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Signalling in auctions: Experimental evidence

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ABSTRACT

We study the relative performance of the first-price sealed-bid auction, the second-price sealed-bid auction, and the all-pay sealed-bid auction in a laboratory experiment where bidders can signal information through their bidding behaviour to an outside observer. We consider two different information settings: the auctioneer reveals either the identity of the winning bidder only, or she also reveals the bidders' payments to an outside observer. We find that the all-pay sealed-bid auction in which the bidders' payments are revealed outperforms the other mechanisms in terms of revenue, while this mechanism underperforms in terms of efficiency relative to the winner-pay auctions.

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1. Introduction

In many auction settings, bidders care about how their behaviour in the auction is interpreted by others. Market analysts can consider the performance of a firm in an auction, winning or losing, as a signal of the firm's management quality, financial position, or confidence in its technological edge on the competition.¹ Signalling has also been shown to be an important motivator for bidders in charity and art auctions: winning a Van Gogh painting comes with a great deal of prestige,² whereas failing to win a charity auction may leave some wondering about the losing bidder's true generosity for the

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E-mail addresses: olivier.bos@u-paris2.fr (O. Bos), francisco.g.martinez@bi.no (F. Gomez-Martinez), onderstal@uva.nl (S. Onderstal), tom.truys@usaintlouis.be (T. Truys).¹ Liu (2012) argues that signalling incentives could arise in bidding contests where the winning bidder issues equity or debt for financing her payment.² Mandel (2009) distinguishes three main motives for buying art: investment, direct consumption, and signalling, and suggests that the latter two explain the old puzzle as to why art systematically underperforms as an investment compared to bonds and equity.

charity.³ In such settings, signalling concerns constitute an additional component in a bidder's bidding strategy. In the past two decades, the theoretical literature has devoted ample attention to signalling in auctions.⁴

In this paper, we study how various auction formats perform in terms of revenue in a setting where bidders can signal information through their bids to an outside observer. We do so using a laboratory experiment. In particular, we compare two winner-pay auctions, the first-price (FP) and second-price (SP) sealed-bid auctions, as well as the all-pay (AP) sealed-bid auction in two information settings, one in which only the winner's identity is publicly revealed and one in which the bidders' payments are publicly revealed. To our knowledge, ours is the first laboratory experiment comparing various auction formats in a setting where bidders have signalling concerns. It provides a first step to understanding the relative performance of auctions in such settings, which may inform future theoretical and empirical research on auctions.

A key finding from the theoretical literature is that an auction's equilibrium revenue depends on both the auction format used and the kind of information that the auctioneer reveals about the outcome of the auction. In settings where bidders have an incentive to overstate their private information, the FP, SP, and AP auctions yield the same expected revenue in a separating equilibrium if the auctioneer reveals only the winner's identity (Giovannoni and Makris, 2014) or the winner's identity and bid (Goeree, 2003; Haile, 2003; Katzman and Rhodes-Kropf, 2008; Giovannoni and Makris, 2014).⁵ Giovannoni and Makris (2014) tie these revenue-equivalence results together by eliciting conditions that guarantee that an auction's expected revenue only depends on the information revealed, independently of the auction format used. In contrast, if the winner's payment is revealed (rather than her bid), revenue equivalence breaks down. In that case, the SP auction dominates the FP auction in terms of expected revenue (Giovannoni and Makris, 2014; Bos and Truys, 2021). Revealing either the winner's bid or the winner's payment increases revenue in both the FP and the SP auction compared to the case where only the winner's identity is revealed (Giovannoni and Makris, 2014; Bos and Truys, 2021). In this paper, we add to this literature by showing that the AP auction yields higher expected revenue if all bidders' payments are revealed than if only the winner's identity is revealed. We also show that in settings where all payments are revealed, the AP auction revenue dominates the FP and SP auctions.

We experimentally test these results using Bos and Truys (2021) framework. We consider symmetric independent private values setting in which the bidders care about the beliefs of an outside observer about their values. The outside observer is partly informed about the auction outcome and uses this information to update her beliefs about the bidders' values. We consider two different information settings: the auctioneer reveals either the identity of the winning bidder to the outside observer only, or she also reveals the bidders' payments. These payments are the winner's payment in the winner-pay auctions, and the payment of each bidder in the AP auction. Revealing all payments is in line with public policy: in the EU, a Directive on Public Procurement stipulates that information about payments must be incorporated in a contract award notice.⁶ Moreover, in many art auctions that attract publicity (i.e., where signalling likely matters) the bidders' payments are published in the press.

As Turocy (2009) notes, signalling games are hard for humans to play. This may explain why experiments regarding signalling games are not very common. Moreover, most of these experiments focus on equilibrium selection, given the usual equilibrium multiplicity in signalling games.⁷ Auctions with signalling opportunities to outside observers have hardly been analysed in the lab.⁸ To the best of our knowledge, Fonseca et al. (2020) is the only exception. They consider a setting where bidders can signal their productivity to firms that are hiring on a labour market. Fonseca et al. (2020) focus on several information disclosure policies within the same auction format: the FP auction. While they find that signalling opportunities lead to more aggressive bids, they observe consistent underbidding compared to equilibrium. Our experimental results complement theirs in that our design facilitates between-auction comparisons.

Our main result is that the AP auction in which the bidders' payments are revealed outperforms the other mechanisms in terms of revenue. Like Fonseca et al. (2020), we find underbidding in the winner-pay auctions relative to the equilibrium predictions. In particular, we observe that bidders are hesitant to bid above value in the SP auction, which they should according to theory. Underbidding is particularly striking for the SP auction where the winner's payment is revealed to the outside observer. As a result, the FP auction yields more revenue than the SP auction in this information regime, in contrast to what theory predicts. Moreover, revealing the bidders' payments boosts revenue in the AP and the FP auctions, but not in the SP auction. The outside observer's tendency to overestimate the winners' values relative to the losers' in the AP auction

³ Charities often raise funds by auctioning objects provided to them by celebrities (Schram and Onderstal, 2009). A broad theoretical and empirical literature suggests that signalling and status are important motives for contributions to charities. Glazer and Konrad (1996) and Harbaugh (1998a,b) show that signalling is an important factor to explain patterns in charitable donations.

⁴ See Goeree (2003), Das Varma (2003), Haile (2003), Katzman and Rhodes-Kropf (2008), Molnar and Virág (2008), Liu (2012), Giovannoni and Makris (2014), Marinovic (2016), and Bos and Truys (2021).

⁵ Goeree (2003) and Das Varma (2003) show that in settings where bidders want to understate their private information, separating equilibria may fail to exist.

⁶ See Annex V part D of Directive 2014/24/EU of the European Parliament and of the Council of 26 February 2014 on public procurement: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02014L0024-20200101&from=EN> (last accessed December 17th 2020).

⁷ Brandts and Holt (1993), de Haan et al. (2011), Drouvelis et al. (2012), and Jeitschko and Normann (2012).

⁸ Previous experimental work on auctions studies the effects of disclosing previous bids (see e.g., Cason et al., 2011; Dufwenberg and Gneezy, 2002; Neugebauer and Selten, 2006), bidders' types (see, e.g., Andreoni et al., 2007), and information about the object (see e.g., Goeree and Offerman, 2002) to bidders.

Table 1
Experimental design.

Treatment	Auction	Information to the outside observer	Do bidders' payoffs depend on outside observer's estimate?
FPW	FP	The winner	Yes
FPWP	FP	The winner and her payment	Yes
SPW	SP	The winner	Yes
SPWP	SP	The winner and her payment	Yes
APW	AP	The winner	Yes
APWP	AP	The winner and the bidders' payments	Yes
FPWcontrol	FP	The winner	No
FPWPcontrol	FP	The winner and her payment	No
SPWcontrol	SP	The winner	No
SPWPcontrol	SP	The winner and her payment	No
APWcontrol	AP	The winner	No
APWPcontrol	AP	The winner and the bidders' payments	No

when the bidders' payments are revealed partly explains why AP auction outperforms the winner-pay auctions. Finally, we observe that the AP auction where the bidders' payments are revealed underperforms in terms of efficiency relative to the winner-pay auctions. In other words, we find a trade-off between revenue and efficiency.

The remainder of this paper is structured as follows. In [Section 2](#), we describe our experimental design and protocol. [Section 3](#) includes the theoretical results and the hypotheses tested. [Section 4](#) contains our experimental findings. [Section 5](#) concludes.

2. Experimental design and protocol

The experiment was computerized⁹ and run at the CREED laboratory of the University of Amsterdam. We employed a full $3 \times 2 \times 2$ factorial design varying (between subjects) the auction type (FP, SP and AP), the information about the auction outcome that is communicated to the outside observer (with or without information about the bidders' payments), and whether the bidders' payoffs depend on the outside observer's estimate (in the main treatments, it did, in the control treatments, it did not). Because we wish to focus on auctions where only the winner or the winner and all payments are revealed, we leave other mechanisms, including the AP auction where only the winner's payment is revealed or the FP auction and SP auction where all bids are revealed, for future research. [Table 1](#) summarizes the resulting twelve treatments of the experiment. The control treatments serve as a benchmark when comparing results between auction types.

