TI 2019-009/VII
Tinbergen Institute Discussion Paper

Cartel stability in experimental auctions

Jeroen (J.) Hinloopen[1,2]
Sander (A.M.) Onderstal[1]
Leonard Treuren[1]

[1] University of Amsterdam
[2] CPB

Cartel stability in experimental auctions[1]

Jeroen Hinloopen,[2] Sander Onderstal,[3] and Leonard Treuren[4]

25 JANUARY 2019

ABSTRACT:

Using laboratory experiments, we compare the stability of bidding rings in the English auction and the first-price sealed-bid auction in a heterogeneous-value setting. In both a re-matching condition and a fixed-matching condition, we observe that biddings rings are more stable in the English auction than in the first-price sealed-bid auction. In both conditions, the first-price sealed-bid auction dominates the English auction in terms of average revenue and the revenue spread. The English auction outperforms the first-price sealed-bid auction in terms of efficiency.

KEYWORDS: Cartel stability; English auction; First-price sealed-bid auction; Laboratory experiments

JEL CODES: C92; D44; L41

[1] We thank the University of Amsterdam Research Priority Area in Behavioral Economics for their financial support.

[2] University of Amsterdam, Tinbergen Institute, and CPB; Roetersstraat 11, 1018 WB Amsterdam, The Netherlands; J.Hinloopen@uva.nl.

[3] University of Amsterdam and Tinbergen Institute; Plantage Muidergracht 12, 1018 TV Amsterdam, The Netherlands; Onderstal@uva.nl.

[4] University of Amsterdam and Tinbergen Institute; Roetersstraat 11, 1018 WB Amsterdam, The Netherlands; l.m.treuren@uva.nl.

1. Introduction

On December 9, 2016, a member of the British nobility sold the painting 'Portrait of a Young Gentleman' for £137,000 in an auction at Christie's in London. Some 18 months later, the buyer, art dealer Jan Six, announced in the press that he recognized the portrait as the work of Rembrandt and that he had found an investor that was prepared to pay millions for it. Later, colleague art dealer Sander Bijl revealed that he had also identified the painting as a genuine Rembrandt and that he had struck a deal with Six that Bijl would abstain from bidding in the auction so that Six would be able to buy the painting at a price far below its actual value (Ribbens, 2018).[1]

Such collusion among bidders is a serious concern for auctioneers like Christie's. The consensus view in the literature is that in settings where bidders are likely to form a bidding ring, auctioneers are well-advised to use the first-price sealed-bid auction rather than the English auction (see, e.g., Klemperer, 2002, Kovacic et al., 2006, and OECD, 2006).[2] The intuition is that collusion is stable in the English auction and not in the first-price sealed-bid auction because only in the former, the designated winner can retaliate defection by overbidding a defecting bidder in the auction itself.[3] In this paper, we report results from laboratory experiments testing this intuition.

The received experimental literature finds little support for the claim that the English auction is more conducive to collusion than the first-price sealed-bid auction. *Tacit* collusion is rarely observed in either auction type in the laboratory: if subjects deviate systematically from the one-shot Nash prediction, they bid more aggressively instead of less (Kagel, 1995).[4,5] Bidders

---

[1] Bijl and Six are now in a dispute over the spoils of the deal. Six even publicly denies (for obvious reasons) that he and Bijl made the deal in the first place.

[2] In the English auction, the price is raised successively until one bidder remains, who wins the object for the final price. In the first-price sealed-bid auction, bidders independently submit sealed bids. The highest bidder wins the object and pays her own bid. In practice, both auction formats feature in prominent cartel cases. For instance, the first-price sealed-bid auction featured in cartels for school milk tenders (Porter and Zona, 1999) and infrastructure procurement (Bajari and Ye, 2003; Clark et al., 2018), and the English auction in cartels involving tobacco (Phillips *et al*., 2003) and stamps (Asker, 2010).

[3] Robinson (1985) provides a formal proof. Marshall and Marx (2007) generalize Robinson's result allowing for partial cartels and side-payments. Marshall and Marx (2009) study how procedural details of the English auction affects its collusive properties.

[4] Tacit collusion is sometimes observed in multi-unit auctions in the lab, in particular in settings where bidders can find ways to 'divide the market'. See Kwasnica and Sherstyuk (2013) for an overview.

[5] In the case of multi-unit auctions, Burtraw *et al*. (2009) find that bidders are better able to sustain collusive agreements in ascending auctions than in sealed-bid auctions when interacting repeatedly.

sometimes manage to collude explicitly when they get the opportunity to communicate with each other before the auction.[6,7]

Several recent experimental studies compare the collusive properties of the English auction and the first-price sealed-bid auction in independent private values settings where bidders can communicate. In Hu *et al.*'s (2011) framework, bidders can decide to form a cartel before the auction at a cost. If a cartel forms, the bidders in the cartel bid in a pre-auction knockout to determine who becomes the provisional auction winner and to establish the side-payments from the provisional winner to the other cartel members. The experimental protocol enforces the agreement that (1) the designated bidder unconditionally divides her winning bid in the knockout among the other cartel members, and (2) the designated winner is the only bidder in the cartel entering the auction. Hu *et al*. (2011) find that at least as many cartels form in the first-price sealed-bid auction as in the English auction.

Llorente-Saguer and Zultan (2017) study collusion in the first-price and the second-price sealed-bid auctions. The second-price sealed-bid auction is closely related to the English auction in that in both auctions, the winning bidder pays the second highest bid and that both auctions have an equilibrium in which bidding value is a weakly dominant strategy in an independent private values setting. Llorente-Saguer and Zultan (2017) examine a two-bidder setting where before the auction, one of the bidders can offer a bribe to the other bidder to stay out of the auction. On the basis of results by Eső and Schummer (2004) and Rachmilevitch (2013), the authors hypothesize that the second-price auction supports collusion in equilibrium, in contrast to the first-price auction. Their data provide strong evidence against this hypothesis in that they do not show any systematic differences in collusive outcomes between the first-price and the second-price auction.

Agranov and Yariv (2018) study the effect of communication (via chat) and post-auction transfer opportunities on collusion in first-price and second-price sealed-bid auctions. They observe that communication alone depresses bids only to a limited extent. When bidders can

[6] See, e.g., Isaac and Walker (1985), Phillips *et al*. (2003), Sherstyuk and Dulatre (2008), Burtraw *et al*. (2009), Noussair and Seres (2017), and Agranov and Yariv (2018). Kagel and Levin (2016). Kwasnica and Sherstyuk (2013) survey this literature.

[7] This finding fits well with the abundant experimental evidence that decision makers tend to benefit from pre-play communication in dilemma games, including the prisoner's dilemma (e.g., Dawes *et al*., 1977), public good games (e.g., Isaac *et al*. 1985), oligopoly games (e.g., Isaac *et al*., 1984, Hinloopen and Soetevent, 2008, Fonseca and Normann, 2012, Gomez-Martinez et al., 2016), and rent-seeking games (Kimbrough and Sheremeta, 2013).

transfer money among each other after the auction, very low prices commonly emerge under both auction formats. The authors do not find the auctions to differ significantly in terms of collusive outcomes.

It is not clear why the experimental literature to date has offered little support for the proposition that the English auction is more conducive to collusion than the first-price sealed-bid auction. Several factors might explain this discrepancy. For instance, cartels are stable by construction in Hu *et al.*'s (2011) and Llorente-Saguer and Zultan's (2017) experiments. And Llorente-Saguer and Zultan (2017) and Agranov and Yariv (2018) use the second-price sealed-bid auction rather than the English auction. In this paper, we aim at improving our understanding of the conditions under which the English auction is more prone to collusion than the first-price sealed-bid auction. We do so closely following Robinson's (1985) simple framework in which, by construction, bidders have formed a cartel before the start of the auction. In two experimental studies, we let groups of three bidders compete in heterogeneous-value auctions. Bidders are commonly informed about each other's values. The bidder with the highest value is the designated winner. All bidders are informed about an (unbinding) agreement that only the designated winner submits a bid. In Study 1, we compare the two auctions in a setting where participants are re-matched after every auction. In Study 2, we let the participants interact within the same group of bidders for a number of rounds. Our results confirm that more cartels are stable in the English auction than in the first-price sealed-bid auction in both a re-matching condition and a fixed-matching condition.[8]

The set-up of the remainder of this paper is as follows. We first review Robinson's (1985) theoretical predictions in Section 2. In Section 3, we present our experimental procedures and design for the re-matching case (Study 1). We report our experimental finding in Section 4. Section 5 contains our findings for the fixed-matching condition (Study 2). Section 6 concludes.

