Cartel stability in experimental first-price sealed-bid and English auctions

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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 bidding 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 revenue and the revenue spread. The English auction outperforms the first-price sealed-bid auction in terms of efficiency,

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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, Dutch art dealer Jan Six, announced that he had 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 Dutch are dealer Sander Bijl revealed that he had also identified the paintingas 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. 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 (e.g. Klemperer (2002), Kovacic et al. (2006), and OECD (2006)).[2] The underlying intuition, formalized by (Robinson, 1985), is that stable collusion is an equilibrium 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] However, this equilibrium is not unique. In fact, the English auction has a multitude of equilibria in which collusion is unstable.

In this paper, we compare the stability of bidding rings in the English auction and the first-price sealed-bid auction using a laboratory experiment. The experiment allows us to address the question which equilibria are most likely to be observed. An additional reason for using laboratory experiments is that it is difficult to study the collusive properties of auctions on the basis of field data. First of all, in the field, the auction format is typically not varied exogenously so that an apples-to-apples comparison between auctions is not feasible. Second, even if the researcher could observe whether bidders in the field formed a bidding ring, it would be difficult to measure if it was stable or unstable, in contrast to the lab, where such measures are readily available. Third, in the lab, the researcher can impose cartel formation to obtain a direct comparison between auction formats in terms of cartel stability. This is arguably much harder to implement in the field.

The received experimental literature finds little support for the claim that the English auction is more conductive to collusion than the first-price sealed-bid auction. *Tacit* collusion is rarely observed in either auction type in the laboratory: if subjects

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[1]Presently, Bijl and Six are in a dispute over the spoils of the deal. Six even publicly denies that he and Bijl had made the deal in the first place.

[2]Both the English auction and the first-price sealed-bid auction are commonly used in practice (McAfee and McMillan, 1987). The first-price sealed-bid auction featured, for instance, in cartels for school milk tenders (Porter and Zona, 1999) and infrastructure procurement (Bajari and Ye (2003), Clark et al. (2018)); the English auction was used, for example, in cartels involving tobacco (Phillips et al., 2003) and stamps (Asker, 2010).

[3]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 affect its collusive properties.

deviate systematically from the one-shot Nash prediction, they bid more aggressively instead of less (Kagel, 1995).[4] Bidders sometimes manage to collude explicitly when they get the opportunity to communicate with each other before the auction.[5][6]

Several recent experimental studies compare the collusive properties of the English auction and the first-price sealed-bid auction in independent private value settings where bidders can communicate. In the framework of Hu et al. (2011), 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 et al. (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 own value is a weakly dominant strategy in an independent private value setting. Llorente-Saguer et al. (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 and post-auction transfers 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 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.

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[4]Tacit collusion is sometimes observed in multi-unit auctions in the lab, in particular in setting where bidders can find ways to "divide the market". See Kwasnica and Sherstyuk (2013) for an overview. Burtraw et al. (2009) find that bidders are better able to sustain collusive agreements in ascending than in sealed-bid multi-unit auctions when interacting repeatedly.

[5]See, e.g. Isaac and Walker (1985), Phillips et al. (2003), Sherstyuk and Dulatre (2008), Burtraw et al. (2009), Noussair and Seres (2020), and Agranov and Yariv (2018). Kagel and Levin (2016) and Kwasnica and Sherstyuk (2013) survey this literature.

[6]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).

It is not clear why the experimental literature to date has offered little support for the proposition that the English auction is more conductive to collusion than the first-price sealed-bid auction. Several factors might explain this discrepancy: Cartels are stable by construction in Hu et al. (2011) and Llorente-Saguer et al. (2017); Llorente-Saguer et al. (2017) and Agranov and Yariv (2018) use a strategically equivalent sealed-bid variant of the English auction;[7] In Agranov and Yariv (2018), communication between bidders is non-binding and side payments are not enforceable. In this paper, we aim to improve 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 the framework of Robinson (1985), where by construction, bidders have formed a cartel before the start of the auction. In two experimental studies, we let groups of three bidders make auction entry decisions in a setting where bidders are commonly informed about each other's values. The bidder with the highest value is the designated winner. All bidders are informed about a non-binding agreement that only the designated winner enters the auction. 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. We consider a cartel to be stable if, and only if, only the designated winner enters the auction. In both studies, we find support for the hypothesis that more cartels are stable in the English auction than in the first-price sealed-bid auction.[8] We conclude that the intuition of Robinson (1985) applies in simple settings, which serves as a starting point in gaining further insight as to why it fails to work in the more complex settings such as those studied by Hu et al. (2011), Llorente-Saguer et al. (2017), and Agranov and Yariv (2018).

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

2 Theoretical Model

We use a discrete version of the model in Robinson (1985) to examine the collusive properties of the English auction (EN) and the first-price sealed-bid auction (FP).The framework used for the experiment is a special case of this model. A seller auctions

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[7]One important insight from the experimental literature is that strategic equivalence does not imply behavioral equivalence. For instance, it is commonly observed that in private value settings, subjects play the dominant strategy of bidding their own value significantly more frequently in the English auction than in the second-price sealed-bid auction (see Li (2017), and the references cited therein). Li (2017) argues that the observed differences across auctions are explained by the fact that the English auction is obviously strategy proof, in contrast to the second-price sealed-bid auction.

[8]Hinloopen and Onderstal (2010) find similar results in a common-value setting where cartel formation is endogenous.

one indivisible object to one bidder out of a set of $n \geq 2$ risk-neutral bidders labelled $i = 1, \ldots, n$. Bidder i attaches value v_i to the object, where $v_1 \geq v_2 \geq \ldots \geq v_n \geq 0$. Assume that $v_2 \geq R + 2\varepsilon$, where R represents the seller's reserve price and $\varepsilon > 0$ is the minimum bid increment. For analytical convenience, we assume that bidders' values and R are multiples of ε and that bids are restricted to the set $\{R, R+\varepsilon, R+2\varepsilon, \ldots, M\}$, where $M \geq v_1$ is a multiple of ε.

Both auctions consist of two stages. In the first stage, bidders simultaneously decide whether or not to submit a bid. If no bidder submits a bid, the seller retains the good. otherwise the second stage starts in which bidders who decide to submit a bid, participate in the auction. In EN, the price is raised successively in steps of size ε, starting at R and up to M. Bidders can indicate at any price whether they leave the auction at that price. The auction stops when one or zero bidders remain. If one bidder remains, this bidder wins the object for the price at which the second highest bidder left the auction. If zero bidders remain, a winner is drawn randomly among the last bidders leaving the auction; the winner obtains the object and pays the price at which she left the auction. When, at a price of M, more than one bidder remains, chance determined which of the remaining bidders wins the auction (for a price of M). In FP, bidders independently submit sealed bids. The highest bidder wins the object and pays her own bid. In the case of a tie at the highest bid, a winner is selected randomly using a uniform distribution among the highest bidders; the winner obtains the object and pays her bid.

A bidder's utility equals zero if she does not win the auction, and equals the difference between her 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] We start by characterizing the set of pure-strategy equilibria for both auctions.[10]

Proposition 1.
In any subgame perfect Nash equilibrium of EN, at least one bidder i for whom $v_i = v_1$ leaves the auction at price $v_1 + \varepsilon$ and the other bidders either do not submit a bid or leave the auction at a price in the set $\{R, R + \varepsilon, \ldots, v_1\}$.

Proposition 2.
(i) If $v_1 \geq v_2 + 3\varepsilon$, in any subgame perfect Nash equilibrium of FP, bidder 1 submits a bid b_1 in the set $\{R, R + \varepsilon, \ldots, b_1 - 2\varepsilon\}$.
(ii) If $v_1 = v_2 + 2\varepsilon$, in any subgame perfect Nash equilibrium of FP, bidder 1 submits

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[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)). An alternative interpretation of the model is that values are common knowledge among bidders from the onset, which may be relevant in cases where bidders know each other intimately and/or where the values depend solely on characteristics that are commonly observed by the bidders.

[10]Proofs of all propositions are in Appendix A.

a bid b_1 in the set $\{v_2, v_2 + \varepsilon\}$. If bidder 1 bids v_2, either at least one bidder bids $v_2 - \varepsilon$ or exactly one of the bidders having value v_2 bids v_2. If bidder 1 bids $v_2 + \varepsilon$, at least one of the other bidders bids v_2. The remaining bidders either do not submit a bid or submit a bid in the set $\{R, R + \varepsilon, \ldots, b_1 - \varepsilon\}$.