Each treatment was comprised of seven groups of four participants. All 336 participants, recruited by public announcement from the undergraduate population of the University, took part in only one session each. At the start of each session, we randomly allocated participants over the computers so they could not infer which other participants were in the same group. We provided computerized instructions to the participants. The instructions for treatment FPWP can be found in [Appendix D](#).¹⁰ Before the experiment started, participants answered test questions to make sure that they understood the experimental protocol.¹¹ Sessions lasted between 45 and 75 min. Payment consisted of a show-up fee of 7 euros, plus a payoff related to the total profits earned in the 30 rounds. The exchange rate was 1 euro for 50 experimental points. On average, participants earned 14.61 euros (including the show-up fee).

In all sessions, participants interacted in fixed groups of four (no rematching). In each of the 30 rounds of a session, a fictitious good was auctioned. In each round, one group member was randomly chosen by the computer to play the role of the outside observer. The remaining three group members were bidders in an auction. We let subjects interact in fixed groups, and have them take turns playing the role of the outside observer in their group. This was done to foster the learning needed to reach a perfect Bayesian equilibrium, which crucially requires coordination between the bidders' strategies and the outside observer's beliefs. Role switching also renders bidder collusion more difficult as that requires coordination amongst more players.

At the start of each round, all bidders were privately informed about their value for the good. Values were independently drawn according to a uniform distribution on the set $\{1,2,3,\dots,100\}$. For the sake of comparability between treatments, we kept the value draws constant across treatments. In the auction, each of the three bidders independently submitted a bid for the fictitious good from the set $\{0,1,2,\dots,200\}$. The bidder with the highest bid won the good. In the FP auction, the winner paid her own bid, while in the SP auction, the winner paid the second highest bid. In the AP auction, finally, all bidders paid their own bid. Ties were resolved randomly. In the main treatments, the bidder payoffs depended on both the outcome of the auction, and the estimate of the outside observer. The outside observer was asked to guess the values of each of the three bidders after obtaining information about the outcome of the auction. Each bidder, win or lose, received half of the

⁹ The program was written using PHP and MySQL.

¹⁰ The instructions of the other treatments are available from the authors upon request.

¹¹ These questions are available from the authors upon request.

Table 2
Equilibrium predictions per treatment.

Treatment	Auction	Information to the outside observer	Equilibrium bids	Expected revenue
FPW	FP	The winner	$B(v) \approx \frac{2}{3}v + 22$	$R \approx 72$
FPWP	FP	The winner and her payment	$B(v) = v$	$R = 75$
SPW	SP	The winner	$B(v) \approx v + 22$	$R \approx 72$
SPWP	SP	The winner and her payment	$B(v) = \frac{v}{2} + 62.5$	$R = 87.5$
APW	AP	The winner	$B(v) \approx \frac{1}{100}v^3 + \frac{22v^2}{100}$	$R \approx 72$
APWP	AP	The winner and the bidders' payments	$B(v) = \frac{1}{100}v^3 + \frac{v}{2}$	$R = 125$
FPWcontrol	FP	The winner	$B(v) = \frac{1}{100}v^3$	$R = 50$
FPWPcontrol	FP	The winner and her payment	$B(v) = v$	$R = 50$
SPWcontrol	SP	The winner	$B(v) = v$	$R = 50$
SPWPcontrol	SP	The winner and her payment	$B(v) = v$	$R = 50$
APWcontrol	AP	The winner	$B(v) = \frac{1}{100}v^3$	$R = 50$
APWPcontrol	AP	The winner and the bidders' payments	$B(v) = \frac{1}{100}v^3$	$R = 50$

Notes: Equilibrium bids in the unique symmetric D1 equilibrium for bidder values v being independently drawn from $U[0, 100]$, and the expected revenue of the auction in this equilibrium.

outside observer's estimate of her value. The resulting payoff for bidder i is given by

$$\pi_i(w, p, v_i, \hat{v}_i) = \begin{cases} v_i - p + \hat{v}_i/2 & \text{if } w = i \\ -p + \hat{v}_i/2 & \text{if } w \neq i \end{cases}$$

where w denotes the auction winner, p the bidders' payments (which is zero for non-winners in the FP and SP auctions), v_i bidder i 's value, and \hat{v}_i the outside observer's estimate for bidder i 's value. This is a reduced-form way to model bidders' benefiting from outsiders believing they attach a high value the good, for example, as it signals their productivity. For instance, a telecommunications firm's value for radio spectrum might be correlated with the quality of its management. A high bid in the auction serves as a positive signal to outside investors so that the firm may be able to attract financial resources under favourable conditions in the future.

In all treatments, the outside observer was informed about which bidder won the auction before reporting her estimates. In the WP treatments, she also obtained information regarding how much the bidders paid. The payoffs of the outside observer depended on the accuracy of her estimates, also in the control treatments. Once she had entered value estimates for all bidders, the computer drew one of the three bidders' estimates at random. When the outside observer's estimate for this bidder deviated x points from the actual value, her payoff was equal to $40 - x$.¹²

One interpretation of the model is that after the auction, the outside observer decides how much to invest in each bidder, win or lose. The outside observer optimally invests more the higher the bidder's value. Bidder i 's expected surplus of the interaction equals $\hat{v}_i/2$ while the outside observer moves further away from its optimal investment level in the bidder the less accurate is her estimate.

3. Theoretical predictions

In this section, we describe the theoretical predictions.¹³ Most of the analysis follows straightforwardly from Bos and Truys (2021). In this paper, we add the theoretical analysis of the all-pay sealed-bid auction with all bidders' payments revealed to the outside observer for the parameters of the experiment (see Appendix A.3). Like Bos and Truys (2021), we restrict our attention to risk-neutral bidders and perfect Bayesian Nash equilibria that survive Banks and Sobel's (1987) D1 criterion (referred to as "equilibrium" in the remainder of this paper). Table 2 contains equilibrium predictions for all treatments. The formal derivations are presented in Appendix A.

In all treatments, a unique strictly increasing and symmetric equilibrium bidding curve exists. For the control treatments, the existence of an outside observer has no effect on the bidders' payoffs. Therefore, the predictions are standard, and imply revenue equivalence across treatments (see e.g., Vickrey (1961)). If only the identity of the winner is revealed to the outside observer, bidders' payoffs when winning are increased by half the difference between the outside observer's value estimates for winners and losers. Equilibrium bids are inflated by this number compared to the control treatments. In Appendix A, we show that a bidder's expected payoff from winning the auction (and hence her equilibrium bid) is increased by about 22.

If both the winner and the bidders' payments are revealed, the bidders will take into account how the outside observer updates her beliefs about the bidders' values as a function of the observed payments. In equilibrium, the winner's value is exactly revealed to the outside observer in the FP auction, since the equilibrium bidding curve is strictly increasing.

¹² Negative payoffs were subtracted from the participants' balances. In principle, the participants' balances might become negative. In the experiment, only one participant accumulated a negative amount of money over the 30 rounds.

¹³ As is common in the experimental literature on auctions, our theoretical predictions are based on a continuous value distribution while our experimental protocol uses a fine grid of discrete values. This greatly facilitates the equilibrium calculations, which in any case closely approximate the equilibrium in the case of a fine grid of discrete values (Riley, 1989).

Therefore, the outside observer will perfectly predict the winner's value. Moreover, bidders will take into account that when losing, the outside observer estimates their value to be equal to half the winner's value. A low-value bidder is better off, in terms of the outside observer's equilibrium estimate, by losing against a sufficiently high-value bidder, rather than by winning the auction. In the opposite case, the difference between winning and losing is large when viewed in terms of the outside observer's equilibrium estimate for high-value bidders. As a result, the equilibrium bids of low [high] value bidders are lower [higher] if the outside observer sees the winner's payment as compared to a situation where only the winner is revealed.

In SPWP, the winner's payment reveals the valuation of the second highest bidder in the fully separating equilibrium, but the outside observer cannot deduce which losing bidder made the second highest bid as no loser pays. The difference between winning and losing is – in terms of the outside observer's estimate – very large for a low-value bidder. If she wins [loses], the outside observer optimally estimates her value to be the average between the second highest value and 100 [3/4 of the second highest value]. This leads a low-value bidder to submit a considerably higher bid when the outside observer obtains information about the winner's payment.

In APWP, all bidders' values are exactly revealed to the outside observer in equilibrium since the equilibrium bidding curve is strictly increasing. Therefore, all bidders will take into account that the outside observer will perfectly predict their values, independently of winning or losing the auction. As a result, bidders have a stronger incentive to bid aggressively than if only the winner's identity is revealed so that the equilibrium bids are higher than in a situation where only the winner is revealed.

The theoretical predictions regarding the auction's revenue yield the following hypotheses which we will test using our experimental design:

Hypothesis 1. In the FP auction, revealing both the winner and her payment to the outside observer increases the average auction revenue as compared to a setting where only the auction winner is revealed.

Hypothesis 2. In the SP auction, revealing both the winner and her payment to the outside observer increases the average auction revenue as compared to a setting where only the auction winner is revealed.

Hypothesis 3. In the AP auction, revealing both the winner and the bidders' payments to the outside observer increases the average auction revenue as compared to a setting where only the auction winner is revealed.

Hypothesis 4. In the setting where both the winner and her payment are revealed to the outside observer, the average auction revenue is higher in the SP auction than in the FP auction.

