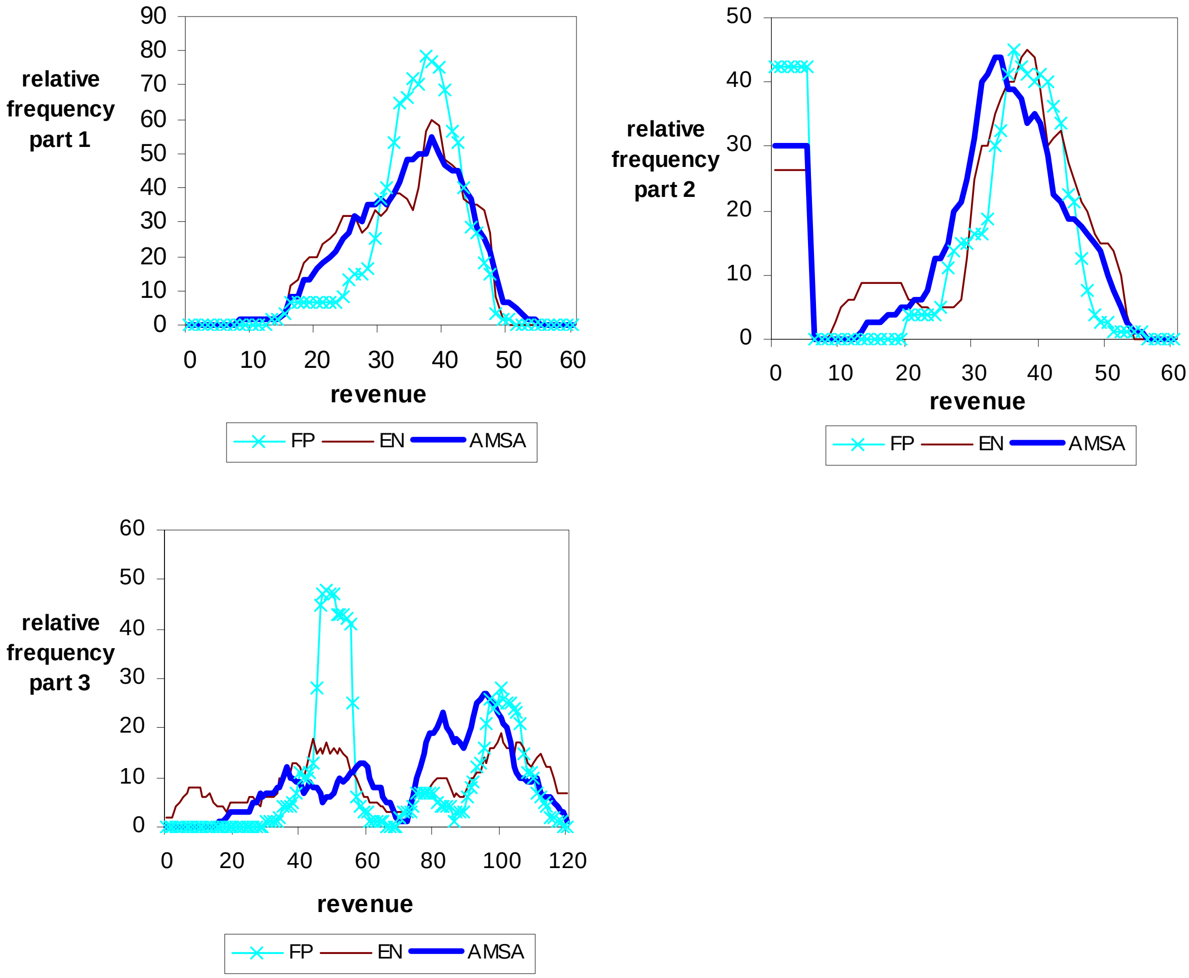
Notes: standard errors in parentheses.