(iii) If $v_1 = v_2 + \epsilon$, in any subgame perfect Nash-equilibrium of FP, bidder 1 submits a bid $b_1 \in \{v_2 - \varepsilon, v_2\}$; if $b_1 = v_2$, either at least one bidder bids $v_2 - \varepsilon$ or at least one bidder having value v_2 bids v_2; if $b_1 = v_2 - \varepsilon$, all bidders having value v_2 bid $v_2 - \varepsilon$ and the other bidders either do not submit a bid or submit a bid in the set $\{R, R + \varepsilon, \ldots, v_2 - \varepsilon\}$.

(iv) If $v_1 = v_2$, in any subgame perfect Nash equilibrium, either (1) all bidders having value v_1 bid $v_1 - \varepsilon$, all bidders having value $v_1 - \varepsilon$ either do not submit a bid or submit a bid in the set $\{R, R + \varepsilon, \ldots, v_1 - \varepsilon\}$, and all other bidders either do not submit a bid or submit a bid in the set $\{R, R + \varepsilon, \ldots, v_1 - 2\varepsilon\}$, or (2) at least two bidders having value v_1 bid v_1, and all other bidders either do not submit a bid or submit a bid in the set $\{R, R + \varepsilon, \ldots, v_1 - \varepsilon\}$.

Now, assume that the bidders make the following cartel agreement before the auction. Among the bidders who have the highest value v_1, a designated winner is appointed. The bidders agree that only the designated winner submits a bid in the auction. In what follows, we sometimes refer to the remaining bidders as the designated losers. We consider a cartel agreement to be stable if, and only if, it constitutes a subgame perfect Nash-equilibrium. Propositions 1 and 2 imply immediately that stable cartel agreements only exist in EN.

Corollary 1.
In EN, the cartel agreement is part of a subgame perfect Nash equilibrium; in FP the cartel agreement is not part of a subgame perfect Nash equilibrium.

The intuition behind this result is the following. In EN, the designated winner can ensure that entry into the auction by other bidders is not profitable by remaining in the auction until the price reaches her value. Of course, such a collusive equilibrium requires the designated losers to play a weakly dominated strategy: irrespective of the bidding strategies of others, a designated loser is always weakly better off by overbidding others up to a price equal to her value. While the play of weakly dominated strategies may make the collusive equilibrium less plausible, note that these strategies can survive iterated elimination of weakly dominated strategies. For the designated winner, bidding below values of the designated losers does not survive iterated elimination of weakly dominated strategies. As a result, abstaining from bidding is no longer dominated for the designated losers once the weakly dominated strategies of the designated winner are sequentially deleted.[11] Whether designated losers play weakly dominated strategies is an empirical question, which we explore in the experiment.

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[11] We thank an anonymous referee for pointing this out.

In FP, the designated winner best responds to the cartel agreement by bidding R. However, this cannot be part of an equilibrium because then at least one other bidder is better off by deviating from the cartel agreement and bidding $R + \varepsilon$. Indeed, in FP, the best a cartel can achieve in equilibrium is obtaining the good at a price $v_2 - \varepsilon > R$ as the following corollary shows.

Corollary 2.
If $v_1 \geq v_2 + 2\varepsilon$, FP has no equilibrium in which the designated winner obtains the object for a price strictly lower than v_2. If $v_1 \in \{v_2, v_2 + \varepsilon\}$, FP has no equilibrium in which the designated bidder obtains the object for a price strictly lower than $v_2 - \varepsilon$.

Notice that both EN and FP are plagued by a multitude of equilibria. We formulate our hypotheses assuming that bidders coordinate on the "least competitive" equilibrium, i.e. the Nash equilibrium that yields the lowest revenue for the auctioneer. In other words, we base our hypotheses on the assumption that in EN, only the designated winner submits a bid and that in FP, the designated winner bids at most the second highest value minus one bid increment. This yields the following hypotheses that we will test using our experiments:[12]

H1: Stable cartels emerge more frequently in EN than in FP.
H2: Revenue in FP is higher than in EN.
H3: EN is at least as efficient as FP.

H1 follows directly from the fact that the least competitive equilibrium of EN is a stable cartel and the least competitive equilibrium of FP is not a stable cartel. H2 follows from the observation that in the least competitive equilibrium, revenue equals R in EN and it equals at least $v_2 - \varepsilon$ in FP. As to H3, an auction is efficient if, and only if, it allocates the object to the bidder with the highest valuation. H3 then follows from the fact that the designated winner always wins the object in the least competitive equilibrium in EN and not necessarily in FP.[13]

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 to euros according to an exchange rate of 50 points equals 1 euro. A show-up fee of 7 euros was converted to 350 points for those subjects that participated in the experiment. To ensure that all subjects understood

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[12]Notice that risk aversion does not affect our hypotheses.
[13]In fact, this result holds true regardless of the equilibrium played in either auction.

the experiment, they had to correctly answer several questions before the experiment started.[14] Average earnings were 12.07 euros per subject while sessions took 60 to 90 minutes to complete.

At the start of each session, matching groups of nine subject were formed randomly. These groups did not change during the sessions and communication between subjects (other than through their play) was not possible. All subjects consisted of at least 35 rounds. From round 35 onward, each next round was the final round with 20% probability.[15] Only after the last round was played, the participants learned that the experiment was over. At the start of each round subjects were randomly matched with two other subjects from the same matching group.[16] We used a between-subject design in which 72 participants participated in FP while the remaining 72 participated in EN, yielding in total 16 statistically independent observations.

Recall that our theoretical analysis relies on the assumption that bidders share their private information before the auction. To be able to isolate the effect of the auction format on cartel stability, we impose this condition in our experiment. In the experiment bidders drew their values from a uniform distribution on the set $\{20, 12, \ldots, 70\}$. These draws were independent across rounds and bidders. To improve the comparison between the treatments, bidder values were drawn before the start of the experiment and the same set of realizations was used for all treatments. Bidders were commonly informed about each other's values. The designated winner is the bidder with the highest value. In case of a tie the designated winner was selected randomly among the bidders with the highest value. Losses, which could occur when a bidder would bid more than her value and win, were subtracted from the participants' starting capital.

After bidders learned their values, they were informed about the 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. This design feature corresponds exactly to the set-up of Robinson (1985) whereby the 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 she follows a particular bidding strategy while requesting other cartel members to be inactive in the bidding (p.143). At the end of each round, we informed the partici-

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[14]Appendix B contains an English translation of the instructions.

[15]We are not the first to use a fixed number of rounds followed by a random stopping rule. See Holt (1985) for an early example. The procedure has the advantage that each group has a minimum of 35 rounds of interactions, which facilitates learning and the statistical comparison across groups. The procedure also softens potential end-game effects.

[16]Subjects were re-matched in such a way that they would not face the same opponent in two consecutive rounds. 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)), 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, were subjects were not re-matched.

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pants about which bidders entered the auction, the bids they submitted, and the own payoffs.

We implemented the following auction rules. In FP, each subject could submit a bid from the set $\{0, 1, \ldots, 70\}$ 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 current price, informing the remaining bidders at what price the bidder left the auction (but not about his or her value). 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 abut the auction outcomes in other groups.[17]

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, to examine if a trade-off exists between cartel instability on the one hand, and revenue and efficiency on the other. In Section 4.3, we zoom in on the bidding behavior.[18]
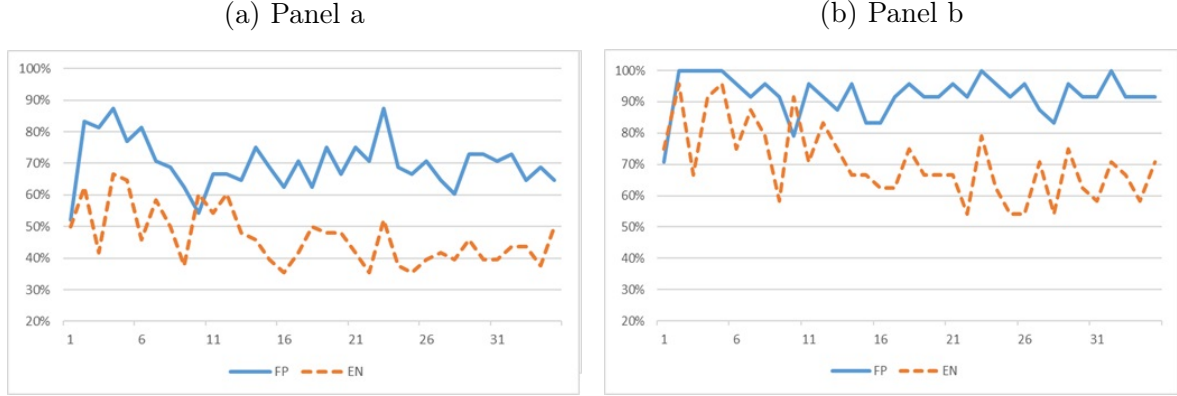
4.1 Cartel Stability

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

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[17]The software was programmed in such a way that in each round, the thermometer started running simultaneously in all groups. If we had stopped the thermometer after all groups in the session had finished, all subjects in the session would have learned about the highest price at which any auction finished in each round, which may have affected behavior across groups.