Hypothesis 5. In the setting where both the winner and the bidders' payments are revealed to the outside observer, the average auction revenue is higher in the AP auction than in the FP and SP auctions.

Hypothesis 6. In the setting where only the winner is revealed to the outside observer, the FP, SP, and AP auctions yield the same revenue, on average.

4. Results

In this section, we present our experimental results. We start in [Section 4.1](#) by comparing the auction revenue between treatments. In [Section 4.2](#), we analyse bidding behaviour. In [Section 4.3](#), we discuss the outside observer's estimates and their effect on bids. Finally, in [Section 4.4](#), we present an efficiency comparison between auctions. Concerning the statistical analysis, two-sided Mann-Whitney U tests are employed in the case of non-parametric analysis, using groups as single observations. The parametric analyses are based on ordinary least-square regressions, where standard errors are clustered by group. Unless stated otherwise, all results refer to the main treatments, that is, where the outside observers' estimates affect bidders' payoffs.

4.1. Auction revenue

In this section, we explore the effect of the auction type and the information revealed to the outside observer on auction revenue. [Fig. 1](#) shows the average auction revenue for each of the treatments. We start by analysing the control treatments. In the existing experimental literature, it is found that the AP auction yields more revenue than winner-pay auctions, and the FP auction yields more revenue than the SP auction.¹⁴ In both the W and the WP control treatments, we observe a similar pattern, although APWcontrol and FPWcontrol do not differ significantly in terms of revenue. The same holds true for FPWPcontrol and SPWPcontrol. Moreover, for each auction type, the revenues in the two W and WP control treatments do not differ significantly. A parametric analysis, where the highest valuation is included as a control variable, confirms these results (see [Table 3](#)). Result 0 summarizes the main findings.

Result 0: *In the control treatments where only the winner is revealed, the revenues in the AP and FP auctions are significantly higher than the revenue in the SP auction; the revenues raised in the AP and the FP auctions do not differ significantly. In the*

¹⁴ See [Noussair and Silver \(2006\)](#) for a comparison between AP and FP auctions, and [Kagel \(1995\)](#) for an overview of experiments on FP and SP auctions.

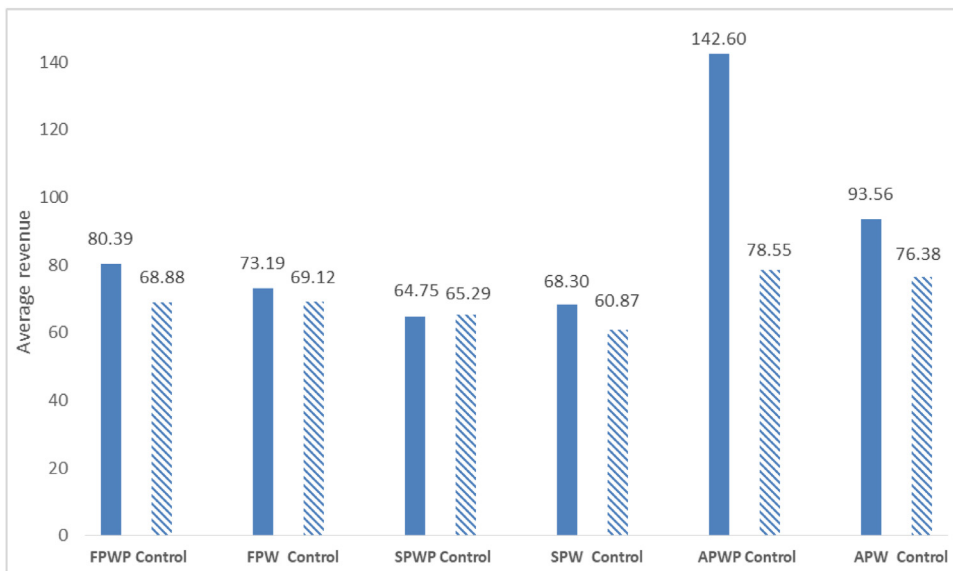


Fig. 1. Average auction revenue by treatment.

Table 3
Auction revenue per control treatment controlling for the highest value.

Dependant variable	Regressor	
	Revenue (1)	Revenue (2)
HighestValue	0.85*** (0.064)	0.85*** (0.064)
FPWPcontrol	-9.87* (5.094)	
FPWcontrol	-9.27** (4.711)	0.60 (2.220)
SPWPcontrol	-13.20** (5.498)	-3.33 (3.599)
SPWcontrol	-17.78*** (4.938)	-7.92*** (2.668)
APWPcontrol		9.87*(5.094)
APWcontrol	-2.68 (7.694)	7.19 (6.473)
Constant	10.85 (7.266)	0.981 (6.090)
Observations	1260	1260
Adjusted R squared	0.129	0.129

Notes: Clustered standard errors in parentheses. APWPcontrol is the reference treatment in (1). FPWPcontrol is the reference treatment in (2). HighestValue denotes the highest value among the three bidders. FPWPcontrol, FPWcontrol, SPWPcontrol, SPWcontrol, APWPcontrol and APWcontrol are dummy variables which are equal to 1 if and only if the observation involves treatments FPWPcontrol, FPWcontrol, SPWPcontrol, SPWcontrol, APWPcontrol and APWcontrol respectively. *p<0.1, **p<0.05, ***p<0.01.

control treatments where the winner and the bidders' payments are revealed, the revenue of the AP auction is significantly higher than the revenue in the FP and SP auctions; the revenues raised in the FP and the SP auctions do not differ significantly. For all auctions, there is no significant difference in terms of revenue between the W and WP control treatments.

Now, we turn to the main treatments. The AP auction where both the winner and the bidders' payments are communicated to the outside observer yields the highest revenue on average; average auction revenue is significantly higher in APWP than in the other treatments ($p < 0.01$ for each other treatment). In particular, in the AP auction, revealing the winner and the bidders' payments increase the auction's revenue, on average, by 50 units as compared to the case where only the winner is revealed. The increase in revenues is even greater when comparing APWP with the winner-pay auction treatments.

The FP auction where both the winner and her payment are revealed to the outside observer also yields significantly higher revenue on average than any other winner-pay auction treatment ($p = 0.04$, $p < 0.01$, and $p < 0.01$ for FPW, SPWP, and SPW, respectively). The revenue in the FP auction, by revealing the winner and her payment, increases by more than 7

Table 4
Auction revenue per treatment controlling for the highest value.

Dependant variable	Regressor		
	Revenue (1)	Revenue (2)	Revenue (3)
HighestValue	1.294*** (0.109)	1.29*** (0.109)	2.14*** (0.248)
FPWP	−62.64*** (9.233)		33.24 (21.275)
FPW	−69.75*** (8.830)	−7.11** (3.372)	38.47* (19.837)
SPWP	−77.85*** (8.799)	−15.21*** (3.291)	9.33 (20.591)
SPW	−74.60*** (9.124)	−11.96*** (4.079)	2.64 (21.45)
APWP		62.64*** (9.233)	
APW	−50.01*** (10.83)	12.63* (7.108)	−11.17 (32.43)
HighestValue*FPWP			−1.20*** (0.283)
HighestValue*FPW			−1.35*** (0.259)
HighestValue*SPWP			−1.09*** (0.269)
HighestValue*SPW			−0.97*** (0.269)
HighestValue*APW			−0.48 (0.444)
Constant	39.473*** (11.74)	−23.167** (8.606)	−28.39 (19.702)
Observations	1260	1260	1260
Adjusted R squared	0.386	0.386	0.403

Notes: Clustered standard errors in parentheses. APWP is the reference treatment in (1). FPWP is the reference treatment in (2). HighestValue denotes the highest value amongst the three bidders. FPWP, FPW, SPWP, SPW, APWP and APW are dummy variables which are equal to 1 if and only if the observation involves treatments FPWP, FPW, SPWP, SPW, APWP and APW respectively.

* $p < 0.1$.

** $p < 0.05$.

*** $p < 0.01$.

units as compared to the case where only the winner is revealed. The increase in revenues is even greater when comparing FPWP with both SP treatments. A parametric analysis, where the highest valuation is included as a control variable, confirms these results (see Table 4). Fig. 2 represents the regression results graphically. The revenue estimates are higher in APWP than in any of the other treatments for all highest values and are higher in FPWP than in any of the other winner-pay auction treatments for all highest values above 20 (i.e., for 98% of the realizations of the highest values in those treatments).

Notice that the revenue ranking $AP > FP > SP$ in both the W and the WP treatments is the same as in the control treatments (although not all differences are significant in the control treatments), which, as said, is in line with what is typically observed in the experimental literature. This begs the question as to what extent the revenue ranking is caused by the outside observer estimates affecting bidder payments. We address that question by decomposing the between-auction effects into effects caused by “typical” auction behaviour and effects of signalling motives. In a difference-in-difference analysis we compare the revenues in the main treatments, correcting for the revenues obtained in the control treatments. We do so by running a linear regression of difference in revenues on treatment dummies. The regression results, reported in Table 5, confirm that APWP yields higher average revenue than the other treatments ($p < 0.01$ for all comparisons), and that FPWP yields higher average revenue than FPW, SPWP, and SPW, although the difference with SPW is no longer statistically significant.

Now, we spell out our main results and confront these with our hypotheses. All results hold true both in a direct comparison between the mechanisms and in the difference-in-difference analysis.