2. THEORETICAL MODEL

We use Robinson's (1985) model to examine the collusive properties of the English auction (EN) and the first-price sealed-bid auction (FP). Consider an auction (EN or FP) where one indivisible object is auctioned to one bidder out of a set of at least two risk-neutral bidders. Before the

[8] Hinloopen and Onderstal (2013) find similar results in a common-value setting where cartel formation is endogenous.

auction, bidders decide independently whether or not to submit a bid. A bidder's utility equals zero if she does not win the auction, and equals the difference between the value for the object and the winning bid if she wins. Before the auction, the bidders have formed an all-inclusive cartel in which they have credibly revealed their private information about their values for the object to each other. The model does not specify how the bidders reveal their private information in a credible way.[9] Suppose bidder h, the designated winner, has the highest value V among all bidders. Assume that $V \geq R$, where R represents the seller's reserve price. Robinson (1985) derives the following result.

PROPOSITION 1 (Robinson, 1985). (i) EN has a Nash equilibrium where bidder h has a dropout price V and all other cartel members have dropout prices of R or do not submit a bid; (ii) FP has no Nash equilibrium in which bidder h bids below the second highest value, or in which the bidder with the second highest value does not submit a bid if her value exceeds R.

The intuition behind this result is the following. In EN, bidder h plays a weakly dominant strategy by staying in the auction until the price reaches her value V. For the other bidders, bidding R or not submitting a bid is a best response, so the proposed strategies constitute a Nash equilibrium. Of course, such collusive equilibria require the designated losers to play a weakly dominant strategy: irrespective of the bidding strategies of others, they are always weakly better off by overbidding others up to a price equal to their value. In the experiment, we explore the extent to which designated losers play weakly dominated strategies. In FP, the cartel member having the second highest value would be able to strictly improve if h bid below the second highest value by submitting a bid slightly above h's bid. That is, bidder h bidding below the second highest valuation cannot be part of a Nash equilibrium.

Proposition 1 has direct implications regarding cartel stability in EN and FP. We consider a cartel to be stable if, and only if, all designated losers refrain from bidding. In EN, stable cartels can be sustained in equilibrium, in contrast to FP:

[9] Generally, side-payments are required for bidders to reveal their private values truthfully in a pre-auction knockout. See, e.g., McAfee and McMillan (1992).

PROPOSITION 2. In EN, stable cartels can be part of a Nash equilibrium; in FP stable cartels cannot be part of a Nash equilibrium

3. STUDY 1: EXPERIMENTAL PROCEDURES AND DESIGN

The computerized experiment was conducted at the Center for Research in Experimental Economics and political Decision making (CREED) of the University of Amsterdam. Students were recruited by public announcement. In total 144 students from the University's entire undergraduate population participated in one of six sessions. The points that subjects earned were converted according to an exchange rate of 50 points = €1. A show-up fee of €7 was converted to 350 points for those subjects that participated in the experiment. To ensure that all subjects understood the experiment, they had to correctly answer several test questions before the experiment started.[10] Average earnings were €12.07 per subject while sessions took 60 to 90 minutes to complete.

At the start of each session, matching groups of nine subjects were formed randomly. These groups did not change during the sessions and communication between subjects (other than through their play) was not possible. All sessions consisted of at least 35 periods. From round 35 onwards, each next round was the final round with 20% probability. At the start of each round subjects were matched randomly with two other subjects from the same matching group.[11] In both auctions 72 subjects participated, yielding in total 16 statistically independent observations.

Recall that Propositions 1 and 2 rely on the assumption that bidders share their private information before the auction. In the experiment bidders drew their values from a uniform distribution on the set {20, 21, …, 70}. These draws were independent across rounds and bidders, but identical across auctions. Bidders were commonly informed about each other's values. By implementing a complete-information setting, we by-pass the question as to how bidders manage to credibly reveal their information to each other before the auction. The designated winner is the bidder with the highest value. In case of a tie the designated winner was

[10] Appendix A contains an English translation of the instructions.

[11] Subjects were re-matched in such a way that they would not face the same opponent(s) in two consecutive periods. Subjects were informed about this conditional re-matching. Although (tacit) collusion is quite unlikely to be observed in groups with four or more subjects (see, e.g., Huck *et al*., 2004 and Fonseca and Normann, 2012), we introduced this conditional re-matching to eliminate any tendency towards (tacit) collusion due to repeated play that might affect a proper comparison between treatments. In section 5, we discuss our second study, where subjects were not re-matched.

selected randomly. In what follows, we sometimes refer to the remaining two bidders as the designated losers.

After bidders learned their values, they were informed about a cartel agreement, according to which only the designated winner submits a bid. Designated losers received the message that [a]ccording to the agreement you are not supposed to submit a bid, while designated winners were informed that [a]ccording to the agreement you are the only bidder who is supposed to submit a bid. The cartel agreement was not binding though. This design feature corresponds exactly to Robinson's (1985) set-up whereby [t]he cartel is assumed to select from among its members a designated winner (who should be the member with the highest valuation if they differ) and to recommend that he follow a particular bidding strategy while requesting other cartel members to be inactive in the bidding (p. 143).

We implemented the following auction rules. In FP, each subject could submit a bid from the set {0, 1, …, 70} or could decide not to submit a bid. The highest bidder won the auction of that round. Ties were resolved randomly (nobody won the object when all group members decided not to submit a bid). The auction winner earned the difference between her value and her bid. In EN, a thermometer showed a price that started at 0 and increased by 1 every half second. Bidders could indicate to leave the auction at any price by pressing a virtual button. When a bidder pressed that button, the thermometer would briefly pause at the then current price, informing the remaining bidders at what price the bidder left the auction. When all but one bidder had left the auction, the remaining bidder bought the item at the price at which the runner-up left the auction. When a bidder was the only one submitting a bid, she immediately obtained the object for a price of 0. When, at a price of 70, less than two bidders had left the auction, chance determined which of the remaining bidders won the auction (for a price of 70). We always let the thermometer run up to 70 to prevent participants from learning about the auction outcomes in other groups.

4. Study 1: Experimental Results

In this section we analyze the experimental data of Study 1. In Section 4.1, we compare FP and EN in terms of cartel stability, the key outcome variable in this paper. Section 4.2 presents the relative performance of the two auctions in terms of revenue and efficiency, two outcome variables an auctioneer may care about. In Section 4.3, we zoom in on the bidding behavior. Unless otherwise noted, the Wilcoxon rank-sum test is employed for comparisons between different treatments, and the Wilcoxon signed-rank-sum test is used for within-treatment comparisons. All tests are two-sided, with each re-matching group taken as one independent observation in the non-parametric tests. For the non-parametric tests, we restrict the statistical analyses to periods 6 through 35 to minimize possible learning and end-game effects. We find qualitatively the same results when we take all periods into account.