[18]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. All reported statistics that correspond to out non-parametric tests are based on matching group averages over rounds 6 to 35. We find quantitatively the same results when we take all rounds into account.

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

(a) Panel a   (b) Panel b

one bidder defects. As a result, cartels that do not break down are stable.[19] 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 ($p = 0.018$). These results are consisten with hypothesis **H1**. As wel will discuss in Section 4.3, the fact that many cartels break down in EN as well is in line with equilibrium.

Taking a closer look at the data, we observe that cartel stability is unaffected by the value draws. Table 2 presents our tests relating bidders' valuations to cartel stability, and Figure 2 shows the probability that a cartel breaks down as a function of the two highest values in the cartel. In FP, the average value draw for stable cartels is 41.79, and 45.59 for unstable cartels (no significant difference, $p = 0.124$), the concomitant standard deviations are 12.48 and 12.46 ($p = 1.000$) respectively, and the difference between the two highest values is, respectively, 13.98 and 9.90 ($p = 0.484$), and 10.56 and 9.60 ($p = 0.208$).[20] In FP (EN), 635 (390) of all 993 (646) defections were committed by the cartel member with the second highest value in the cartel. In

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[19]Our definition of cartel stability is arguably conservative. Our results do not change qualitatively when relaxing the definition to instances where the designated winner wins (see Sections 4.2 and 5.2 where we discuss efficiency).

[20]Comparing the highest, median, and lowest values between stable and unstable cartels yields similar results. For EN, the highest (median) [lowest] value in stable cartels, 57.57 (47.01) [30.93], does not differ from the concomitant value in unstable cartels, 56.74 (47.14) [33.38] (respective p-values: $p = 0.889$, $p = 0.327$, $p = 0.124$). For FP, the highest (lowest) value in stable, 54.36 (30.36), and unstable cartels, 56.70 (33.27), do not differ (respective p-values: $p = 0.327$, $p = 0.124$). For FP, the median value in stable cartels (40.38) is smaller than the median value in unstable cartels, 46.80 ($p = 0.093$).

Table 1: Cartel instability and efficiency measures, across auctions

	Propensity to defect (by subject)	Cartel breakdown	Probability that a cartel is efficient	Fraction of maximum efficiency
EN	0.45 (0.20)	0.68 (0.19)	0.93 (0.04)	0.98 (0.02)
	$\wedge^{**}$	$\wedge^{**}$	$\vee^{***}$	$\vee^{***}$
FP	0.69 (0.11)	0.92 (0.08)	0.78 (0.05)	0.93 (0.02)

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; Probability that a cartel is efficient = probability that the designated winner wins the auction; Fraction of maximum efficiency = the ratio of the difference between the winner's value and the lowest value, and the difference between the highest and the lowest value in the cartel; standard deviation based on matching group averages in brackets; ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

Table 2: Cartel instability and bidders' valuations, across auctions

	Average value unstable cartels		Average value stable cartels	SD of values unstable cartels		SD of values stable cartels
EN	45.75 (0.90)	>	45.17 (3.44)	12.45 (0.38)	<	14.32 (4.90)
FP	45.59 (0.28)	>	41.79 (5.85)	12.46 (0.36)	<	12.48 (2.39)
	$v_1 - v_2$ in unstable cartels		$v_1 - v_2$ in stable cartels	Probability that bidder with 2nd value defects		Probability that bidder with 3rd value defects
EN	9.60 (0.71)	<	10.56 (4.04)	0.53 (0.18)	$>^{**}$	0.36 (0.22)
FP	9.90 (0.55)	<	13.98 (5.63)	0.86 (0.09)	$>^{**}$	0.51 (0.15)

Notes: v_1 and v_2 are the highest and second-highest values in a cartel, respectively; Unstable cartel = at least one designated loser submits a bid; Stable cartel = no designated loser submits a bid; standard deviation based on matching group averages in brackets; ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

FP, the probability that the cartel member with the second highest value in the cartel defects from the agreement, 0.86, is higher than the probability that the cartel member with the lowest value in the cartel defects, 0.51 ($p = 0.012$). For EN, these respective numbers are 0.53 and 0.36 ($p = 0.012$).[21]

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[21]In 16 auctions, both the designated losers were assigned the same value, but a strictly lower value than the designated winner. In this case, both designated losers are counted as having the second highest value in the auction.

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 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.

Figure 2: Cartel breakdown probability as a function of the two highest values in FP (panel a) and EN (panel b)

(a) Panel a   (b) Panel b
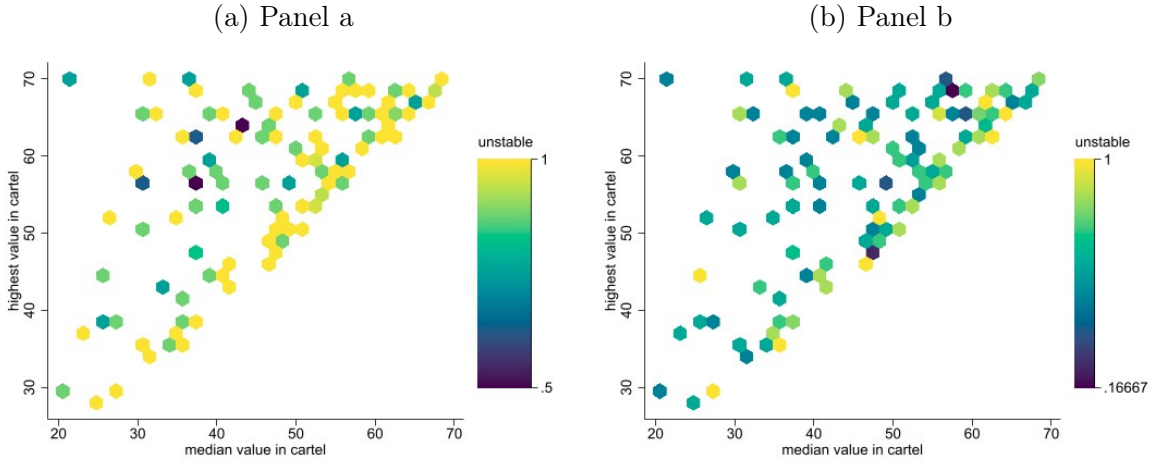
4.2 Revenue and Efficiency

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 3 contains the aggregate results and Figure 3 displays revenue for both stable and unstable cartels over time. In line with **H2**, 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 ($p = 0.009$).[22]

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[22]The observation that winning bids in a stable cartel in FP are almost 100% of the second highest value is explained by the facts that (1) before the auction, the designated winner was not informed whether designated losers entered the auction and (2) the fraction of stable cartels (in which the other two bidders did not enter the auction) among all auctions is very low (8%).

Table 3: Revenue of stable and unstable cartels, across auctions

	FP		EN
Stable Cartels	0.97 (0.10)	>***	0.00 (0.00)
	∧		∧**
Unstable Cartels	0.99 (0.02)	>***	0.85 (0.10)
All Cartels	0.98 (0.03)	>***	0.58 (0.16)

Notes: Stable cartel = no designated loser submits a bid; Unstable cartel = at least one designated loser submits a bid; standard deviation based on matching group averages in brackets; ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

The variance in revenue in EN is 0.198, which is significantly higher than the variance of 0.012 in FP ($p = 0.001$). As Figure 4 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.