Result 1: In the FP auction, revealing both the winner and her payment significantly increases auction revenue as compared to the case where only the winner is revealed.

Result 2: In the SP auction, revealing both the winner and her payment does not significantly increase auction revenue as compared to the case where only the winner is revealed.

Result 3: In the AP auction, revealing both the winner and the bidders' payments significantly increase auction revenue as compared to the case where only the winner is revealed.

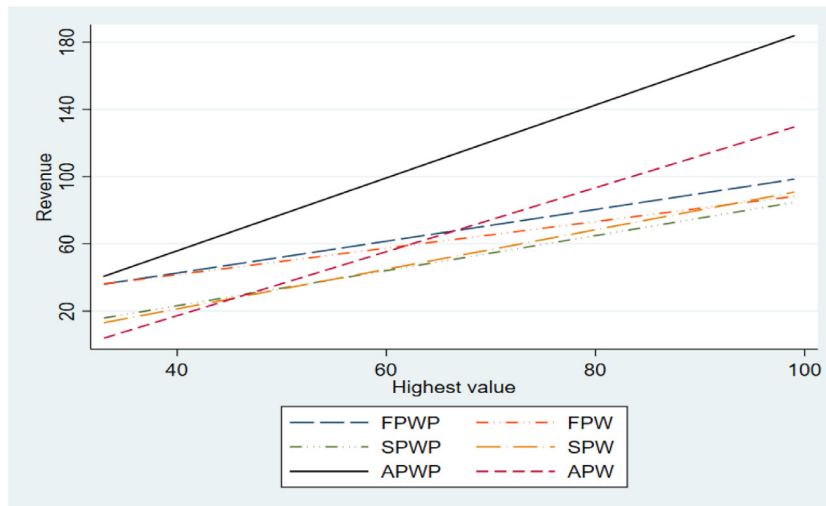


Fig. 2. Auction revenue per treatment controlling for the highest value.
 Note: The curves are based on the linear regression estimates reported in Table 3.

Table 5
 Auction revenue per treatment relative to control treatment.

Dependant variable	Regressor	
	DiffRevenue (1)	DiffRevenue (2)
FPWP	-52.60*** (7.923)	
FPW	-59.84*** (8.076)	-7.24*** (2.681)
SPWP	-64.28*** (8.403)	-11.68*** (3.546)
SPW	-55.68*** (8.622)	-3.08 (4.038)
APWP		52.60*** (7.923)
APW	-46.97*** (11.698)	5.63 (8.877)
Constant	64.01*** (7.772)	11.41** (1.540)
Observations	1260	1260
Adjusted R squared	0.200	0.200

Notes: Clustered standard errors in parentheses. APWP is the reference treatment in (1). FPWP is the reference treatment in (2). FPWP, FPW, SPWP, SPW, APWP and APW are dummy variables which are equal to 1 if and only if the observation involves treatments FPWP, FPW, SPWP, SPW, APWP and APW respectively. The dependant variable is the difference between the revenue obtained in a group in a round and the average revenue obtained in the corresponding group in the corresponding control treatment in the same round.

* $p < 0.1$.
 ** $p < 0.05$.
 *** $p < 0.01$.

Results 1 and 3 confirm Hypotheses 1 and 3. FPWP and APWP yield higher revenues for the auctioneer than FPW and APW respectively. This means that in the FP and AP auctions, the auctioneer can increase her revenue by publishing how much the bidders pay, rather than only publishing the winner's identity. According to result 2, revenue does not differ significantly between SPWP and SPW ($p = 0.41$). This result contradicts Hypothesis 2.

Result 4: When both the winner's identity and bidders' payments are revealed, the FP auction raises significantly more money than the SP auction does.

Result 4 is inconsistent with Hypothesis 4. The analysis of bidding behaviour in Section 4.2 sheds more light on this discrepancy between the experimental results and the theoretical predictions.

Result 5: When both the winner's identity and bidders' payments are revealed, the AP auction raises significantly more money than the FP and SP auctions do.

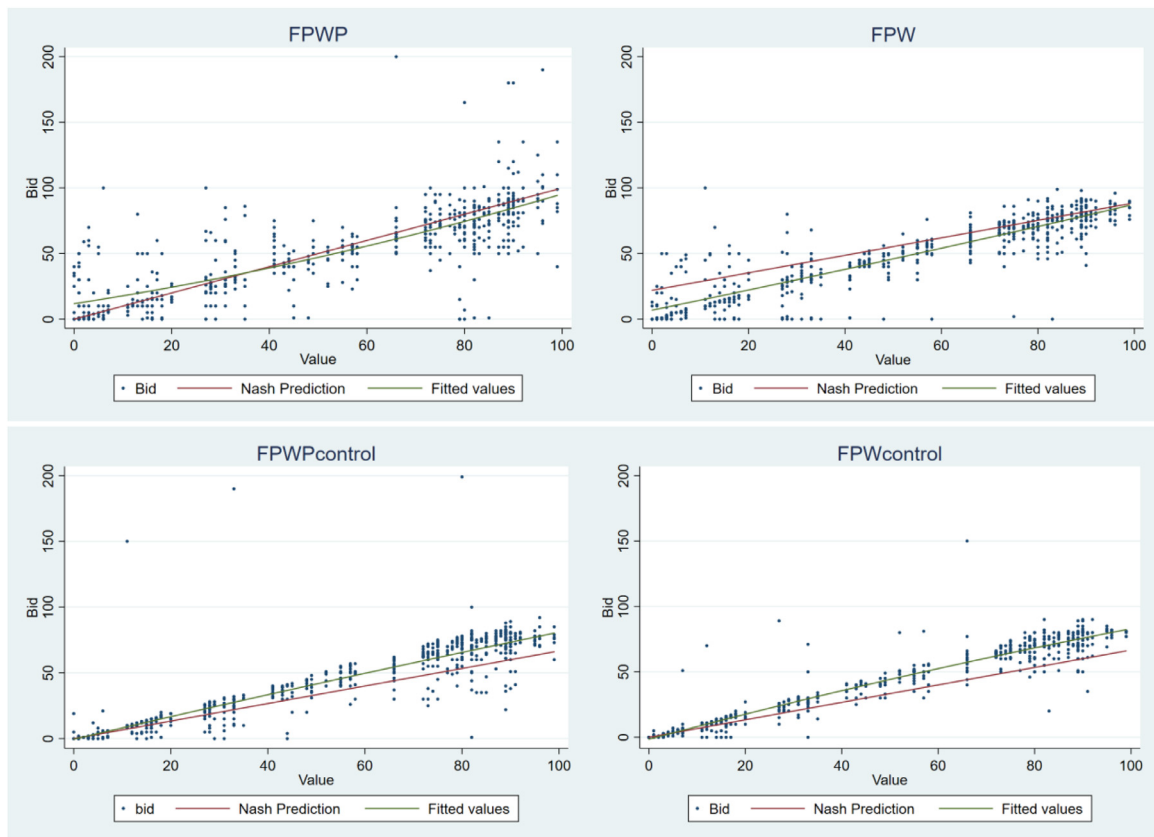


Fig. 3. Bids submitted for the FP auction.

In line with Hypothesis 5, APWP yield higher revenues for the auctioneer than both winner-pay auctions. This means that when in the auctioneer publishes both the winner's identity and the bidders' payments, he can increase the revenue by running the AP auction instead of the FP and the SP auctions.

Result 6: *When only the winner is revealed, the AP auction raises significantly more money than the FP and SP auctions do while the FP and SP auctions do not differ significantly in terms of average auction revenue.*

In contrast to Hypothesis 6, the AP auction generates more revenue than both winner-pay auctions. The revenue equivalence between FP and SP is in line with Hypothesis 6.

4.2. Bidding behaviour

In this section, we analyse the subjects' bidding behaviour to discover the extent to which it is in line with the theoretical predictions and, if not, how it contributes to the rejection of some of our hypotheses in the previous section. Figs. 3–5 contrast bids submitted with the theoretical predictions.

We start by exploring how bidding strategies depend on whether the outside observer influences bidders' payoffs. The scatter plots in Figs. 3–5 indicate that the bid distributions in the control treatments are in line with what is commonly observed in FP, SP, and AP auctions in the lab (see e.g., Kagel (1995), Noussair and Silver (2006), Schram and Onderstal (2009), and Müller and Schotter (2010)): Bids in the FP are typically in between the risk-neutral equilibrium bid and value; in the SP auction, quite some bids are above value, perhaps even more than what is commonly observed; in the AP auction, bids are close to zero for low values and above the equilibrium bid for high values.

We now zoom in on bidding behaviour in the main FP treatments. A linear regression of bid on value reveals that bids in FPWP diverge from the theoretical predictions to some extent.¹⁵ The intercept is significantly greater ($p = 0.00$) and the slope is less steep ($p = 0.02$) than the theoretical prediction. As a consequence, low-value bidders submit higher bids than in equilibrium, while high-value bidders submit slightly lower bids. For FPW, the estimated bidding curve lies below the theoretical prediction ($p = 0.03$ and $p = 0.02$ for the differences in slope and intercept, respectively, between the observed bids and the theoretical prediction) for low and intermediate values. As the scatter plot in Fig. 3 indicates, it is mainly subjects with low and intermediate values who underbid. Notice that for values below 66 equilibrium bidding entails bids

¹⁵ The regression results are reported in Appendix B, Table B.1.