Figure 1: Propensity to defect (panel a) and cartel breakdown (panel b), over time across auctions

Panel a Panel b

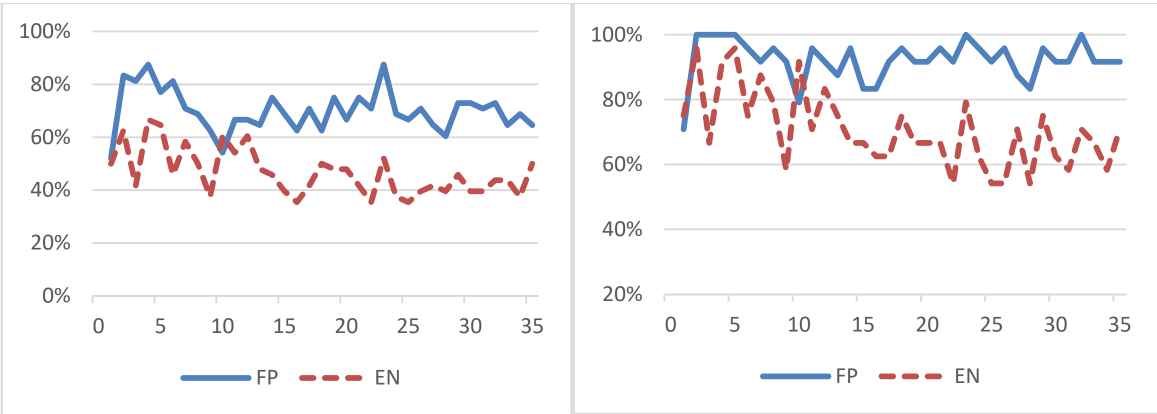


Table 1: Cartel stability across auctions

	Propensity to defect (by subject)	Cartel breakdown
EN	0.45	0.68
	$\wedge^{**}$	$\wedge^{**}$
FP	0.69	0.92

Notes: Propensity to defect (by subject) = probability that a designated loser submits a bid; Cartel breakdown = probability that at least one designated loser submits a bid; ***, ** and * indicate statistical significance at the 1%, 5% and 10% level, respectively.

4.1 Cartel Stability

We mark a bidder as defecting from the cartel agreement if, and only if, she submits a bid while being a designated loser. We say that a cartel breaks down if at least one bidder defects. As a result, cartels that do not break down are stable. Table 1 presents the aggregate results of cartel stability across auctions, and Figure 1 shows subjects' propensities to defect (panel a) and cartel breakdown (panel b) over time. Cartels in EN are substantially more likely to be stable than cartels in FP. Subjects defect in 69% of the cases in FP and in 45% of the cases in EN. As a result, in FP 92% of the cartels break down, as opposed to 68% in EN. In other words, cartels are about 4 times more likely to be stable in EN than in FP, a difference that is statistically significant. These results are consistent with the theory in Section 2. However, notice that many cartels break down in EN as well.

Taking a closer look at the data, we observe that cartel stability is unaffected by the value draws. In FP, the average value draw for stable cartels is 41.79, and 45.59 for unstable cartels ($p = 0.124$), the concomitant standard deviations are 12.48 and 12.46 ($p = 1.000$) respectively, and the difference between the two highest values is, respectively, 9.90 and 13.98 ($p = 0.124$). For EN these respective numbers are 45.17 and 45.75 ($p = 0.484$), 14.32 and 12.45 ($p = 0.484$), and 10.56 and 9.60 ($p = 0.208$). In FP (EN), 635 (390) of all 993 (646) defections were committed by the cartel member with the second highest value. In FP, the probability that the cartel member with the second highest value defects from the agreement, 0.84, is higher than the probability that the cartel member with the lowest value defects, 0.52 ($p = 0.012$). For EN, these respective numbers are 0.52 and 0.37 ($p = 0.012$).

Result 1: Cartel stability. The fraction of stable cartels is significantly greater in EN than in FP. In FP, 92% of all cartels break down, while in EN 68% of all cartels break down. In both auctions, cartel stability is not related to the average value in a cartel, value variance, or the difference between the highest and the second highest value. The cartel member with the second highest value is significantly more likely to defect than the cartel member with the lowest value.

4.2 Revenue and Efficiency

For the sake of comparability across rounds, we normalize revenue by reporting it as a fraction of the second highest value among the three bidders in a cartel. Table 2 contains the aggregate results and Figure 2 displays revenue for both stable and unstable cartels over time. Normalized revenue is significantly lower in EN (0.58) than in FP (0.98). This is also true if we distinguish between stable and unstable cartels. In EN revenue for stable cartels (which is zero by construction) is significantly lower than revenue for unstable cartels. In FP, there is no significant difference in terms of revenue between stable and unstable cartels. Revenue of unstable cartels in EN is significantly lower than revenue of stable cartels in FP (p = 0.009).

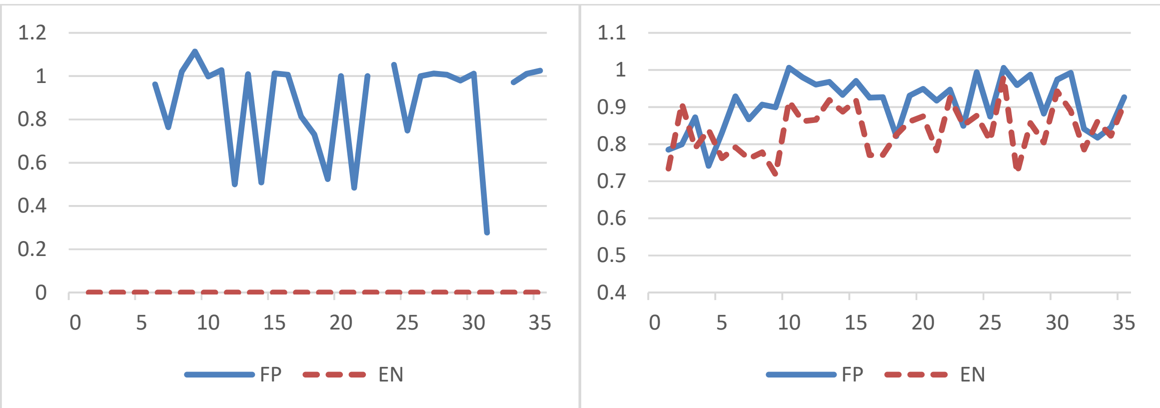
Table 2: Revenue of stable and unstable cartels across auctions

	FP		EN
Stable cartels	0.97	$>^{***}$	0
	∧		$\wedge^{**}$
Unstable cartels	0.99	$>^{***}$	0.85
All cartels	0.98	$>^{***}$	0.58

Notes: Stable cartel = no designated loser submits a bid; Unstable cartel = at least one designated loser submits a bid; ***, ** and * indicate statistical significance at the 1%, 5% and 10% level, respectively.

Figure 2: Revenue as a fraction of the second highest value.

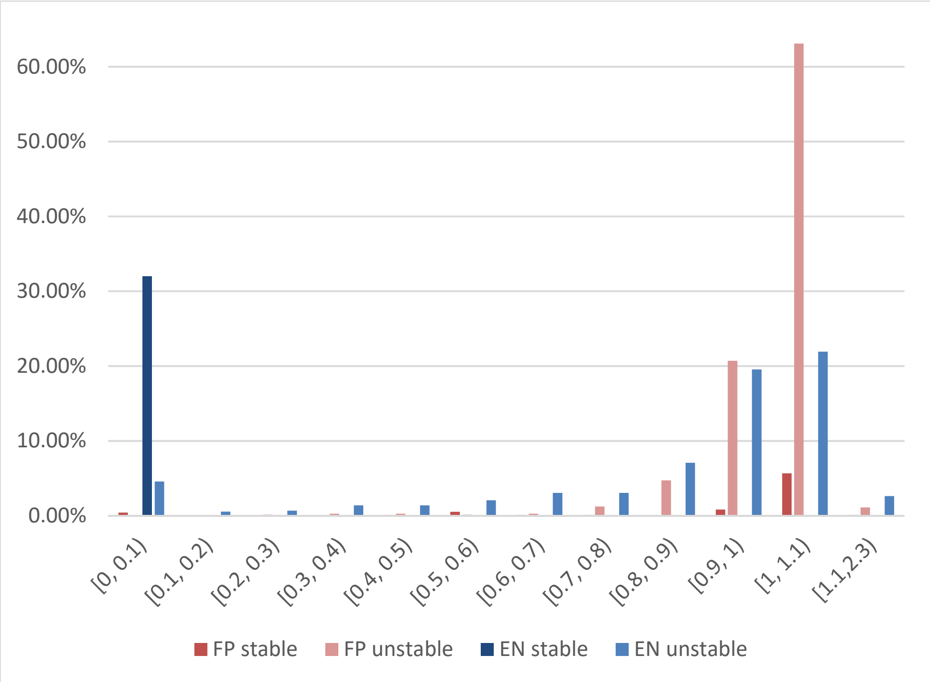
Panel a: Stable cartels Panel b: Unstable cartels



The variance in revenue in EN is 0.197, which is significantly higher than the variance of 0.004 in FP (p = 0.001). As Figure 3 shows, fundamentally different revenue distributions underlie this observed difference. For both auctions, a large fraction of revenue is concentrated around the second highest value. In addition, in EN a spike in the distribution of revenue arises at 0 due to stable cartels, that yield no revenue by construction. Such a spike is not visible in FP. As a result, the variance in revenue is much lower in FP than in EN. We discuss individual bidding behavior underlying the revenue distributions in the next subsection.