Figure 1: Votes for collusion



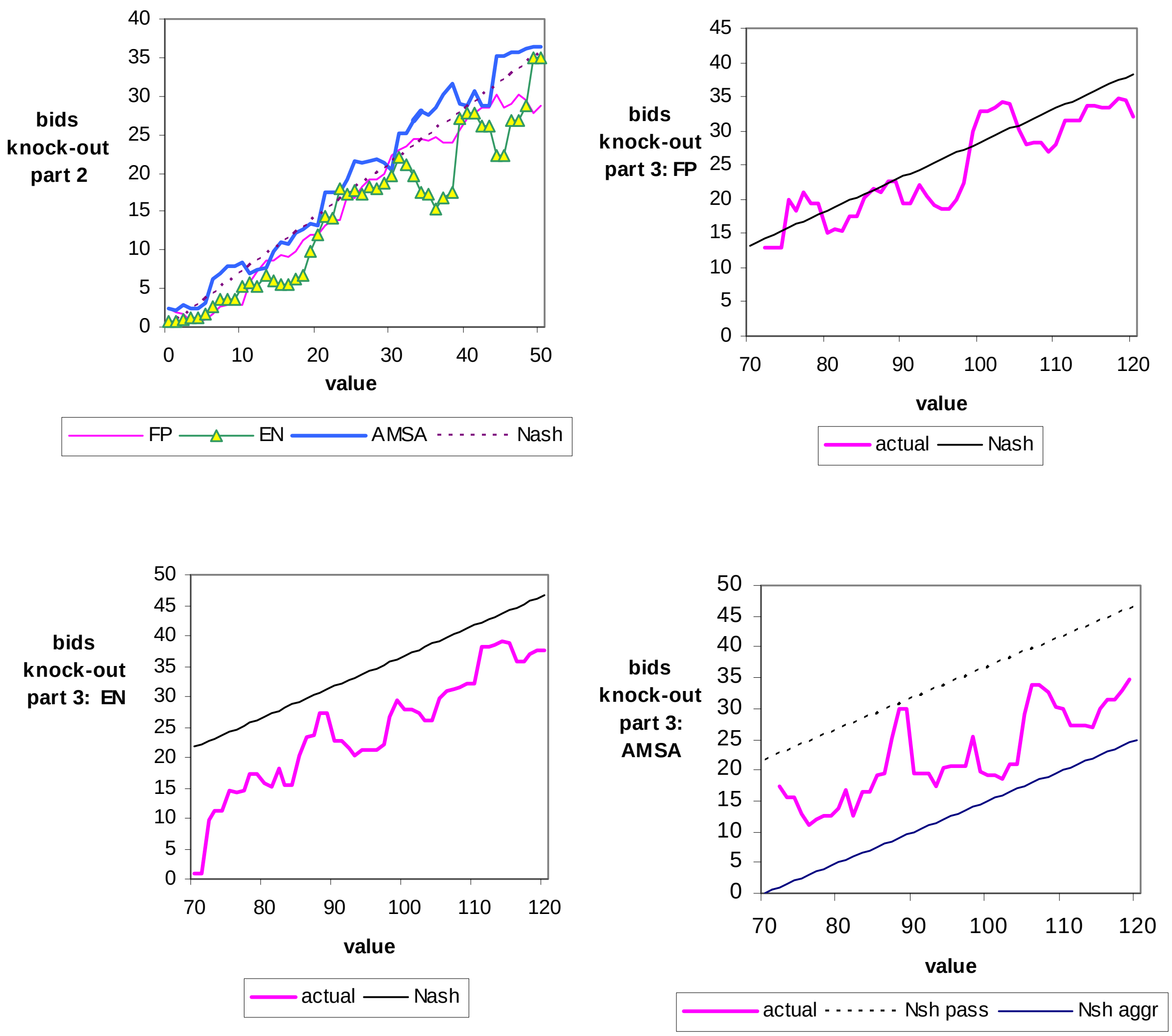
Notes: for each cost of collusion level the proportion of strong bidders' votes for collusion is displayed (vote collusion=1 if individual voted for collusion). Left panel: part2; right panel: part 3.