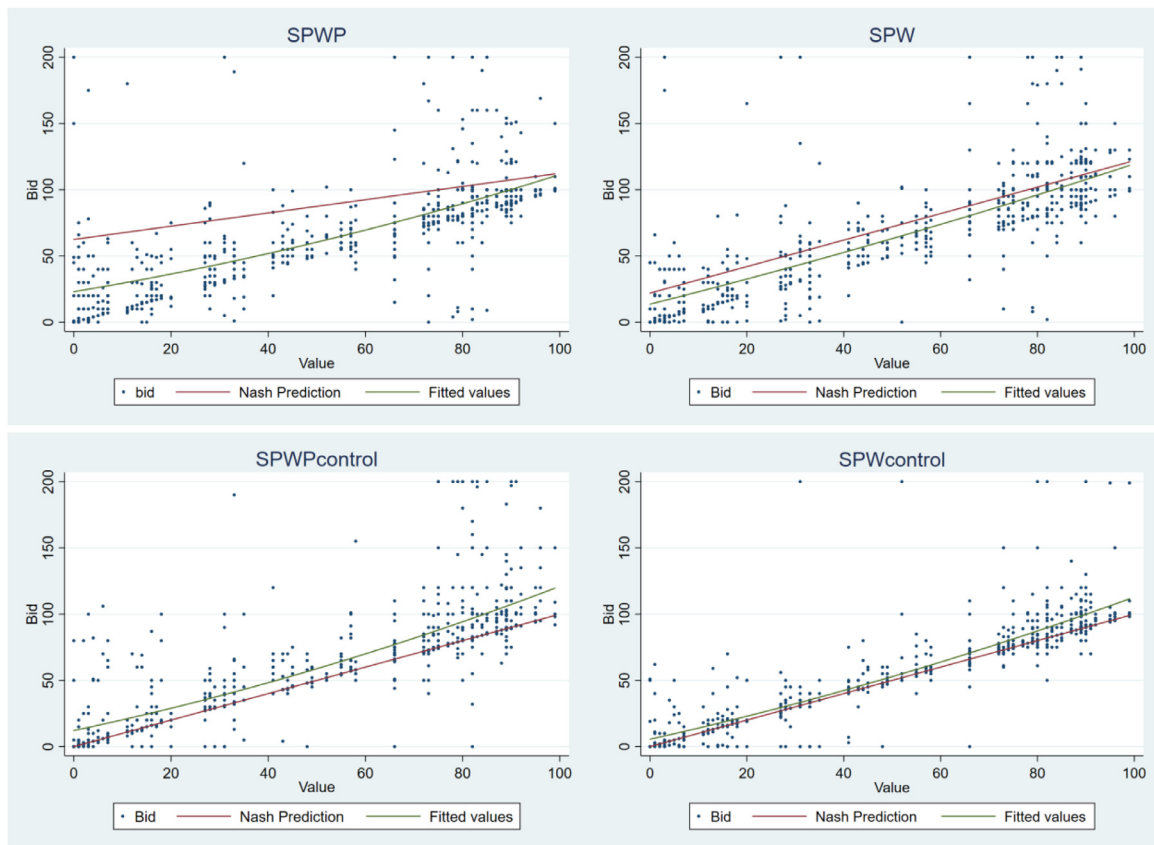


Fig. 4. Bids submitted for the SP auction.

above value, whereas 70% of the bids are actually below value in the experiment when the value is below 66. Result 7 summarizes the main findings for bidding behaviour in the FP auction.

Result 7: In FPWP, bidders overbid for low values and underbid for high values. Bidders in FPW tend to underbid relative to the equilibrium prediction, particularly for low and intermediate values.

We now turn to the main SP treatments. In both the W and the WP treatments, bidders tend to significantly underbid relative to the equilibrium predictions.¹⁶ In SPWP, low-value bidders bid substantially lower than the equilibrium prediction ($p < 0.01$ for the differences between the observed bids and the theoretical prediction for both the slope and intercept estimates). They seem to feel hesitant to bid as much as 62.5 points above their value. In SPW, bidders underbid on average over the entire value range ($p = 0.45$ and $p = 0.01$ for the differences in slope and intercept respectively between the observed bids and the theoretical prediction). Bidders optimally bid 22 points above their value according to the equilibrium prediction in SPW. In contrast, subjects do not always submit bids significantly above their values: Only 63% of the bids are above value, and the majority of these are in between value and value plus 22. Again, subjects seem hesitant to submit bids which are significantly greater than their values.

The bidding functions in SPWP and SPW differ significantly from each other, even though average bids do not differ between both treatments. In particular, low-value bidders place higher bids in SPWP than in SPW (the intercept is significantly higher in SPWP). This result is reversed for high-value bidders (bidding function is significantly steeper in SPW). As such, these findings are qualitatively in line with the theoretical predictions.

Result 8: In SPWP, bidders tend to underbid as compared to the equilibrium prediction, particularly bidders with low values. In SPW, bidders tend to underbid as compared to the equilibrium predictions. SPWP and SPW differ in terms of bidding curves, SPWP's bidding curve having a significantly higher intercept and significantly lower slope than SPW's.

Across treatments, underbidding relative to equilibrium is most prominent in SPWP. This is likely the case because bidders feel hesitant to bid substantially more than their value as the equilibrium prediction dictates. Moreover, the high bids of low-value bidders in the equilibrium prediction crucially depend on the outside observer making the correct inferences. In the next subsection, we shall see that the observed outside observer's estimates are systematically biased, and that this

¹⁶ The estimated bidding functions are in [Appendix B, Table B.2](#).

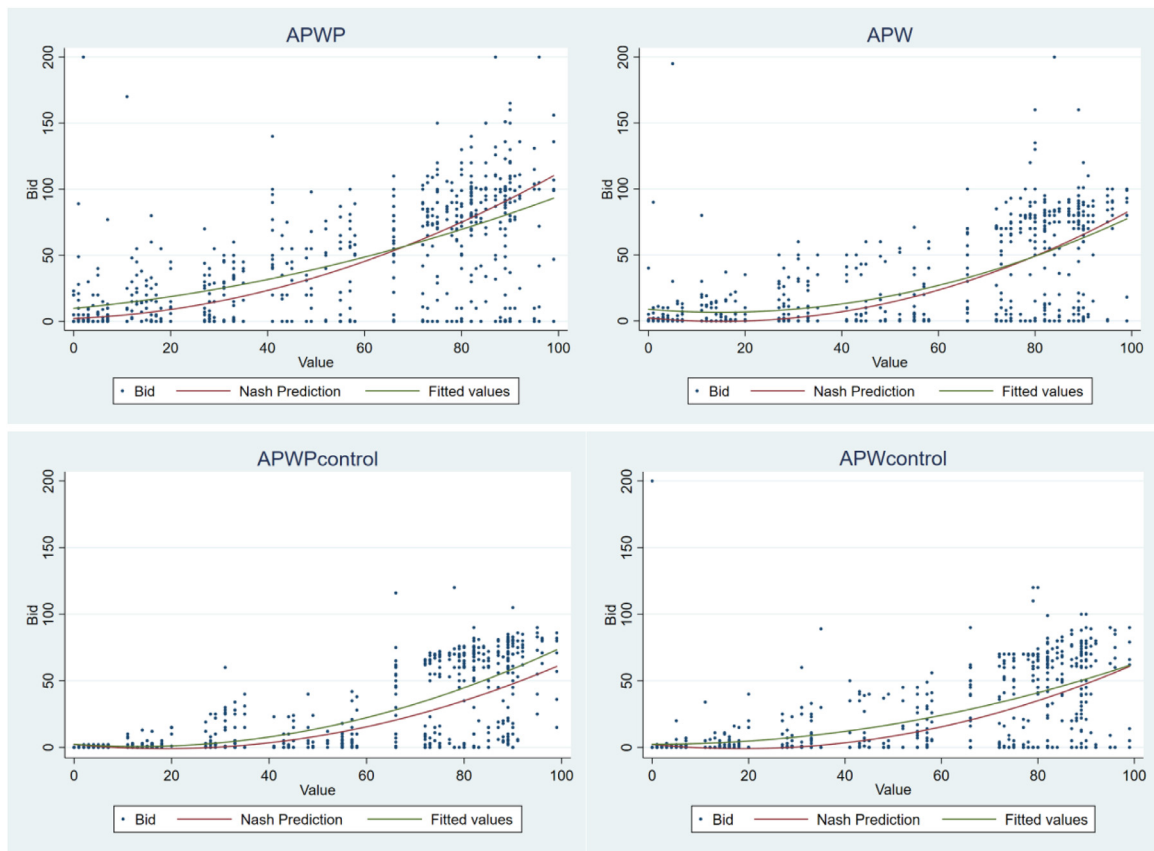


Fig. 5. Bids submitted for the AP auction.

is particularly the case for SPWP in the case of low payments by the winner. As a result, revenue in SPWP is not greater than in FPWP or SPW, in contrast to Hypotheses 2 and 4.