RESULT 2: REVENUE. EN raises significantly less revenue than FP. The variance of revenue as a fraction of the second highest value is significantly higher in EN than in FP.

Figure 3: Relative frequencies of revenue

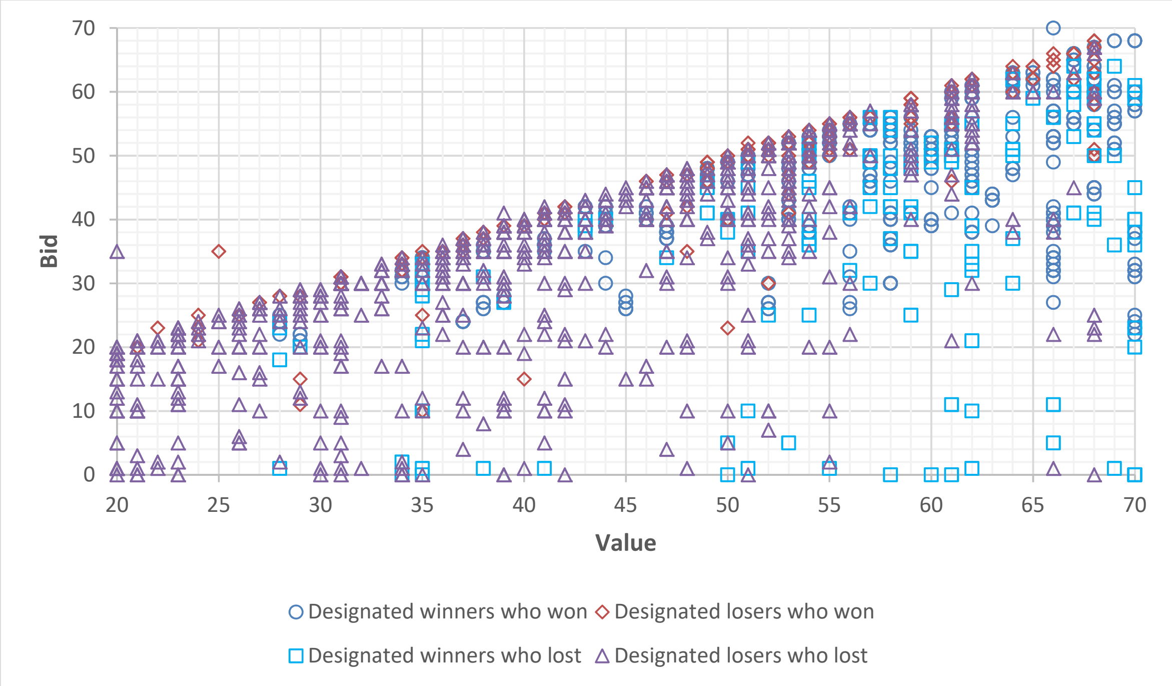


How do the auctions perform in terms of efficiency? An auction is efficient if, and only if, the bidder with the highest value wins the auction. In other words, efficiency dictates that the designated winner secures the object. This happens in 78% of the cases in FP and 93% of the cases in EN. This difference is significant (p = 0.001). An alternative measure of efficiency is the ratio of realized to maximum efficiency: $(w - v)/(V - v)$, where w is the winner's value, and v [V] refers the lowest [highest] value in the cartel (see, e.g., Hu *et al*., 2011). Using this measure, efficiency in EN is 0.98, which is significantly higher than the efficiency of 0.93 in FP (p = 0.005).

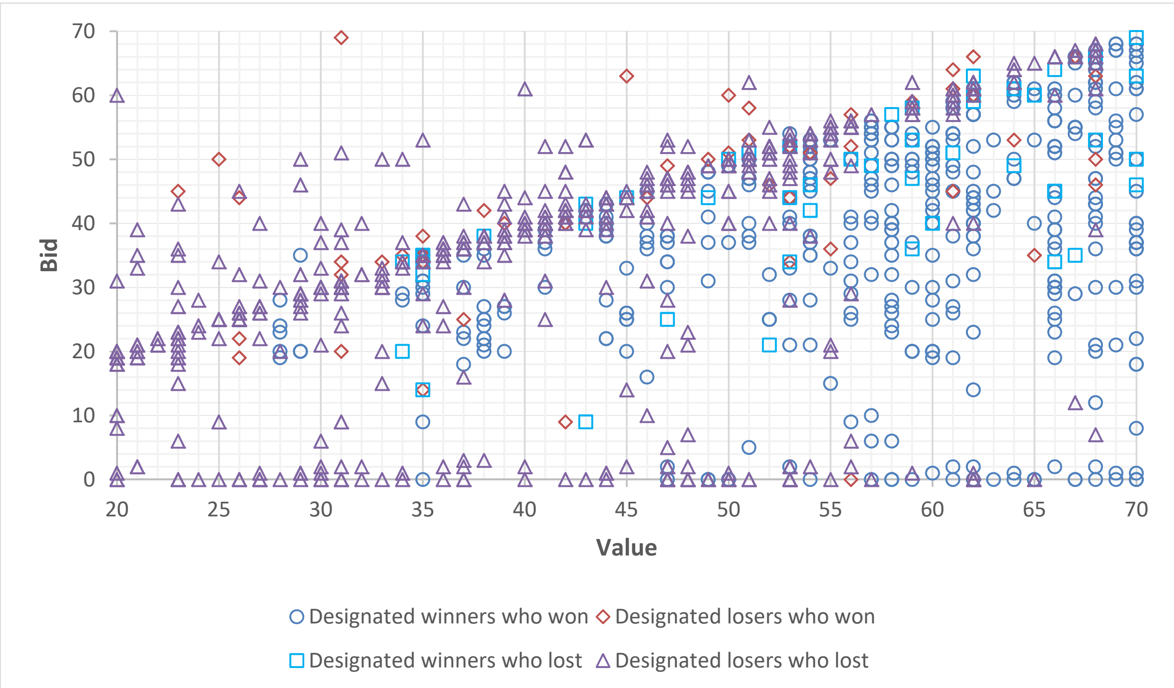
RESULT 3: EFFICIENCY. EN is more efficient than FP.

Figure 4: Bids as a function of value for FP (in panel a) and for unstable cartels in EN (in panel b)

Panel a: FP



Panel b: EN



4.3 BIDDING BEHAVIOR

Figure 4 displays all bids for stable and unstable cartels in FP and dropout prices for unstable cartels in EN (recall that in the case of a stable cartel, the price equals zero in EN by construction). Overall, we observe a high concentration of bids around value for both auctions, which are mainly losing bids, and bids submitted by designated losers. In EN, bids above value are relatively common. Such bids are typically non-winning bids submitted by designated losers.[12] For both auctions, winning bids by designated winners are typically below value, especially for higher values.