Figure 3: Revenue as a fraction of the second highest value for stable cartel (panel a), and unstable cartels (panel b), over time

(a) Panel a   (b) Panel b
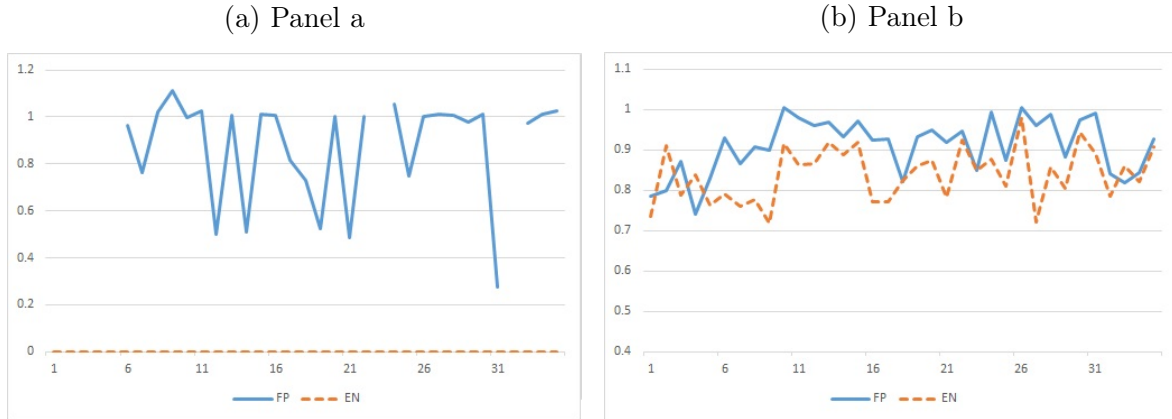
Result 2: Revenue
EN raises significantly more revenue than FP. The variance of revenue as a fraction of the second highest value is significantly higher in EN than in FP.

How do the auctions perform in terms of efficiency? Table 1 also reports our concomitant results. 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 $\frac{w-v}{V-v}$, where w is the winner's value, and v [V] refers to the lowest [highest] value in the cartel (see e.g. Hu et al. (2011)). Using this measure, efficiency in EN is 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.

Result 3 is in line with **H3**. The relative inefficiency of FP is rooted in off-equilibrium behavior in that designated winners frequently bid lower than the second highest value minus one bid increment, as we will discuss in the next subsection. As a result, they are sometimes outbid by a designated loser so that the object does not end up in the hands of the bidder having the highest value.

Figure 4: Relative frequencies of revenue as a fraction of the second highest value
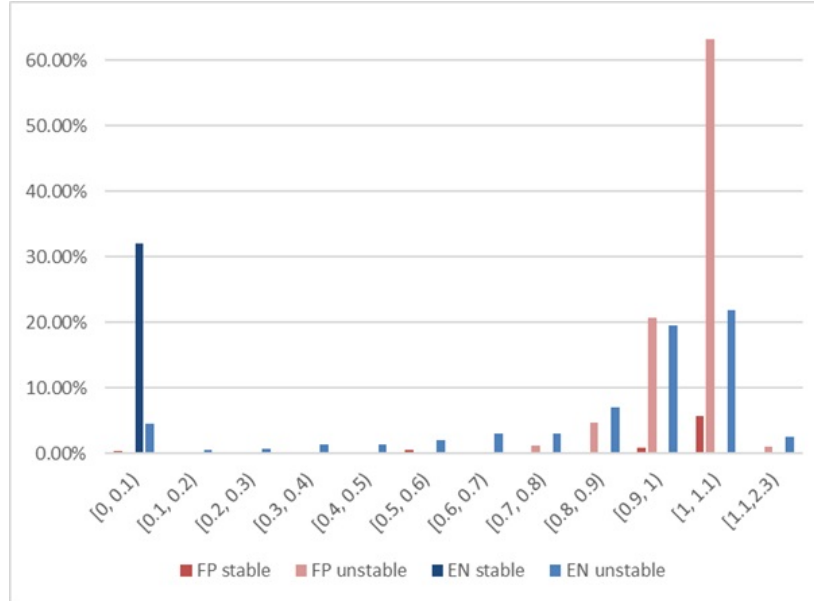
4.3 Bidding Behavior

To what extent is bidding behavior consistent with equilibrium play? Figure 5 shows average bids of designated winners as a function of the two highest values in the auction.

For FP, the designated winner bids at least the second highest value in equilibrium according to Corollary 2. As Proposition 2 shows, a large range of Nash equilibria produces such an outcome. Such equilibria have in common that (1) the designated winner surely wins if her value differs more than two bid increments with the second highest value, (2) she bids an amount at least equal to the second highest value minus one bid increment, and (3) at least one of the designated losers submits a bid of at least the second highest value minus one bid increment, 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% rather than at least 85.56% 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 ($p = 0.012$).[23]

Figure 5: Average bids by designated winners as a function of the two highest values in the auction in FP (panel a) and EN (panel b)

(a) Panel a   (b) Panel b
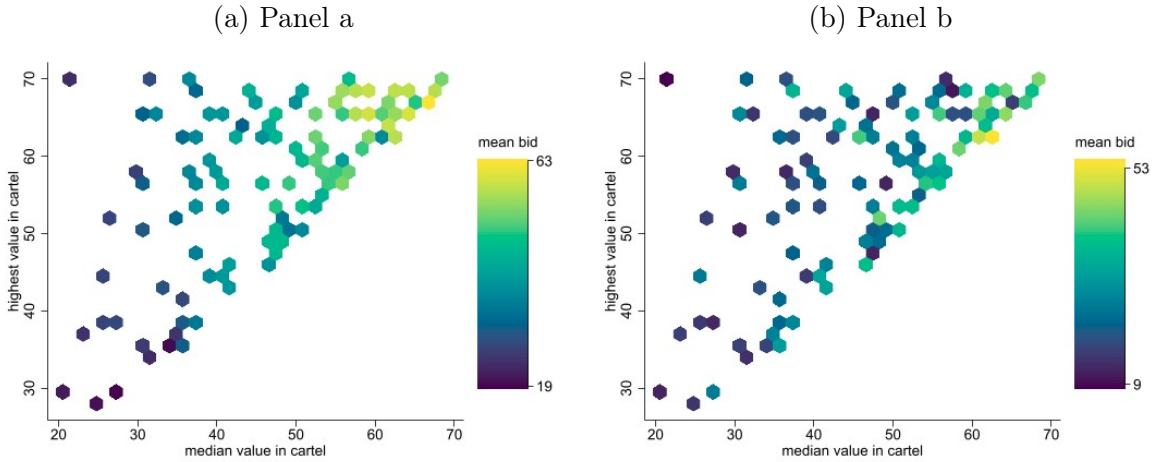
To get a more refined picture of deviations from equilibrium play in FP, we compare actual bidder behavior with the bidders' best responses to the empirically observed bidding behavior by the bidders in their matching group. We separately analyze the bidding behavior of designated winners and designated losers.[24] We predict the bids of all bidders using a linear bid function with the three values in the auction as predictors, and apply a two-step procedure to correct for the fact that not all designated losers submit a bid. These estimates are used to predict the bid distributions for each auction, one for each subject. The risk-neutral best response of subject i having value V is then estimated as

$$\arg\max_{b \in \{0,1,\dots,70\}} (V - b)\hat{G}(b), \tag{1}$$

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[23]In only seven cases did the designated loser bid above value, resulting in winning the auction on four occasions.

[24]Details are in Appendix C.

where $\hat{G}(b)$ is the distribution of the maximum bid that subject i is expected to face.[25] We compute the difference between the estimated best response and the actual bid at subject-auction level, and then obtain matching group averages of this difference which we subsequently test against zero using a Wilcoxon rank sum test. Bids, as a fraction of the second highest value, (0.91 on average) and estimated best responses (0.92) of designated winners do not differ significantly ($p = 1.000$). Designated losers with the highest value in an auction who submit a bid, bid significantly lower (0.85) than the estimated best response (0.92) ($p = 0.000$). Likewise, designated losers with the lowest value in an auction who submit a bid, bid significantly less (0.59) than the estimated best response (0.74) ($p = 0.000$). However, bidding the best response always yields positive profits in expectation: sticking to the cartel agreement is not *ex ante* optimal for designated losers.[26] In sum, designated winners best-respond on average to the bidding behavior of designated losers, whereas designated losers could do better by always defecting from the cartel agreement, and submitting higher bids than they did on average.