Finally, we look at bidding behaviour in the main AP treatments. Fig. 5 displays estimated third-order polynomial bidding functions.¹⁷ In all AP treatments, bidders tend to bid close to the theoretical predictions on average. The estimated parameters of the third-order polynomial bidding functions do not differ significantly from the theoretical predictions for APWP and APW. At the same time, bidding behaviour is very noisy witnessing the poor goodness of fit of the estimated third-order polynomial bidding curves. In particular, many bidders submit either a zero bid or a high bid as the scatter plot in Fig. 6 indicates. This is consistent with previous experiments on the AP auction without signalling (see e.g., [Noussair and Silver \(2006\)](#), [Schram and Onderstal \(2009\)](#), and [Müller and Schotter \(2010\)](#)).

Result 9: *On average, bidders in APWP and APW tend to bid close to the equilibrium predictions. However, bidding behaviour is very noisy in both auctions.*

4.3. Outside observers' estimates and their effect on bids

In [Section 4.1](#), we observed that the availability of information about bidders' payments on top of the identity of the auction winner increases the auctioneer's revenue in the FP and AP auctions, but not in the SP auction. In general, signalling is driven by a dialectic between signals and how an outside observer interprets these signals, and acts upon them. In this subsection, we explore the extent to which the outside observer's behaviour drives the above bidding patterns. In particular, we conjecture two mechanisms through which the outside observer can affect bidding strategies: first, the difference in the outside observers' estimates for winners and losers may differ between treatments, and this may influence bidding behaviour. Second, the accuracy of the outside observer's estimates may have an effect on the bids. We will explore the latter in the next subsection.

[Table 6](#) and [Fig. 6](#) contrast the value estimates of the outside observers and the actual values, focusing on the differences between winners and losers for the main treatments. When outside observers are only informed about the identity of the winner, their guesses cannot depend on the bidders' payments. Therefore, by construction, estimates for winners and losers

¹⁷ Bidding curve estimates are in [Appendix B, Table B.3](#).

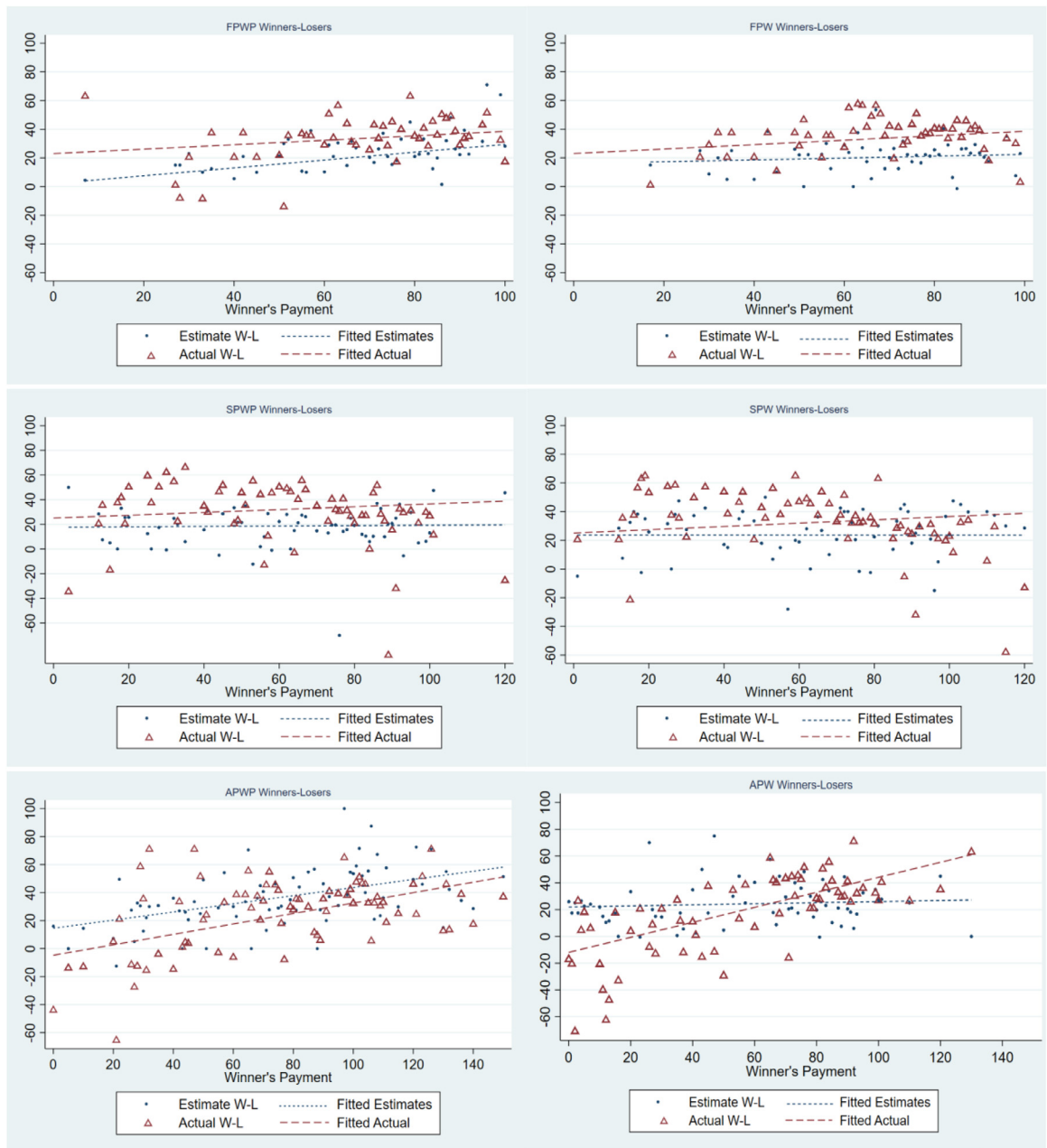


Fig. 6. Average outside observer's estimates, and average bidder's values, conditional on winner's payment in the main treatments.
 Notes: The dots plot the difference in the outside observers' value estimates between winning and losing bidders. The triangles refer to the actual differences in values between winning and losing bidders; the dashed lines represent the outcomes of linear regressions of the difference in the outsider observers' value estimates and the actual value differences on the winner's payment.

do not depend on the winner's payment in FPW and SPW, and on the bidders' payments in the APW. In FP and SP auctions where only the winner is revealed, outside observers underestimate the difference between winners' and losers' values on average. As a consequence, the additional benefit of winning the auction is smaller than in the theoretical prediction. On average, the estimated difference between the value of the winner and the value of the losers is 20.63 [22.83] for FPW [SPW], while the actual difference is 37.7 [34.57]. The bidders' best response is to inflate their bids relative to the control treatments by half that difference, i.e., by 10.32 [11.42] points in FPW [SPW]. According to the data, bidders inflate their bids with respect to the controls by 3.66 [9.20] points on average in FPW [SPW]. So, overbidding is lower than expected, but qualitatively in line with the theoretical predictions. In contrast to what happens in FPW and SPW, the difference between the value of the winners and the value of the losers is slightly overestimated in the APW auction. In particular, the estimated

Table 6
Regression of difference in outside observers' estimates between winner and losers on treatment dummies.

Dependant variable	Regressor	
	W-L estimate (1)	W-L estimate-actual (2)
FPWP	-15.411*** (1.237)	-23.434*** (2.404)
FPW	-17.989*** (1.105)	-30.113*** (2.101)
SPWP	-20.115*** (2.194)	-27.020*** (3.566)
SPW	-15.799*** (0.980)	-24.787*** (3.781)
APWP	-	-
APW	-14.433*** (1.503)	-10.136** (4.083)
Constant	38.628*** (0.926)	13.049*** (2.239)
Observations	1260	1260
Adjusted R squared	0.217	0.206

Notes: Clustered standard errors in parentheses. APWP is the reference treatment in (1) and (2). FPWP, FPW, SPWP, SPW, and APW are dummy variables which are equal to 1 if and only if the observation involves treatments FPWP, FPW, SPWP, SPW, APWP and APW respectively. *W-L Estimate* is the difference in estimates between winner and losers of a certain outside observer in a certain round. *W-L Estimate-Actual* is the difference in estimates between winner and losers of a certain outside observer in a certain round compared to the actual value difference.

**p* < 0.1.
** *p* < 0.05.
*** *p* < 0.01.

difference between the value of the winner and the value of the losers is 24.23, compared to the actual value difference that is 21.27. The bidders' best response would be to inflate their bids by 12.12 but they only do it by 5.7.

In FPWP, SPWP, and APWP, outside observers can adjust their estimates for winners and losers depending on the information received regarding the bidders' payments (the highest bid in FPWP, the second highest bid in SPWP, and all bids in APWP). Estimates for the values of both the winners and the losers increase with the winners' payment in FPWP, SPWP (*p* = 0.01) and the bidders' payments in APWP (*p* = 0.01). Again, the outside observers generally underestimate the difference between winners' and losers' values in the FP and SP auctions. On average, the difference between the estimated value of the winner and the value of the loser is 23.22 [18.45] for FPWP [SPWP], while the actual difference is 33.61 [32.57]. Bidders inflate their bids with respect to the controls by 8.78 [0.69] points on average in FPWP [SPWP]. On the other hand, the difference between the value of the winner and the values of the losers is clearly overestimated in APWP. In particular, the estimated difference between the winners' and losers' values is 38.59, which is higher than the actual value difference of 25.48. The bidders inflate their bids on average by 21.34, which is close to best response behaviour. In conclusion, the difference in the outside observer's estimates between winners' and losers' values is the highest in the APWP auction (*p* < 0.01 for all comparisons), which may partly explain why this mechanism yields the highest average revenue amongst all mechanisms.