Figure 2: Revenue



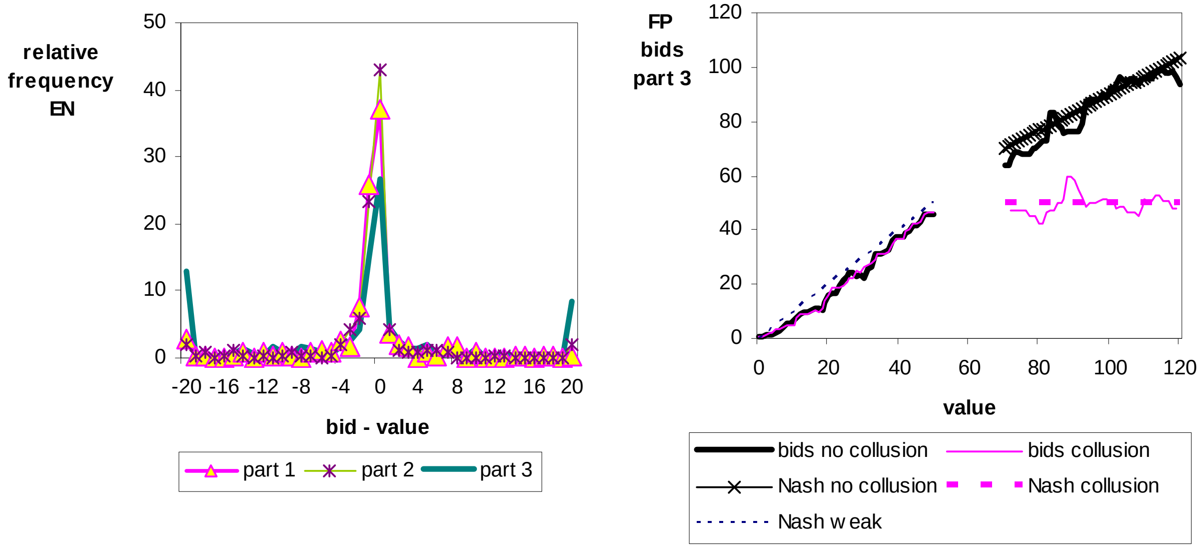
Notes: for each revenue level the percentage of outcomes that fall in the interval [revenue-5, revenue+5] is displayed. Upper-left panel: part 1; upper-right panel: part 2; lower panel: part 3.

Figure 3: Bids knock-out auction



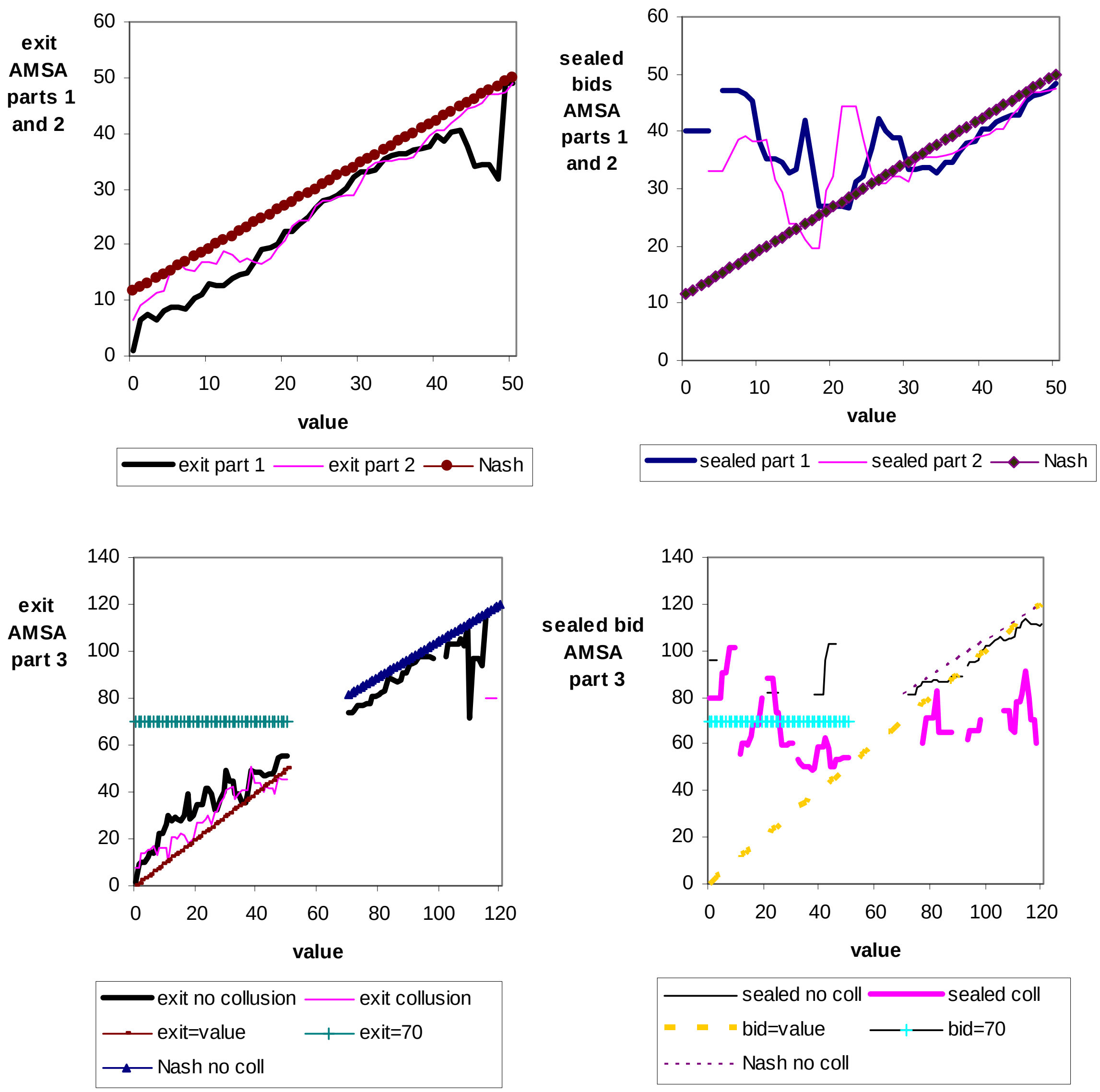
Notes: for each value the average of knock-out bids that fall in the interval [value-2, value+2] is displayed. Upper-left panel: part 2 all auctions; upper-right panel: part 3 FP; lower-left panel: part 3 EN; lower-right panel: part 3 AMSA.