While the observed behavior could point to collusion,[27] it is miles away from the collusive outcome in which both designated losers abstain from bidding. It is not obvious what drives these results. Cognitive limitations of designated losers is an unlikely explanation as designated winners do best respond, and all subjects randomly alternate between being designated winners and designated losers throughout the experiment. A possible explanation is that subjects view the cartel agreement as a promise, and have a preference for sticking to promises.[28]

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.[29] As said, in 32% of the cases, the bidders reach

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[25]$\hat{G}(b)$ is the product of the other two subjects in the auction.

[26]Risk aversion does not offer an explanation either because the designated loser always earns at least zero when winning with a bid below value.

[27]We find no evidence of an end-game effect whereby designated losers start bidding their best response in the final rounds of the experiment. Restricting our analysis to all rounds past the 30th round, we find that designated losers with the highest value in the auction bid (0.87) significantly less than their best response (0.92) ($p = 0.007$). The concomitant values for designated losers with the lowest value in the auction are 0.60 and 0.67 ($p = 0.007$). See Appendix C for more details.

[28]Vanberg (2008) documents a preference for promise keeping per se.

[29]In 27 of those cases, the winning bid of the designated loser was below her value. Across rounds, designated winners tend to learn avoiding losing the auction by dropping out at a price below their value. Considering all rounds, disproportional 55% of all such cases occur in the first 10 rounds. The size of the mistake also tends to decline: in the first 10 rounds, 84% of the designated winners losing the auction drops out at a price more than 10 below value, while after round 10, only 42% does so.

the collusive equilibrium outcome in which both designated losers abstain from bidding and the designated winner obtains the object for a price of zero. There are two typical scenarios when a designated loser submits 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 $[\text{value} - 5, \text{value}]$.[30] 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 ($p = 0.484$).[31] As we observed in the previous section, the designated winner wins in 93% of the cases.

Figure 6: Designated winners' bids as a fraction of the second highest value (panel a) and the likelihood of winning the auction (panel b), over time

| (a) Panel a | (b) Panel b |
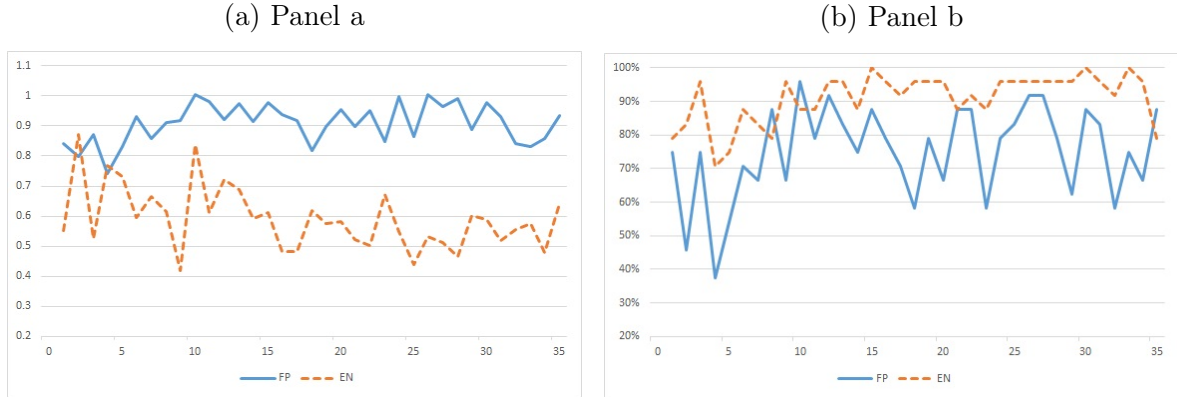
Does behavior converge towards equilibrium play over time? Figure 6 suggests it does. The figure shows the bids of the designated winners over time (panel a), and the probability that the designated winner wins the auction (panel b).[32] In EN, after round 10, designated winners are almost certain to win the auction, which is in line with equilibrium. In FP, bids by the designated winner exhibit a non-significant upward trend towards the second highest value, with a concomitant increase of the likelihood that the designated winner wins the auction.[33]

> **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

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[30] 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.

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

[32] For EN, the "bids" refer to the price paid by the designated winner when winning the auction, and to the dropout price otherwise.

[33] Appendix D provides regressions investigating the trend of bids and convergence point of FP.

losers that submit a bid either step out of the auction almost immediately or exit 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.[34] The experimental procedures are the same as in Study 1 with the only exception that the three subjects that where 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 euros on average in sessions that lasted, again, between 60 and 90 minutes. As we explain in more detail below, the results are qualitatively very similar across Studies 1 and 2.

In line with Result 1, under fixed matching, 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. For cartels in both FP and EN, the designated loser with the highest value defects significantly more often than the designated loser with the lowest value.[35] 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 concomitant standard deviations are 11.66 and 13.13 ($p = 0.116$). For FP the corresponding numbers are 46.28 and 38.78 ($p = 0.018$), and 12.27 and 13.75 ($p = 0.237$). In other words, in FP, cartels are more likely to break down when 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 value-draws affect cartel stability in the fixed-matching condition, at least to some extent.

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, the variance of revenue is significantly lower in FP than in EN, as with re-matching. Again, efficiency is higher in EN than in FP. More details are in Tables E2 and E3 in Appendix

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[34]In practice, cartels often center around a set of bidders that interact repeatedly (Phillips et al., 2003).

[35]For auctions in FO, 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, 39.76% and 26.04% ($p = 0.042$). See Table E3 in Appendix E for further details.

E. All in all, Results 2 and 3 are robust with respect to the matching protocol.

The similar 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 ($p = 0.008$).[36] 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, observed 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 all cases. Designated losers that submit a bid tent 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 $[\text{value} - 5, \text{value}]$.[37]

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 rounds 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 rounds up to the point that some bidder deviates. From then on, all bidders bid according to a one-shot Nash equilibrium in all subsequent rounds.

While the theory suggest that the matching protocol may affect auction outcomes, we do not find substantive differences between the two studies, at least not in the sense of statistical significance.[38] 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, revenue and revenue variance do not differ statistically between the two matching protocols. The matching protocol does not significantly affect efficiency for E; for FP, efficiency is (marginally) significantly lower under re-matching than under fixed matching, but only in terms of potential value realization.[39] Finally, for both

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[36]In 19 cases did a designated loser bid above value, resulting in winning the auction on 12 occasions.

[37]The bids of designated losers are significantly below the second highest value in the cartel ($p = 0.018$). In 62 of all 173 defections, the designated losers bids above her value. In 7 of those cases, the designated loser won the auction.

[38]More details regarding the comparison across matching protocols are in Table E2, E3, and E4 in Appendix E.

[39]For all rounds, the difference is statistically significant at the 5% level ($p = 0.021$).

auctions, designated winners' and designated losers' bidding strategies do not differ significantly between the fixed-matching and re-matching protocols. However, given the small sample sizes, one should be cautious in interpreting the insignificant differences, also because non parametric tests tend to be more conservative than parametric tests.

> **Result 5: Fixed Matching vs. Re-Matching**
> For both FP and EN, the two matching protocols do not differ statistically significantly 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.[40] This begs the question as to what is the best way to fight bidding rings.[41] The theoretical result of Robinson (1985) that cartels are more stable in the English auction than in the first-price sealed auction would suggest that auction designers should follow the advice of the OECD (2006) to use the first-price sealed-bid auction rather than the English auction in environments where collusion is a significant threat (p.36). However, Hu et al. (2011), Llorente-Saguer et al. (2017), and Agranov and Yariv (2018) fail to provide empirical support to the OECD's advice in that they do not find the auctions to differ in terms of collusion. Indeed, why does Robinson's (1985) insight not hold true experimentally? Our experiment is a first step in addressing this question by studying the collusive properties of the two auctions in a simple setting. In contrast to the earlier experimental evidence, our results are in line with the theory in that in our experiments, cartels are more stable and average revenue is lower in the English auction than in the first-price sealed-bid auction.