Result 10: *The difference between the outside observers' value estimates for winners and those for losers are higher in APWP than in the other main treatments. Moreover, these differences are generally underestimated in the FP and SP auctions, and they are overestimated in the AP auction.*

4.4. Efficiency

In this subsection, we analyse whether the superior performance of APWP in terms of revenue may be compromised by lower efficiency. For a given group and auction type, the efficiency in period *t* comprises the sum of three terms:

$$Efficiency_t = ValueWinner_t + EarningsOO_t + \frac{1}{2} \sum_{i=1}^3 Estimate_{it}$$

where *ValueWinner_t* is the value of the winner of the auction at period *t*, *EarningsOO_t* are the earnings of the outside observer at period *t*, and *Estimate_{it}* is the outside observer's estimate of bidder *i* at period *t*. *ValueWinner_t* measures the auction's allocative efficiency. The second term expresses the payoffs of the outside observer, which is a measure of the accuracy of the outside observer's estimation. The last term represents the sum of the payoffs obtained by the three bidders through the estimates from the outside observer. As payments from buyers to the seller are welfare-neutral transactions,

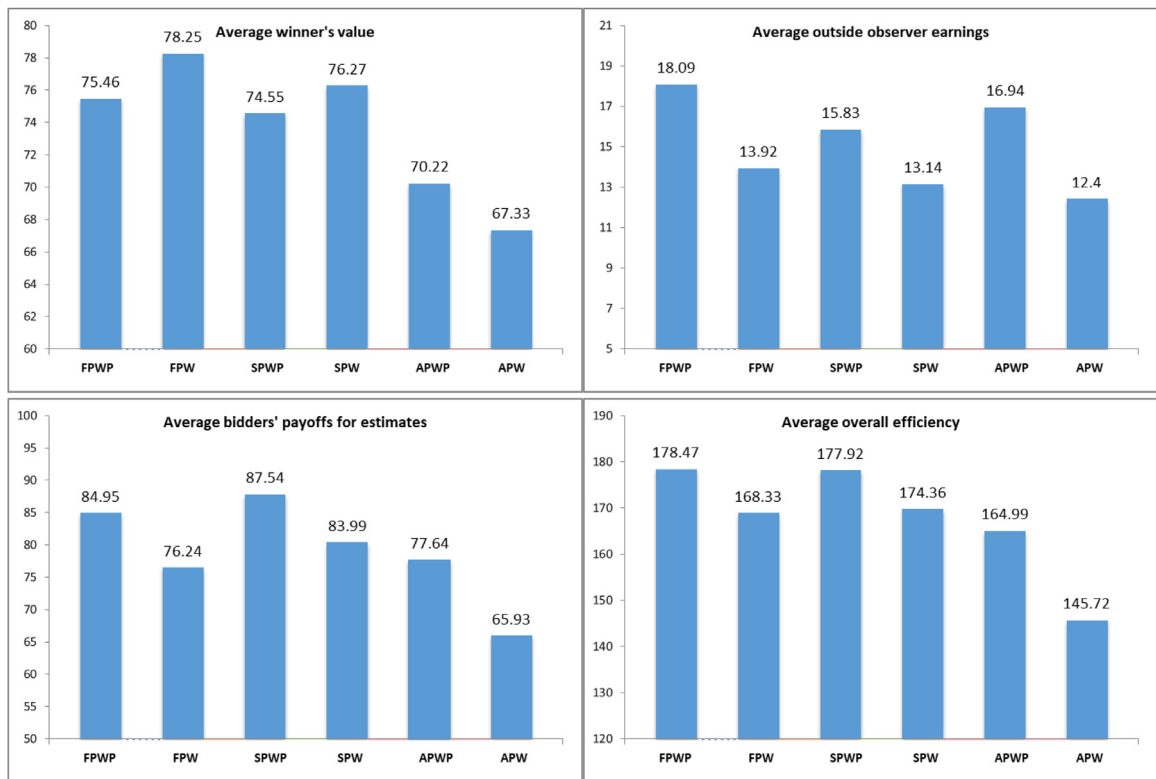


Fig. 7. Efficiency components across treatments.

Table 7
Regressions of the efficiency components on treatment dummies.

Dependant variable	Regressor			
	Overall efficiency (1)	Winner's value (2)	Profit outside observer (3)	Bidders' payoffs from estimates (4)
FPWP	13.476** (4.384)	5.232** (1.544)	1.166 (1.458)	7.379* (3.641)
FPW	3.336 (4.814)	7.966*** (2.077)	-3.052* (1.676)	-1.299 (3.000)
SPWP	12.926* (6.099)	4.323* (2.107)	-1.061 (1.376)	10.130* (4.540)
SPW	9.368 (5.510)	5.875* (2.550)	-2.819* (1.480)	6.346 (4.458)
APW	-19.275* (10.080)	-2.896 (4.220)	-4.544* (2.151)	-11.704** (3.367)
Constant	164.993*** (3.857)	70.225*** (1.900)	16.943*** (1.087)	77.547*** (3.113)
Observations	1260	1260	1260	3780

Notes: Clustered standard errors in parentheses. APWP is the reference treatment in (1)–(4). FPWP, FPW, SPWP, SPW, and APW are dummy variables which are equal to 1 if and only if the observation involves treatments FPW, SPWP, SPW, APWP, and APW respectively.

* $p < 0.1$.
 ** $p < 0.05$.
 *** $p < 0.01$.

efficiency does not depend on the auction's revenue. Fig. 7 compares the average value of each term and the overall average efficiency between treatments. Table 7 contains regressions of the efficiency components on treatment dummies where APWP is taken as the reference treatment.

The regression results in Table 7 show that FPWP and SPWP perform significantly better in terms of overall efficiency than APWP. As APWP dominates the other two mechanisms in terms of revenue, this finding points to a trade-off between revenue and efficiency. In addition, total average efficiency is higher in FPWP, SPWP and APWP than in FPW, SPW and APW

Table 8
Allocative efficiency.

Treatment	% highest value wins	Difference with APWP	Value winner/ highest value	Difference with APWP	R ² bidding curve
FPWP	71.9%	+12.57%**	93.9%	+7.55%***	0.633
FPW	83.3%	+24.00%***	97.5%	+11.23%***	0.800
SPWP	76.2%	+16.86%**	92.7%	+6.39%*	0.490
SPW	75.2%	+15.90%*	95.0%	+8.64%**	0.590
APWP	59.3%		86.3%		0.367
APW	60.0%	+0.67%	82.8%	−3.56%	0.377

Notes: R² is the goodness-of-fit of OLS regressions of third-order polynomial bidding functions.

* $p < 0.1$.

** $p < 0.05$.

*** $p < 0.01$.

($p = 0.03$, $p = 0.09$, and $p = 0.04$) respectively. Therefore, more information increases overall average efficiency in all three auction formats.

We now zoom in into the various efficiency components. According to Table 7, allocative efficiency, measured by the average value of the auction winner, is significantly lower in APWP than in all FP and SP treatments as Table 7 shows. Table 8 presents two other measures of allocative efficiency: the percentage of auctions in which the bidder with the highest value wins and the winner's value as a fraction of the highest value. Also according to these measures, the AP auction performs significantly worse than the FP and SP auctions in terms of allocative efficiency.

APWP's ranking of allocative efficiency is rooted in the noisiness of bidding behaviour measured by the goodness of fit of third-order polynomial bidding curves (see Table 8). In Appendix C, we present scatterplots of individual bidding strategies in APWP. We observe subjects deviating from the symmetric equilibrium in two important ways. First of all, instead of bidding according to strictly increasing bidding curves, some subjects tend to bid zero or high bids, potentially resulting in inefficient allocations. Second, there is a lot of heterogeneity in terms of individual bidding strategies, which can also result in inefficient allocations. Both patterns are consistent with the findings of Noussair and Silver (2006) and Müller and Schotter (2010), who ran experiments on the all-pay auction in settings without signalling opportunities. Noussair and Silver (2006) attribute the pattern of bidding zero or high bids to risk aversion, while Müller and Schotter (2010) attribute it to loss aversion. Heterogeneity in terms of risk aversion or loss aversion is consistent with subjects' using different individual bidding strategies. Of course, behaviour being qualitatively consistent with risk aversion and loss aversion does not prove that either is the main cause.

Bidders' payoffs from estimates follow a similar pattern as overall efficiency. In particular, APWP does significantly worse in this dimension than FPWP and SPWP. We also find that in FPWP, SPWP, and APWP, bidders obtain significantly higher payoffs from the outside observer's estimates than in FPW, SPW and APW, respectively ($p = 0.03$, $p = 0.09$, and $p = 0.01$, respectively). In other words, revealing more information induces outside observers to increase their value estimates so that, in turn, bidders benefit more from signalling. In contrast to the other efficiency components, APWP performs relatively well in terms of the outside observer's average earnings: None of the other mechanisms performs significantly better in this dimension than APWP. This is unsurprising, since all payments and thereby the bids of each bidder are revealed to the outside observer in APWP, whereas the latter only observes one out of three bids in the FPWP and SPWP.