To what extent is bidding behavior consistent with equilibrium play? For FP, the designated winner bids at least the second highest value in equilibrium according to Proposition 1. A large range of Nash equilibria produces such an outcome. Such equilibria have in common that 1) the designated winner wins the auction, (2) she bids an amount at least equal to the second highest value, and (3) at least one of the designated losers submits a bid of at least the second highest value, such that the designated winner could not reduce her bid and still win. The observed bidding behavior deviates from this pattern in that we observe that (1) the designated winner secures the object in only 78% of the cases, (2) the bid of designated winners (0.92) is significantly below the second highest value ($p = 0.012$), and (3) bids of designated losers (0.76) are significantly below the second highest value ($p = 0.012$).[13] While aggregate behavior cannot be supported by equilibrium play, it is miles away from the collusive outcome in which only the designated winner submits a bid, winning the object for a price of zero.

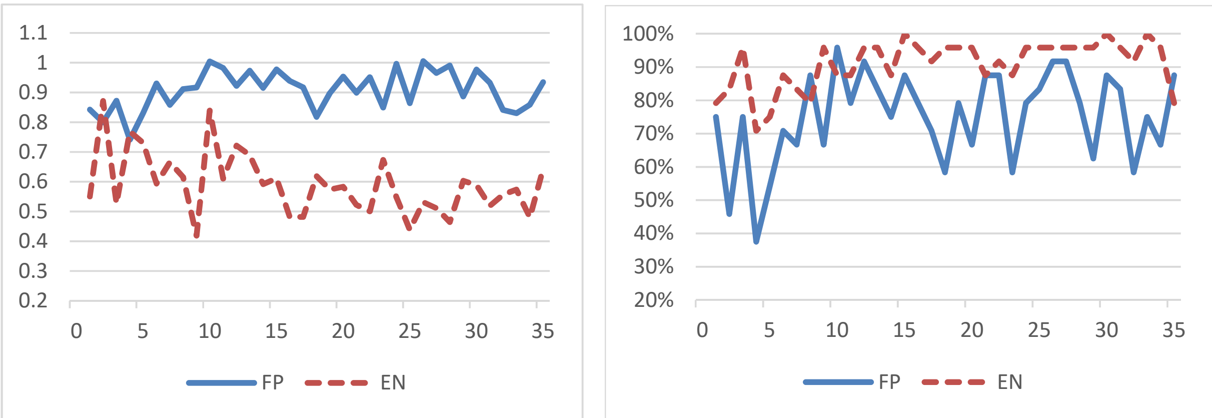
In EN, an even larger range of outcomes can be supported in equilibrium than in FP. In any equilibrium (1) designated losers, when submitting a bid, leave the auction at a price between 0 and the highest value, (2) the designated winner stays in the auction until the price reaches her value, and (3) the designated winner wins the auction. Observed behavior is reasonably in line with this prediction. The designated winner typically does not exit the auction at a price below her value: Only in 44 instances (6% of all auctions), the designated winner leaves the auction at a price below her value allowing a designated loser to win.[14] As said, in 32% of the cases, the bidders reach the collusive equilibrium outcome in which both designated losers abstain from

[12] In EN, 89 times a subject bid above her value, resulting in winning the auction 65 times. In FP, the concomitant values are eight and three.
[13] In only seven cases a designated loser bid above value, resulting in winning the auction on four occasions.
[14] In 27 of those cases, the winning bid of the designated loser was below her own value.

bidding and the designated winner obtains the object for a price of zero. Figure 3 highlights two typical scenarios when a designated loser submitted a bid: either the designated loser leaves the auction almost immediately, or she exits the auction at a price close to her value. More specifically, 7.89% bid 0, 4.64% bid in the interval [1, 5], and 63.16% bid in the interval [value-5, value].[15] In line with equilibrium, deviating from the agreement is hardly profitable: The price paid by a designated loser winning the auction does not differ significantly from the second highest value (p = 0.484).[16] As we observed in the previous section, the designated winner wins in 93% of the cases, which is significantly less than 100% (p=0.012).

Figure 5: Designated winners' bids as a fraction of the second highest value (panel a) and the likelihood of winning the auction (panel b), over time across auctions.

Panel a Panel b



Does behavior converge towards equilibrium play over time? Figure 5 suggests it does. The figure shows the bids of the designated winners over time (panel a) and the probability that the designated winner wins the auction (panel b). In EN, after round ten, designated winners are almost certain to win the auction; bids are somewhat higher than half the second highest value. In FP, bids by the designated winner exhibit a slightly upward trend towards the second highest

[15] In 86 auctions (13.31% of all defections) a designated loser left the auction at a price exceeding her value, which resulted in winning the auction 21 times.

[16] Over all periods, the designated loser pays significantly less than the second highest value (p = 0.017).

value, with a concomitant increase of the likelihood that the designated winner wins the auction.[17]

> **RESULT 4: BIDDING BEHAVIOR.** In FP, designated winners and deviating designated losers submit a bid close to, but statistically significantly below, the second highest value. In EN, designated winners hardly ever leave the auction at a price below their value while designated losers that submit a bid either step out of the auction almost immediately or exits the auction at a price close to their value.

5. STUDY 2: FIXED MATCHING

In the previous section, we observed that cartels are more likely to be stable in EN than in FP, although also in EN the majority of the cartels break down. The purpose of this second study is to test the robustness of this result in the case of repeated interaction.[18] The experimental procedures are the same as in Study 1 with the only exception that the three subjects that were matched at the beginning of the session remained in the same group over the course of the experiment. In both FP and EN, 27 subjects participated yielding nine independent observations per auction. Subjects earned €12.67 on average in sessions that lasted, again, between 60 and 90 minutes.

The structure of this section is as follows. In section 5.1, we report our findings for cartel stability. Section 5.2 contains an analysis of revenue and efficiency. In section 5.3, we report our findings on bidding behavior. We conclude in section 5.4 by comparing the fixed-matching case with the re-matching case.

5.1 CARTEL STABILITY

Table 3 summarizes the results on cartel stability. As with re-matching, subjects have a significantly higher propensity to defect in FP than in EN. Accordingly, a significantly higher fraction of cartels breaks down in FP than in EN. For cartels in both FP and EN, the designated

[17] Appendix B provides regressions investigating the trend of bids and convergence point of FP.
[18] In practice, cartels often center around a set of bidders that interact repeatedly (Phillips *et al.*, 2003).

loser with the highest value defects significantly more often that the designated loser with the lowest value.[19]

Table 3: Cartel stability across auctions and matching schemes

	Propensity to defect (by subject)			Cartel breakdown		
	Re-matching		Fixed matching	Re-matching		Fixed matching
EN	0.45	>	0.32	0.68	>	0.45
	$\wedge^{**}$		$\wedge^{*}$	$\wedge^{**}$		$\wedge^{*}$
FP	0.69	>	0.64	0.92	>	0.88

Notes: Propensity to defect (by subject) = probability that a designated loser submits a bid; Cartel breakdown = probability that at least one designated loser submits a bid; ***, ** and * indicate statistical significance at the 1%, 5% and 10% level, respectively.

How do the value draws affect cartel stability? In EN, the average value is 46.06 for unstable cartels and 43.21 for stable cartels (p = 0.345), and the variances are, respectively, 136.05 and 172.49 (p = 0.116). For FP the corresponding numbers are 46.28 and 38.78 (p = 0.018), and 150.66 and 189.00 (p = 0.237). In other words, in FP, cartels are more likely to break down when the bidders draw larger values. Also, in FP, the difference between the highest and second highest value is 18.96 for stable cartels, and 11.08 for unstable cartels. The latter is significantly below the former (p = 0.018). In EN these differences are, respectively, 13.86 and 8.58 (p = 0.028). That is, cartel defection is more likely to occur the smaller is the difference between the highest and second highest value. So, in contrast to the re-matching condition, we observe that the value draws affect cartel stability in the fixed-matching condition, at least to some extent.