We conclude that Robinson's (1985) intuition works in simple settings, which serves as a starting point in gaining insight as to why it fails to work in the more complex settings studied by Hu et al. (2011), Llorente-Saguer et al. (2017), and Agranov and Yariv (2018). Two potential reasons why our results are differ from theirs come to mind. First of all, in our set-up (and in line with Robinson (1985)) cartels are exogenously

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[40]The set of bidding rings discovered by antitrust authorities may only be the tip of the iceberg. Kawai and Nakabayashi (2018) estimate that almost 40% of 15,000 Japanese construction projects is inconsistent with competitive behavior, suggesting that the number of bidding rings is substantially greater than the four cartel cases that were initiated in connection with the projects in their sample. McMillan (1991) presents anecdotal (and amusing) evidence about how bidders for Japanese public-works contracts organize and enforce cartel agreements. Based on simulations, he estimates that the excess profits from collusion amount to 16% to 33% of the price.

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

imposed. While this is instrumental in identifying the effect of auction format on cartel stability, in practice, cartel formation may be endogenous. Second, we impose common knowledge of values among bidders. Indeed, by doing so, our experimental design mimics Robinson's (1985) framework on which we build our hypotheses. 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 endogeneity of cartel formation, whether or not the values are common knowledge, the precise auction rules, the way bidders can communicate, the possibility of side payments, the number of bidders, the value structure, and so forth.

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, J. (2010). A study of the internal organization of a bidding cartel. *American Economic Review*, 100:724–62.

Bajari, P. and Ye, L. (2003). Deciding between competition and collusion. *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. *The Journal of Law, Economics, and Organization*, 34:301–363.

Dawes, R. M., McTavish, J., and 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. and 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. *The 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. (2010). Collusion and the choice of auction: An experimental study.

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

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

Holt, C. A. (1985). An experimental test of the consistent-conjectures hypothesis. *American Economic Review*, 75:314–325.

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

Huck, S., Normann, H.-T., and 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 restraint of trade. *Journal of Economic Behavior & Organization*, 5:191–222.

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

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

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

Kawai, K. and Nakabayashi, J. (2018). Detecting large-scale collusion in procurement auctions. Working paper, UC Berkely.

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*, 16:169–189.

Kovacic, W. E., Marshall, R. C., Marx, L. M., and 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.

Li, S. (2017). Obviously strategy-proof mechanisms. *American Economic Review*, 107:3257–87.

Llorente-Saguer, A., Zultan, R., et al. (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. (1987). Auctions and bidding. *Journal of Economic Literature*, 25:699–738.

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

McMillan, J. (1991). Dango: Japan's price-fixing conspiracies. *Economics & Politics*, 3:201–218.

Noussair, C. N. and Seres, G. (2020). The effect of collusion on efficiency in experimental auctions. *Games and Economic Behavior*, 119:267–287.

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. H. and Zona, J. 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.

Vanberg, C. (2008). Why do people keep their promises? an experimental test of two explanations. *Econometrica*, 76:1467–1480.

Wooldridge, J. M. (2010). *Econometric analysis of cross section and panel data*. Cambridge, MA: MIT press.

Appendices

A   Proofs of Propositions

This appendix contains the proofs of Propositions 1 and 2. To avoid tedious case distinctions, we prove the propositions for $v_1 \geq v_2 + 3\varepsilon$ and $M \geq v_1 + 2\varepsilon$. The proofs proceed analogously for other parameter constellations.

Proof of Proposition 1
When reached, in any final subgame, i.e., at price $M - \varepsilon$, leaving the auction is a dominant strategy for all remaining bidders. As a result, each bidder's equilibrium payoffs when reaching the final subgame are strictly negative. Reasoning backwards, all bidders leave the auction in equilibrium when reaching any price $p > v_1$. At price $p = v_1$, for all bidders apart from bidder 1, it is a strict best response to leave the auction. Bidder 1, in turn, best responds by remaining (and paying $v_1 - \varepsilon$). At any price $p < v_1$, when reached, remaining in the auction is a strict best response for bidder 1. On the equilibrium path, the other bidders are indifferent between not entering the auction and entering and leaving at any price $p \leq v_1$.

Proof of Proposition 2
Let, for $i = 1, \ldots, n$, b_i denote the bid submitted by bidder i, where, by convention, $b_i = -1$ if bidder i does not enter the auction. Define $b_{-1} \equiv \max\{b_2, b_3, \ldots, b_n\}$ as the highest bid submitted by the bidders other than bidder 1. We distinguish 4 cases.
Case 1: $b_{-1} \leq v_2 - 2\varepsilon$. Bidder 1's unique best response is to bid $b_1 = b_{-1} + \varepsilon$. However, bidder 2's bid cannot be part of the equilibrium because bidder 2 is strictly better of by bidding b_1 instead of b_2.
Case 2: $v_2 - \varepsilon \leq b_{-1} \leq v_1 - 3\varepsilon$. Bidder 1's unique best response is to bid $b_1 = b_{-1} + \varepsilon$. An equilibrium is established as b_i is a best response for bidders $i = 2, 3, \ldots, n$.
Case 3: $b_{-1} = v_1 - 2\varepsilon$. If $b_1 = b_{-1} + \varepsilon$, an equilibrium is established. If $b_1 = b_{-1}$, bidder $k > 1$ for whom $b_k = b_{-1}$ is strictly better off by biding $b_{-1} - \varepsilon$, so that bidder k's bid cannot be part of an equilibrium.
Case 4: $b_{-1} \geq v_1 - \varepsilon$. For bidder 1's best response bid b_1 it holds true that $b_1 \leq b_{-1}$. However, bidder $k > 1$ for whom $b_k = b_{-1}$ is strictly better off by bidding $b_{-1} - \varepsilon$, so that bidder k's bid cannot be part of an equilibrium.
So, any equilibrium belongs to either case 2 or case 3, resulting in the equilibrium set described in the proposition.

B   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 euro**.

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.

C Out of Equilibrium Bidding Behavior for the First-Price Sealed-Bid Auction

This appendix outlines our analysis of out-of-equilibrium bidding behavior in FP. We estimate bidding functions to generate empirical best responses for designated winners and designated losers, and compare best responses to actual bids. We find that designated winners best respond to designated losers' bidding behavior, while designated losers should always defect and bid more conditional on defection. We first turn to the analysis of designated winners' bidding behavior.

To generate an empirical best response of designated winner i in auction c, we need to predict the bid of each designated loser in auction c conditional on the values of all subjects in the auction. We need to take into account that designated winner i does not observe the identity of the designated losers she faces in auction c, but can predict their bids from observed behavior of designated losers in all auctions of i's matching group. In the main text, we show that designated losers with the highest value are significantly more likely to submit a bid than designated losers with the lowest value. We therefore estimate two separate bidding functions for each designated winner i: one to predict bids of the designated loser with the highest value, and one to predict bids of designated losers with the lowest value. The sample used to predict bids of the designated loser with the highest value contains all auctions in i's matching group where subject i was not the designated loser with the highest value. Likewise, the sample used to predict the bid of the designated loser with the lowest value contains all auctions in i's matching group where subject i was not the designated loser with the lowest value. We therefore assume that designated winner i only takes into account behavior of subjects she actually encounters in the experiment, and the values in an auction. We Heckman's two-step procedure to correct for selection effects: not all designated losers submit a bid. This procedure is run separately for each subject i.