Figure 4: Bids in FP (part 3) and EN



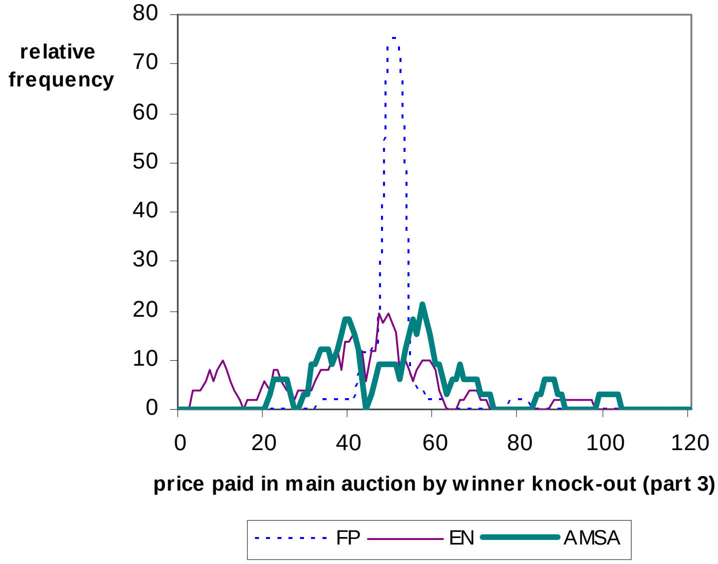
Notes: the left-panel shows the histogram of deviations from value (bid-value) in main-auction EN; the right-panel presents for each value the average of main-auction FP bids that fall in the interval [value-2, value+2].

Figure 5: Bids in AMSA



Notes: for each value the average of main-auction sealed bids in AMSA that fall in the interval [value-2, value+2] is displayed. Upper-left panel: AMSA exit first phase parts 1 and 2; upper-right panel: AMSA sealed bids second phase parts 1 and 2; lower-left panel: AMSA exit first phase part 3; lower-right panel: AMSA sealed bids second phase part 3.

Figure 6
Prices paid in main auction by designated bidder part 3



Notes: for each price paid in the main auction the percentage of outcomes that fall in the interval [price-2, price+2] is displayed.