> **Result 5: Cartel stability.** In the case of fixed matching, the fraction of stable cartels is significantly larger in EN than in FP. In FP, 88% of cartels break down, while in EN 45% of the cartels break down. In both auctions, cartel stability is not related to value variance and

[19] For cartels in FP, the designated loser with the highest value defected in 77.66% of all cases, while the designated loser with the lowest value defected in 51.04% of the cases (p = 0.008). In EN, these numbers are, respectively, 36.76% and 26.04% (p = 0.042).

cartels are more stable the greater is the difference between the highest and second highest value. In FP, cartels are less likely to be stable when bidders draw larger values on average. In EN, cartel stability is not significantly affected by the average value draw.

Table 4: Revenue, re-matching and fixed matching

	FP		EN
Fixed matching			
Stable cartels	0.94	$>^{***}$	0.00
	∨		$\wedge^{**}$
Unstable cartels	0.93	>	0.83
All cartels	0.93	$>^{***}$	0.42
	∧		∧
Re-matching	0.98	$>^{***}$	0.58

Notes: Stable cartel = no designated loser submits a bid; Unstable cartel = at least one designated loser submits a bid. ***, ** and * indicate statistical significance at the 1%, 5% and 10% level, respectively.

Table 5: Variance of revenue, across auctions and matching protocols

	FP		EN
Re-matching	0.004	$<^{***}$	0.197
	∧		$\vee^{***}$
Fixed matching	0.013	$<^{*}$	0.051

Notes: ***, ** and * indicate statistical significance at the 1%, 5% and 10% level, respectively.

5.2 Revenue and Efficiency

Table 4 lists auction revenue for both stable and unstable cartels across auctions. As with re-matching, revenue is lower in EN than in FP. This also holds (again) if we consider stable and unstable cartels separately, although there is no statistically significant difference anymore between the revenue of unstable cartels. Moreover, as Table 5 shows, the variance of revenue is significantly lower in FP than in EN, as with re-matching. All in all, Result 2 is robust with respect to the matching protocol.

RESULT 6: REVENUE. In the case of fixed matching, EN raises significantly less revenue than FP. In EN, revenue is significantly lower in the case of stable cartels than in the case of unstable cartels; in FP, stable and unstable cartels do not differ significantly in terms of revenue. The variance of revenue as a fraction of the second highest value is significantly higher in EN than in FP.

Finally, we consider the relative efficiency of EN and FP (Table 6). As in the re-matching case, EN is more efficient than FP: the probability that the designated winner wins the auction is significantly higher in EN, and significantly more of the potential value is realized.

RESULT 7: EFFICIENCY. In the case of fixed matching, EN is more efficient than FP.

Table 6: Efficiency, across auctions and matching protocol

	Designated winner wins			Value realization		
	FP		EN	FP		EN
Re-matching	0.78	$<^{***}$	0.93	0.93	$<^{***}$	0.98
	$\vee$		$\vee$	$\vee^{*}$		$\vee$
Fixed matching	0.73	$<^{***}$	0.93	0.87	$<^{**}$	0.96

Notes: ***, ** and * indicate statistical significance at the 1%, 5% and 10% level, respectively.

5.3 BIDDING BEHAVIOR

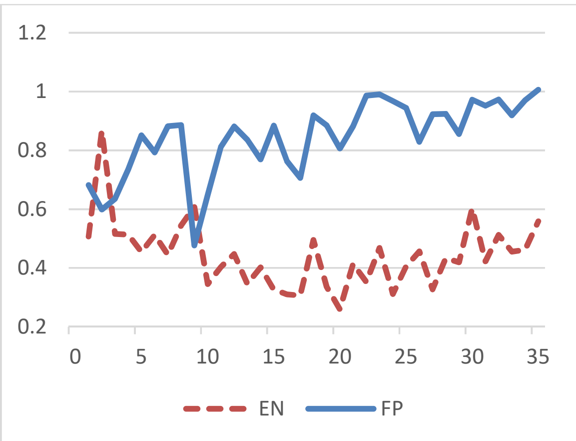
The comparable results across matching protocols for cartel stability, revenue, and efficiency suggests that the underlying bidding behavior is also similar. This indeed turns out to be the case. In FP, (1) the designated winner secures the object in 73% of the cases, (2) the bid of designated winners (0.87) is significantly below the second highest value (p = 0.011), and (3) the bid of designated losers that submit a bid (0.74) is significantly below the second highest value (p =

0.008).[20] These bidding patterns suggest that also with fixed matching the designated winner weighs the possibility that no designated loser submits a bid against the likelihood of defection. In contrast to the re-matching case, deviation is profitable: If designated losers win the auction, their winning bid is significantly below the second highest value (p = 0.015).

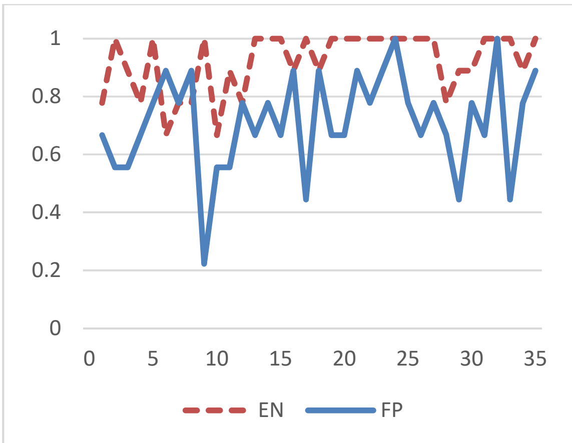
In EN, as with the re-matching case, the designated winner typically does not exit the auction at a price below her value, and wins the auction in 93% of the cases. Only in 7.41% of all auctions, a designated loser secures the object at a price below the designated winner's value. The collusive equilibrium outcome, in which both designated losers do not submit a bid, emerges in 55% of the cases. Designated losers that submit a bid tend to step out of the auction at a price close to their value. More specifically, only 1.16% bid in the interval [0, 5], while 50.87% bid in the interval [value-5, value].[21]

Figure 6: Designated winner's bids (panel a) and probabilities of the designated winner securing the item (panel b), over time

Panel a



Panel b



Considering the evolution over time of bids submitted by the designated winner and the probability of winning the auction (Figure 6), reveals a comparable pattern to that under re-matching. In FP, initially designated winners submit a relatively low bid; in time they learn that

[20] In 19 cases a designated loser bid above value, resulting in winning the auction in 12 occasions.
[21] The bids of designated losers (0.80), are significantly below the second highest value in the cartel (p = 0.018). In 62 of all 173 defections, the designated loser bid above her value. In 7 of those cases, the designated loser won the auction.

these bids are not high enough to win the auction, which prompts them to significantly increase their bids.[22] In EN, after an initial phase, designated winners in EN are quite certain to win the auction.

RESULT 8: BIDDING BEHAVIOR. In the case of fixed matching, in FP, designated winners and deviating designated losers submit a bid close to, but statistically significantly below, the second highest value. In EN, designated winners hardly ever leave the auction at a price below their value. Likewise, bids of designated losers are concentrated around their value.

5.4 FIXED MATCHING VS. RE-MATCHING

How do the auction outcomes differ between the re-matching condition (Study 1) and the fixed-matching condition (Study 2)? Repeated interaction, as with the fixed-matching case, does not affect the collusive properties of EN; cartels remain stable in equilibrium. However, from the theory of supergames (Friedman, 1971), it follows that stable cartels may form in FP too if the auction is repeated an indefinite number of periods and if bidders are 'patient enough' (Aoyagi, 2007). A stable cartel emerges in equilibrium if bidders play a grim strategy that tells the designated losers to abstain from bidding and the designated winner to bid zero in all periods up to the point that some bidder deviates. From then on, all bidders bid according to a one-shot Nash equilibrium in all subsequent periods.