As an example, consider designated winner i in auction c. We now outline the estimation of the predicted bid for the designated loser with the highest value in auction c. Recall that the sample consists of all auctions j in subject i's matching group provided subject i is not the designated loser with the highest value in auction j. This implies that we will obtain subject-specific estimates, and, as a consequence, subject-specific best-responses to a value draw. Let $\tilde{b}_j$ be a binary variable that equals one when the designated loser with the highest value in auction j submits a bit, and b_j be the bid that is submitted if that designated loser does indeed defect. The selection equation is:

$$Pr(\tilde{b}_j = 1) = \Phi(\alpha_0 + \alpha_1 v_j^1 + \alpha_2 v_j^2 + \alpha_3 v_j^3 + \alpha_4 X_t), \tag{C1}$$

where v_j^k indicates the kth highest value in auction j, and X_t consists of variables relating to the round auction j occurred in. We report results for X_t consisting of round fixed effects, and X_t consisting of one dummy for the first five rounds (the early-

dummy), and one dummy for all rounds after the 35th round (the late dummy).[42] The bid equation is:

$$b_j = \beta_0 + \beta_1 v_j^1 + \beta_2 v_j^2 + \beta_3 v_j^3 + \beta_4 \hat{\lambda}_j + \epsilon_j, \tag{C2}$$

where $\hat{\lambda}_j$ is the inverse Mills ratio (Wooldridge, 2010). The estimates of (C2) allow us to construct the predicted bid of the designated loser with the highest value in auction c, conditional on the three values in auction c. Denote the estimated bid of the designated loser with the highest value in auction c by $\hat{b}_c^H$. Repeating estimation of (C1) and (C2) on the sample of all auctions j in subject i's matching group provided subject i is not the designated loser with the lowest value in auction j gives and estimated bid of the designated loser with the lowest value in auction c: $\hat{b}_c^L$. Denote the concomitant bid distributions by $F_H^{v_c^1, v_c^2, v_c^3}$ and $F_L^{v_c^1, v_c^2, v_c^3}$. Under (C1), and the additional assumption that errors in (C1) and (C2) satisfy conditional mean independence, the estimated bids are asymptotically normal. As an approximation, we therefore have:

$$F_H^{v_c^1, v_c^2, v_c^3} \sim N(\hat{b}_c^H, se(\hat{b}_c^H)); \qquad F_L^{v_c^1, v_c^2, v_c^3} \sim N(\hat{b}_c^L, se(\hat{b}_c^L)). \tag{C3}$$

Equation (C3) allows us to construct the empirical best response of designated winner i in auction c. The best response of the designated winner i in auction c is:

$$b_i^{br} = \arg\max_{b \in \{0,1,\ldots,70\}} (v_i - b) G_i(b), \tag{C4}$$

where $G_i(b) = F_H^{v_c^1, v_c^2, v_c^3} F_L^{v_c^1, v_c^2, v_c^3}$, and G is indexed by i to indicate that the estimated distributions differ by subject, and v_c^k is the kth highest value in auction c. For each auction c, (C4) gives the best response of the designated winner based on the bidding behavior of designated losers in her matching group, conditional on the values in auction c.

To determine the best response of the designated loser with the highest value in auction c, subject l, the above procedure is repeated twice with some slight alterations. To estimate the bid of the designated loser with the lowest value in the auction, the sample of all auctions in l's matching group such that subject l is not the designated loser with the lowest values is used. To estimate the bid of the designated winner, equation (C2) is estimated by OLS, and equation (C1) is omitted.[43] With both estimates in hand, equation (C4) gives the best response of the designated loser with the highest value in auction c. The best response of the designated loser with the lowest value in auction c is determined similarly.

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[42]Including a variable in the selection equation that is not present in the bid equation is necessary to prevent collinearity issues in the bid equation: the so-called exclusion restriction. Using variables related to rounds amounts to assuming that the designated winner in an auction anticipates round- (for round fixed effects) or begin- and end-game effects (for the early- and late-dummy specification) on defection.

[43]Selection is unimportant for designated winners as in all but 6 auctions, the designated winner submits a bid.

Table C1 shows comparisons of the estimated best responses from equation (C4) to the actual bids.[44] Bids and estimated best responses of designated winners do not differ significantly, indicating that designated winners are best responding to the bidding behavior of designated losers in their matching group.[45] In all auctions the expected profit of submitting a bid equal to the best response is positive for all designated losers, suggesting that the 31% of designated losers that abstain from bidding are not best responding. In addition, designated losers who do submit a bid, bid less than the best response. Bids by designated losers with the highest value (0.85) are significantly below best responses (0.92).[46] Likewise, designated losers with the lowest value bid (0.57) significantly less than the estimate best response (0.70).[47] In sum, designated winners best respond to the bidding behavior of designated losers, whereas designated losers could do better by always defecting and bidding more conditional on defection. Table C1 shows that these results are robust to varying the exclusion restriction.

Table C2 shows comparisons of best responses to actual bids for all rounds past the 30th round. We find no evidence for an end-game effect whereby designated losers start best responding. Bids by designated losers with the highest value (0.87) are significantly below best responses (0.92).[48] Likewise, designated losers with the lowest value bid (0.60) significantly less than the estimated best response (0.67).[49] Time-series of the difference between estimated best responses and actual bids are provided in Figures C1-C3. Plotted are the mean +/- two standard deviations. If anything, designated losers bid below their best response in the latter rounds.[50] However, these end-game results should be interpreted with caution due to the small sample sizes underlying the matching group averages, and the ordinal nature of our non parametric tests.

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[44]As in the main text, we use non parametric tests that take each matching group average as one independent observation. We first compute the difference between the best response and the bid for individual bidders, and then compute matching group averages of these differences that we test against a difference of 0. Our results are robust to first generating matching group averages of bids and best responses, and then testing whether these averages are different.

[45]P-values: $p = 1.000$ for the round fixed effect specification, and $p = 0.370$ for the early- and late-dummy specification.

[46]P-values: $p = 0.000$ for both specifications.

[47]P-values: $p = 0.000$ for both specifications.

[48]P-values: $p = 0.007$ for the round fixed effects specification, and $p = 0.073$ for the early- and late-dummy specification.

[49]P-values: $p = 0.007$ for the round fixed effects specification, and $p = 0.073$ for the early- and late-dummy specification.

[50]P-values: $p = 0.073$ for both specifications.

Table C1: Comparison best responses to bids, first-price sealed-bid auction

	Designated winners	Designated losers (highest value)	Designated losers (lowest value)	Exclusion restriction
Best response	0.92 (0.02)	0.92 (0.05)	0.70 (0.01)	Round FE
	$\vee$	$\vee$***	$\vee$***	
Bids	0.91 (0.02)	0.85 (0.05)	0.57 (0.08)	
Best response	0.93 (0.02)	0.92 (0.04)	0.70 (0.01)	Early- and late-dummies
	$\vee$	$\vee$***	$\vee$***	
Bids	0.91 (0.02)	0.85 (0.05)	0.57 (0.08)	

Notes: Exclusion restriction = variables that are included in the selection equation, but not in the second stage; Early-dummy = dummy variable indicating an observation from the first 5 rounds; Late-dummy = dummy variable indicating an observation from rounds after the 35th round; standard deviation based on matching group averages in brackets; ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

Table C2: Comparison best responses to bids for rounds 31 and onward, first-price sealed-bid auction

	Designated winners	Designated losers (highest value)	Designated losers (lowest value)	Exclusion restriction
Best response	0.92 (0.04)	0.92 (0.05)	0.67 (0.02)	Round FE
	$\vee$*	$\vee$***	$\vee$***	
Bids	0.89 (0.14)	0.87 (0.07)	0.60 (0.09)	
Best response	0.90 (0.04)	0.92 (0.05)	0.67 (0.02)	Early- and late-dummies
	$\vee$*	$\vee$*	$\vee$*	
Bids	0.89 (0.14)	0.87 (0.07)	0.60 (0.09)	

Notes: Exclusion restriction = variables that are included in the selection equation, but not in the second stage; Early-dummy = dummy variable indicating an observation from the first 5 rounds; Late-dummy = dummy variable indicating an observation from rounds after the 35th round; standard deviation based on matching group averages in brackets; ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

Figure C1: Difference between best responses and actual bids, designated winners
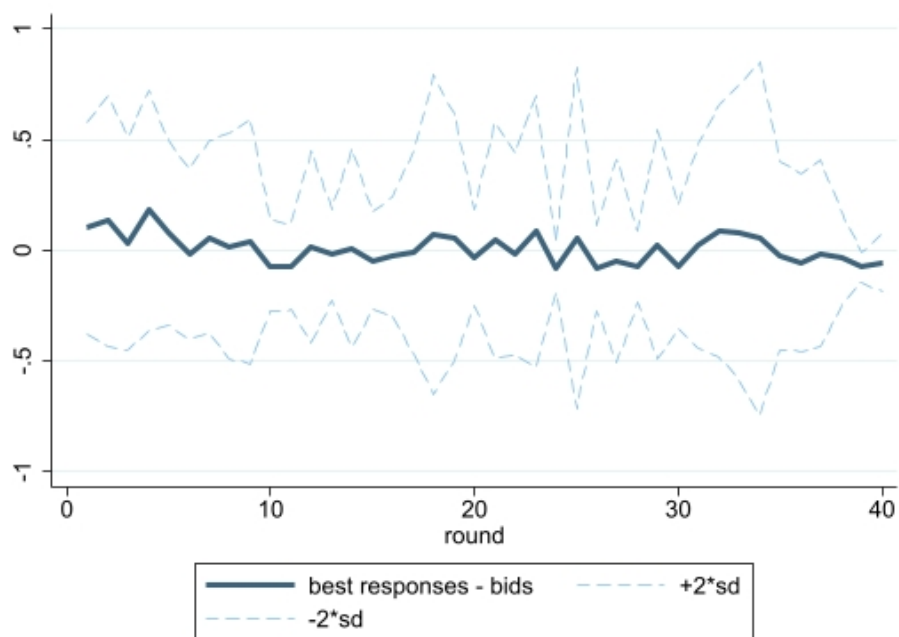