While the theory suggests that the matching protocol may affect auction outcomes, we do not find substantive differences between the two studies. According to Table 3, for both auctions, defection and cartel breakdown is not significantly less likely in the case of fixed matching than in the case of re-matching. Moreover, Tables 4 and 5 show that revenue and revenue variance do not differ significantly between the two matching protocols. And Table 6 indicates that the matching protocol does not significantly affect efficiency for EN; for FP, efficiency is (marginally) significantly lower under re-matching than under fixed matching, but only in terms of potential value realization.[23] Finally, for both auctions, designated winners' and designated losers' bidding strategies do not differ markedly between the fixed-matching and re-matching protocols (cf. Results 4 and 8).

[22] See the regressions in appendix B.
[23] For all periods, the difference is statistically significant at the 5% level ($p = 0.021$).

RESULT 9: FIXED MATCHING VS. RE-MATCHING. For both FP and EN, the two matching protocols do not differ markedly in terms of cartel stability, revenue, efficiency, and bidding behavior.

6. CONCLUSION

Bidding rings are commonly observed in antitrust cases. In the 1980s, about 75% of the US cartel cases were related to auctions (Krishna, 2009). Based on more recent data, Agranov and Yariv (2018) report that since 1994, around 30% of the antitrust cases filed by the US Department of Justice involve collusion in auctions. This begs the question as to what is the best way to fight bidding rings. As a former Chief Economist of the European Commission observes: …it is better to try to create an environment that discourages collusion in the first place than trying to prove unlawful behavior afterwards. A clear advantage of auction markets is that the environment can be affected directly, since the rules of the game are specified at the beginning by the auctioneer (Motta, 2004, p. 192).[24] The theoretical result that cartels are more stable in the English auction than in the first-price sealed-bid auction would suggest that auction designers should follow the OECD's (2006) advice to use the first-price sealed-bid auction rather than the English auction in environments where collusion is a significant threat (p. 36). In contrast to the earlier experimental evidence discussed in the introduction, our findings back up this advice in that in our experiment, (1) cartels are more stable, (2) average revenue is lower, and (3) the revenue spread is higher in the English auction than in the first-price sealed-bid auction. Our results and those of related experiments suggest that the OECD's (2006) advice is well taken in some settings, while it is less relevant in other environments. The experiments to date differ in too many dimensions to identify the key conditions under which the advice of the OECD (2006) applies. Further experimental research should create a more detailed map of how the relative performance of the two auctions in terms of collusion depends on the precise auction rules, the way the bidders can communicate, whether or not the values are common knowledge, the possibility of side payments, the number of bidders, the value structure, and so forth.

[24] Hinloopen and Onderstal (2014) observe antitrust policies to be ineffective in the English auction and partially effective in the first-price sealed-bid auction.

References

Agranov, M. and Yariv, L. (2018). Collusion through communication in auctions. *Games and Economic Behavior* 107: 93 – 108.

Aoyagi, M. (2007). Efficient collusion in repeated auctions with communication. *Journal of Economic Theory* 134: 61 – 92.

Asker (2010). A Study of the internal organization of a bidding cartel. *American Economic Review* 100: 724 – 762.

Bajari, P. and Ye. L. (2003). Deciding between competition and collusion. *The Review of Economics and Statistics* 85: 971 – 989.

Burtraw, D., Goeree, J., Holt, C. A., Myers, E., Palmer, K., and Shobe, W. (2009). Collusion in auctions for emission permits: An experimental analysis. *Journal of Policy Analysis and Management* 28: 672 – 691.

Clark, R., Coviello, D., Gauthier, J.-F. and Shneyerov, A. (2018). Bid rigging and entry deterrence in public procurement: Evidence from an investigation into collusion and corruption in Quebec. *Journal of Law, Economics, and Organization* 34: 301 – 363

Dawes, R. M., McTavish, J., Shaklee, H. (1977). Behavior, communication, and assumptions about other people's behavior in a commons dilemma situation. *Journal of Personality and Social Psychology* 35: 1 – 11.

Eső, P., & Schummer, J. (2004). Bribing and signaling in second price auctions. *Games and Economic Behavior* 47: 299 – 324.

Fonseca, M. A. and Normann, H.-T. (2012). Explicit vs. tacit collusion – the impact of communication in oligopoly experiments. *European Economic Review* 56: 1759 – 1772.

Friedman, J. W. (1971). A non-cooperative equilibrium for supergames. *Review of Economic Studies* 38: 1 – 12.

Gomez-Martinez, F., Onderstal, S., and Sonnemans, J. (2016). Firm-specific information and explicit collusion in experimental oligopolies. *European Economic Review* 82: 132 – 141.

Hinloopen, J. and Onderstal, S. (2013). Collusion and the choice of auction: An experimental study. Tinbergen Institute working paper 10-120/1.

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

Hinloopen, J. and Soetevent, A. R. (2008). Laboratory evidence on the effectiveness of corporate leniency programs. *RAND Journal of Economics* 39: 607 – 616.

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

Huck, S., Normann, H.-T., & Oechssler, J. (2004). Two are few and four are many: number effects in experimental oligopolies. *Journal of Economic Behavior & Organization* 53: 435 – 446.

Isaac, R. M., McCue, K. F., and Plott, C. R. (1985). Public goods provision in an experimental environment. *Journal of Public Economics* 26: 51 – 74.

Isaac, R. M., Ramey, V., and Williams, A.W. (1984). The effects of market organization on conspiracies in the restraint of trade. *Journal of Economic Behavior and Organization* 5: 191 – 222.

Isaac, R. M. and Walker, J. M. (1985). Information and conspiracy in sealed bid auctions. *Journal of Economic Behavior and Organization* 6: 139 – 159.

Kagel, J.H. (1995). Auctions: A survey of experimental research. In: J.H. Kagel and A.E. Roth (eds.), *The Handbook of Experimental Economics*, Princeton (NJ): Princeton University Press, 501 – 585.

Kagel, J. H. and Levin, D. (2016). Auctions: A survey of experimental research, 1995–2010. In: J. H. Kagel and A. E. Roth (eds.), *The Handbook of Experimental Economics, Volume II*. Princeton (NJ): Princeton University Press.

Kimbrough, E. O. and Sheremeta, R. M. (2013). Side-payments and the costs of conflict. *International Journal of Industrial Organization* 31: 278 – 286.

Klemperer, P. (2002). What really matters in auction design. *Journal of Economic Perspectives*, *16*(1), 169 – 189.

Kovacic, W. E., Marshall, R. C., Marx, L. M., & Raiff, M. E. (2006). Bidding rings and the design of anti-collusion measures for auctions and procurements. *Handbook of Procurement* 15.

Krishna, V. (2009). *Auction theory*. Cambridge, MA: Academic press.

Kwasnica, A. M. and Sherstyuk, K. (2013). Multiunit auctions. *Journal of Economic Surveys* 27: 461 – 490.

Llorente-Saguer, A. and Zultan, R. (2017) Collusion and information revelation in auctions. *European Economic Review* 95: 84 – 102.

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

Marshall, R. C. and Marx, L. M. (2009). The vulnerability of auctions to bidder collusion. *Quarterly Journal of Economics* 124: 883 – 910.

McAfee, R. P. and McMillan, J. (1992). Bidding rings. *The American Economic Review* 82: 579 – 599.

Motta, M. (2004). *Competition policy: Theory and practice*. Cambridge: Cambridge University Press.

Noussair, C. and Seres, G. (2017) The effect of collusion on efficiency in experimental auctions. Working paper, University of Arizona.

OECD (2006). Competition in Bidding Markets. OECD Policy and Roundtable discussion paper.

Phillips, O.R., Menkhaus, D.J., and Coatney, K.T. (2003). Collusive practices in repeated English auctions: Experimental evidence on bidding rings. *American Economic Review* 93: 965 – 979.

Porter, R. and Zona, D. (1999). Ohio school milk markets: An analysis of bidding. *RAND Journal of Economics* 30 263 – 288.

Rachmilevitch, S. (2013). Bribing in first-price auctions. *Games and Economic Behavior* 77: 214 – 228.