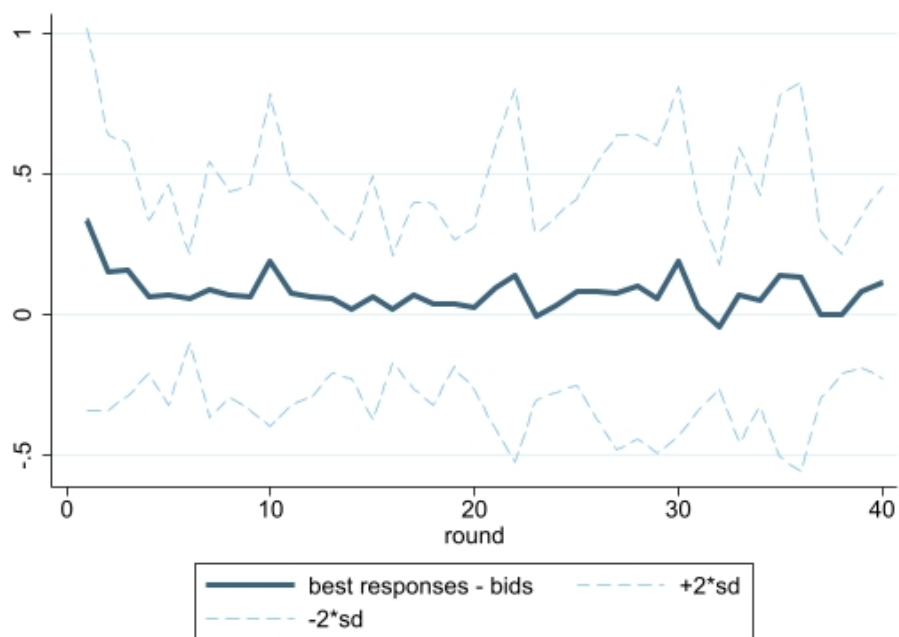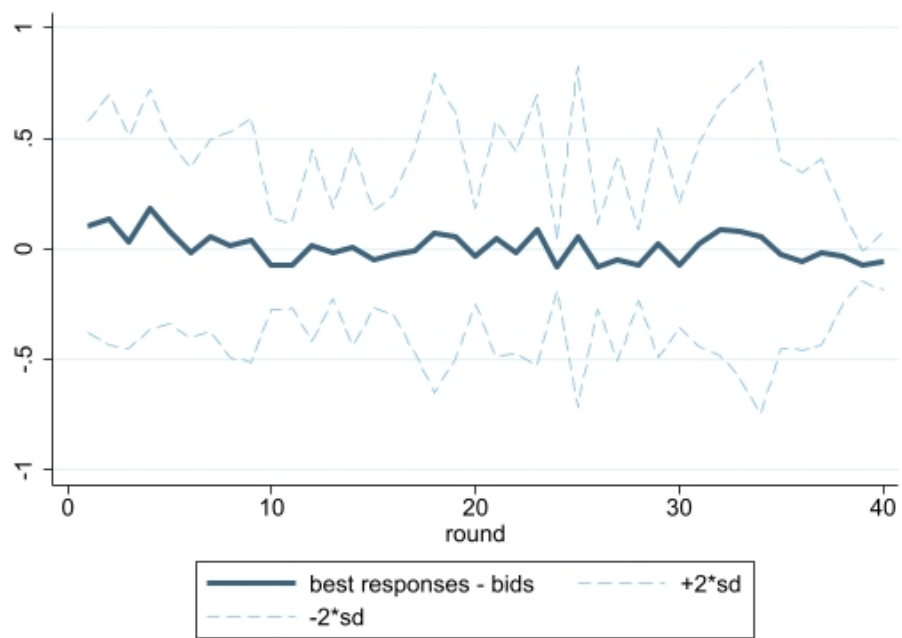Figure C2: Difference between best responses and actual bids, designated losers with the highest value

Figure C3: Difference between best responses and actual bids, designated losers with the lowest value

D   Convergence of Bidding Behavior for the First-Price Sealed-Bid Auction

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

$$\text{bid}_{it} = \beta_1 t + \alpha_i + u_{it}, \tag{D1}$$

$i = 1, 2, \ldots, n$, $t = 1, \ldots, 40$, where n is the number of subjects, and bid_{it} is the submitted bid as a fraction of the second-highest value in the auction.[51] Standard errors are clustered at the matching group level. The regression results are in Table D1.

Table D1: Fixed effects estimates of bid-trend in first-price auctions

	Re-matching		Fixed Matching	
	Designated winners	Designated losers	Designated winners	Designated losers
	(1)	(2)	(3)	(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

Notes: Standard errors clustered at the matching group level in brackets; ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

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 highest valu in the auction that submit a bid:

$$\text{bid}_{it} = \beta_1 T1_t + \beta_2 T2_t + \alpha_i + u_{it}, \tag{2}$$

$i = 1, 2, \ldots, n$, $t = 1, \ldots, 40$, where n and bid_{it} are defined as before, $T1_t = \max\{0, 35 - t\}$ and $T2_t = \max\{0, t - 35\}$. Note that the inclusion of the two time trends implies

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[51]Due to the random stopping rule, sessions need not have an equal number of rounds. No session had more than 40 rounds.

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 round 35. Standard errors are clustered at the matching group level. The regression results are in Table D2.

Table D2: 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

Notes: Standard errors clustered at the matching group level in brackets; ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

E   Additional Tables

Table E1: Cartel instability, across auctions and matching schemes

	Propensity to defect (by subject)			Cartel breakdown		
	Re-matching		Fixed Matching	Re-matching		Fixed Matching
EN	0.45 (0.20)	>	0.32 (0.35)	0.68 (0.19)	>	0.45 (0.45)
	$\wedge^{**}$		$\wedge^{*}$	$\wedge^{**}$		$\wedge^{*}$
FP	0.69 (0.11)	>	0.64 (0.13)	0.92 (0.08)	>	0.88 (0.13)

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; standard deviation based on matching group averages in brackets; ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

Table E2: Revenue, across auctions and matching schemes

	FP		EN
Fixed matching			
Stable cartels	0.94 (0.22)	>***	0.00 (0.00)
	$\vee$		$\wedge^{**}$
Unstable cartels	0.93 (0.12)	>	0.83 (0.22)
All cartels	0.93 (0.12)	>***	0.42 (0.45)
	$\wedge$		$\wedge$
Re-matching	0.98 (0.03)	>***	0.58 (0.16)

Notes: Stable cartel = no designated loser submits a bid; Unstable cartels = at least one designated loser submits a bid; standard deviation based on matching group averages in brackets; ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

Table E3: Variance of revenue, across auctions and matching schemes

	FP		EN
Re-matching	0.012 (0.018)	$<^{***}$	0.198 (0.031)
	$\wedge$		$\vee^{***}$
Fixed Matching	0.018 (0.023)	$<^{*}$	0.070 (0.060)

Notes: Standard deviation based on matching group averages in brackets; ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

Table E4: Efficiency, across auctions and matching schemes

	Designated winner wins			Value realization		
	FP		EN	FP		EN
Re-matching	0.78 (0.05)	$<^{***}$	0.93 (0.04)	0.93 (0.02)	$<^{***}$	0.98 (0.02)
	$\vee$		$\vee$	$\vee^{*}$		$\vee$
Fixed matching	0.73 (0.08)	$<^{***}$	0.93 (0.09)	0.87 (0.07)	$<^{**}$	0.96 (0.05)

Notes: Standard deviation based on matching group averages in brackets; ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.