Ribbens, A. (2018). Sensationele vondst Rembrandt inzet van vete kunsthandelaren. *NRC* (main Dutch newspaper), September 13.

Robinson, M.S. (1985). Collusion and the choice of auction. *RAND Journal of Economics* 16: 141 – 145.

Sherstyuk, K. and Dulatre, J. (2008). Market performance and collusion in sequential and simultaneous multi-object auctions: Evidence from an ascending auctions experiment. *International Journal of Industrial Organization* 26: 557 – 572.

Appendix A: Instructions

The instructions are computerized. Subjects could read through the html-pages at their own pace. Below is a translation of the Dutch instructions for the English auction with fixed groups. The instructions for the other treatments are available from the authors upon request.

Welcome!

You are about to participate in an auction experiment. The experiment consists of at least **35 rounds** and each round consists of **2 steps**. Those steps are the same in each round and will be explained later in more detail.

In every round of the experiment, all participants will be randomly divided in **groups of 3** members. This will be done in such a way that participants will never be in the same group in two subsequent rounds; at the beginning of every round, you will be matched with two other participants than in the previous round.

Group members remain anonymous; you will not know with whom you are matched. Moreover, there will not be contact between separate groups during any round.

From round 35 onwards, a next round starts with 80% probability. In other words, from round 35 onwards, the experiment stops with 20% probability.

Earnings

In every round of the experiment, you can earn points. At the end of the experiment, points will be exchanged for Euros. The exchange rate will be

50 points = € 1

At the beginning of the experiment, you will receive a **starting capital** of **350 points**. At the end of every round, the points you will earn in this round will be added to your capital. If you earn a negative number of points in a round, these points will be subtracted from your capital.

In the remainder of these instructions, we will present an overview of the experiment followed by a further explanation of the two steps that are played in each round. We will conclude with examples and test questions.

Overview of the experiment

In every round, a product can be bought. Only 1 item of the product is available in each round. The product is sold in an **auction**.

Every round consists of two steps.

In **step 1**, all groups members learn their value for the product in the current round. The bidders also learn about an agreement as to who of the three group members will participate in the auction (and who will not). This agreement is made on your behalf; you only learn the outcome of the agreement as far as it concerns you. The agreement is not binding. Subsequently, you indicate whether or not you want to participate in the auction. The other group members have to decide as well at the same moment. Group members only know their own choice regarding auction entry.

In **step 2**, the product is auctioned. Only group members who indicated to be willing to participate in the auction can submit a bid. You only earn points if you win the auction. If you win, the number of points that you earn in the auction will be equal to

your value – the winning bid

Now, an explanation of both steps follows.

Step 1: Agreement

At the start of each round, you will be informed about your value for the auctioned product. This value differs from one round to the next. You are also informed about the other group members' value for the product. Values are always in between 20 and 70 points and are drawn at the start of every round. This happens randomly: Every value between 20 and 70 is equally likely. The value for each group member is independent of the values of the other two group members. The values are also independent of the round that is being played.

At the start of each round, you will also be informed about the agreement between all group members. According to this agreement, the group member with the highest value is the only one submitting a bid in the auction. This is the designated winner. The agreement is not binding though.

Finally, you have to decide in step 1 of each round whether or not you want to submit a bid in the auction. To answer the question Would you like to submit a bid? you must press yes or no. The two other group members simultaneously answer the same question.

Step 2: The auction

The auction is an increasing thermometer: the price starts at 0 and is raised in steps of 1 point. While the thermometer increases, all participating bidders can click on the Stop button. A bidder who presses the Stop button leaves the auction. All bidders observe the price at which a bidder presses the Stop button (but not which bidder it is). The auction stops when only one bidder remains who has not pressed the Stop button.

The bidder who has not pressed the Stop button, wins the auction. He or she pays the price at which the auction stopped. This is the price at which the second-last remaining bidder pressed the Stop button.

If only one bidder participates in the auction, the auction stops directly at a price of 0.

Step 2: The auction (continued)

If the remaining two (or three) bidders happen to press the Stop button at the same price, chance determines which bidders buys the product. Also in this case, the auction winner pays the price at which the thermometer stops.

The thermometer always stops at a price of 70. If at this price, two or three bidders have not pressed the Stop button, chance determines which of those bidders buys the product (for a price of 70).

Invisibly to the bidders, the thermometer always runs up to 70, even if the auction stops at a lower price. The next round only starts when the thermometer has reached 70.

The auction winner obtains

the winner’s value – the winning bid

The other group members obtain zero points.

If in step 1 all group members choose not to participate in the auction, the product will not be auction and all group members (including the designated winner) obtain zero points.

APPENDIX B: CONVERGENCE OF BIDDING BEHAVIOR FOR THE FIRST-PRICE SEALED-BID AUCTION

We estimate two fixed-effects models to investigate potential convergence to Nash-equilibrium bidding behaviour in first-price auctions, whereby we explicitly control for possible within-matchinggroup correlations. For the first regression, we run the following specification separately for designated winners that submitted a bid, and designated losers with the second-highest value in the cartel that submitted a bid:

$$bid_{it} = \beta_1 t + \alpha_i + u_{it},$$

$i = 1, 2, \ldots, n^X$, $t = 1, \ldots, 40$, where n^X is the number of subjects in case of $X \in \{\text{FP re} - \text{matching designated winners submitting bids, FP fixed matching designated winners submitting bids, FP rematching designated losers with second} - \text{highest value submitting bids, FP fixed matching designated losers with second} - \text{highest value submitting bids}\}$, and bid_{it} is the submitted bid as a fraction of the second-highest value in the cartel. Standard errors are clustered at the matchinggroup level. The regression results are in Table B1.

Table B1: Fixed effects estimates of bid-trend in first-price auctions

	Re-matching		Fixed matching	
	Designated winners (1)	Designated losers (2)	Designated winners (3)	Designated losers (4)
Time trend	0.0015	0.0015	0.0073***	0.0083***
	(0.0012)	(0.0008)	(0.0012)	(0.0012)
Average FE	0.8881***	0.8196***	0.7075***	0.6564***
	(0.2428)	(0.1672)	(0.0236)	(0.0244)
Observations	906	798	347	287

[a] Standard errors are within parentheses; ***, **, and * denote statistical significance at the 1%, 5%, and 10% respectively; standard errors are clustered at the matching group level.

The second specification we estimate is a fixed effects model that examines convergence over time of the winning bids in first-price auctions. Again, we run this specification separately for designated winners that submit a bid, and designated losers with the second-highest value in the cartel that submit a bid:

$$bid_{it} = \beta_1 T1_t + \beta_2 T2_t + \alpha_i + u_{it},$$

$i = 1, 2, \dots, n^X$, $t = 1, \dots, 40$, where n^X and bid_{it} are as defined in the previous paragraph, $T1_t = \max\{0, 35 - t\}$ and $T2_t = \max\{0, t - 35\}$. Note that inclusion of the two time trends implies that the average of the estimated value of α_i corresponds to the value of the scaled bid to which the bidding behavior converges in period 35. Standard errors are clustered at the matchinggroup level. The regression results are in Table B2.

Table B2: Fixed effects estimates of bid convergence-point in first-price auctions

	Re-matching		Fixed matching	
	Designated winners (1)	Designated losers (2)	Designated winners (3)	Designated losers (4)
Time trend 1-35	-0.0014	-0.0014	-0.0084***	-0.0082***
	(0.0015)	(0.0010)	(0.0012)	(0.0014)
Time trend 36-40	0.0037	0.0060	-0.0193	0.0099
	(0.0109)	(0.0065)	(0.0193)	(0.0113)
Average FE	0.9388***	0.8694***	0.9871***	0.9457***
	(0.0258)	(0.0156)	(0.0209)	(0.0222)
Observations	906	798	347	287

[a] Standard errors are within parentheses; ***, **, and * denote statistical significance at the 1%, 5%, and 10% respectively; standard errors are clustered at the matching group level.