All in all, we observe a trade-off between revenue and efficiency. While the APWP outperforms the other mechanisms in terms of revenue, it performs relatively poorly in terms of efficiency, in particular allocative efficiency and bidders' payoffs from estimates. Comparing WP treatments to W treatments, we find less of a trade-off between revenue and efficiency as FPWP and APWP outperform FPW and APW respectively on both dimensions.

Result 11: Overall efficiency is lower in APWP than in FPWP and SPWP.

Result 12: Overall efficiency is higher in FPWP, SPWP and APWP than in FPW, SPW and APW respectively.

5. Conclusion

In many auction settings, bidders have the opportunity to signal their generosity, wealth, or productivity to outside observers. Signalling in auctions has received ample attention in recent literature. Still, our paper is the first experimental study that examines the relative performance of various auction formats in a setting where bidders have the opportunity to signal their value to an outside observer. This may be a good model of an auction where outside observers interpret a firm's bidding behaviour as a signal of the firm's management quality, financial position, or confidence in its technological edge on the competition. Our study is a first step to learn about the effect of the information the auctioneer reveals about the auction on bidding behaviour. In the experiment, we compared the first-price, second-price, and all-pay sealed-bid auctions under two information regimes: in one, the auctioneer only reveals the identity of the winner, and in the other, she also publishes the bidders' payments.

Our key finding is that the all-pay sealed-bid auction in which the bidders' payments are revealed performs the best amongst the mechanisms studied in terms of revenue. Moreover, revealing the bidders' payments inflates the bids in the first-price and the all-pay sealed-bid auctions, but it does not do so in the second-price sealed-bid auction. These findings

are robust in that we obtain qualitatively the same results in a difference-in-difference analysis where we compare the revenues in the main treatments correcting for the revenues obtained in control treatments where bidders do not have signalling incentives. The superior performance of the all-pay sealed-bid auction relative to the winner-pay auctions when the bidders' payments are revealed is partly explained by the outside observer's tendency to overestimate the winners' values relative to the losers' in the former auction. Our efficiency analysis reveals that the superior performance of the all-pay sealed-bid auction in terms of revenue is compromised by a loss in efficiency relative to the winner-pay auctions.

Overall, our experimental results suggest that in a context where bidders care about how their behaviour in the auction is interpreted by others, both the auction type and the amount of information revealed can have a significant impact on the auction performance. A natural follow-up question concerns the extent to which our results can be extrapolated to different parameterizations than the one used in our experiment, for example, to settings where the bidders desire to signal generosity (e.g., in charity auctions) or wealth (e.g., in art auctions), or to settings where bidders' values are less well defined than in the private-values paradigm induced in our laboratory experiment. Future research may also reveal psychological mechanisms underlying bidder behaviour.

We think our theoretical and experimental results may inspire new research, in particular to test the performance of the APA in relevant contexts in the field. This is, for example, what happened recently in the context of charity auctions. Theoretical analysis by Goeree et al. (2005) reveals that the APA outperforms the FPA and the SPA, which was confirmed in the lab (Schram and Onderstal, 2009). However, this mechanism fails in the field (Carpenter et al., 2008; Onderstal et al., 2013) and is still rarely used in practice as far as we know. Endogenous participation, crowding out of intrinsic pro-social motivations, and asymmetries have been proposed as potential driving forces (Carpenter et al., 2010; Bos, 2011; Onderstal et al., 2013). This led to the elaboration of a new all-pay design based on behavioural perspectives, the *bucket* auction, which is optimal theoretically, in the lab, and in the field (Carpenter et al., 2014, 2018). We have good hopes that our experimental results give rise to an equally rich research agenda.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A: Derivation of equilibrium bidding curves

In this appendix, we derive the equilibrium bidding curves. Consider a setting with $n \geq 2$ bidders, indexed $i = 1, \dots, n$, bidding for a single, indivisible object. Bidders' values for the object are i.i.d. according to a smooth distribution function F on $[0, \bar{v}]$, $\bar{v} > 0$. The auction outcome is partly revealed to an outside observer. We assume that a bidder's payoffs are increased by $\gamma \tilde{v}$ ($\gamma > 0$), if the outside observer's estimate of the bidder's value equals \tilde{v} . For the analysis, we presume that bidders bid according to the same, strictly increasing, bidding curves. In equilibrium, the outside observer updates her beliefs about the bidders' values accordingly.

The structure of this appendix is as follows: in Sections A.1, A.2, and A.3, we derive equilibrium bidding curves for settings in which the outside observer is informed about who wins the auctions and how much the bidders pay in a first-price sealed-bid auction, second-price sealed-bid auction and all-pay sealed-bid auction, respectively. In section A.4, we consider the case where the outside observer is only informed about the winner of the auction.

A.1 First-price sealed-bid auction winner payment

Assume that bidders bid according to a strictly increasing bidding curve $B(v)$. Now, consider a bidder with a value v bidding as if her value were $w \in [0, \bar{v}]$. If the other bidders stick to the equilibrium bidding curve, this bidder's expected payoffs equal

$$U(v, w) = F^{(1)}(w)(v - B(w) + \gamma w) + \gamma \int_w^{\bar{v}} \tilde{V}(x) dF^{(1)}(x),$$

where $F^{(1)}$ denotes the distribution of the highest-order statistic of $n - 1$ i.i.d. draws from F . The first term on the RHS refers to the case in which the bidder wins and then the outside observer induces that the bidder's value equals w . The second term is the bidder's payoff when losing the auction, where $\tilde{V}(x)$ denotes the outside observer's optimal value estimate for losing bidders. The equilibrium FOC is given by

$$\frac{\partial U(v, w)}{\partial w} \Big|_{w=v} = f^{(1)}(v)(v - B(v) + \gamma v) - F^{(1)}(v)(B'(v) - \gamma) - \gamma \tilde{V}(v)f^{(1)}(v) = 0$$

$$\Leftrightarrow f^{(1)}(v)(B(v) - \gamma v) + F^{(1)}(v)(B'(v) - \gamma) = (v - \gamma \tilde{V}(v))f^{(1)}(v),$$

where $f^{(1)}$ is the density function corresponding to $F^{(1)}$. Taking into account the boundary condition $B(v) = 0$, we find the following solution for the resulting differential equation:

$$B(v) = \frac{\int_0^v (x - \gamma \tilde{V}(x))dF^{(1)}(x)}{F^{(1)}(v)} + \gamma v.$$

For the parameters used in the experiment ($\gamma = 1/2, n = 3, F = U[0, 1]$), we have $\tilde{V}(x) = x/2$ and $F^{(1)}(v) = v^2$ from which it follows that $B(v) = v$.

A.2 Second-price sealed-bid auction winner payment

The analysis for the second-price sealed-bid auction is analogous to the first. Let $V(x)$ and $L(x)$ denote the outside observer's estimate of the winner's value and the loser's value respectively, conditional on the second-highest value being x . Recall that the identity of the second highest bidder is unknown to the outside observer. A type v loser is the second highest bidder with probability $H(v) = (n - 1)F^{n-2}(v)(1 - F(v))$ and another bidder with probability $K(v) = (n - 1)F^{n-2}(v) - (n - 2)F^{n-1}(v)$. We denote h and k the density functions associated with H and K respectively. Therefore the bidder's expected payoffs equal

$$U(v, w) = \int_0^w v - B(x) + \gamma V(x)dF^{(1)}(x) + H(w)\gamma L(w) + \gamma \int_w^{\tilde{v}} L(x)dK(x),$$

with $V(x) = \frac{\int_x^{\tilde{v}} ydF(y)}{1 - F(x)}$ and $L(w) = \frac{w}{n-1} + \frac{n-2}{n-1} \frac{\int_0^w x dF(x)}{F(w)}$.

The FOC is given by

$$\frac{\partial U(v, w)}{\partial w} \Big|_{w=v} = f^{(1)}(v)(v - B(v) + \gamma V(v)) + h(v)\gamma L(v) + H(v)\gamma L'(v) - \gamma L(v)k(v) = 0$$

$$\Leftrightarrow B(v) = v + \gamma V(v) + \frac{h(v)}{f^{(1)}(v)}\gamma L(v) + \frac{H(v)}{f^{(1)}(v)}\gamma L'(v) - \gamma L(v)\frac{k(v)}{f^{(1)}(v)}.$$

For the parameters used in the experiment ($\gamma = 1/2, n = 3, F = U[0, 1]$), we have $V(v) = \frac{1+v}{2}, L(v) = \frac{3}{4}v, F^{(1)}(v) = v^2, H(v) = 2v(1 - v), K(v) = v(2 - v)$ and $F^{(1)}(v) = v^2$ from which it follows that $B(v) = v/2 + 5/8$.

A.3 All-pay sealed-bid auction all-bidders payments

The analysis of the all-pay sealed-bid auction when all bids are revealed to the outside observer is close to the previous ones. The outside observer's estimate of a bidder's value is equal to her value, for both winner and losers. Therefore the bidder's expected payoffs equal

$$U(v, w) = F^{(1)}(w)v - B(w) + \gamma w,$$

The equilibrium FOC is given by

$$\frac{\partial U(v, w)}{\partial w} \Big|_{w=v} = f^{(1)}(v)v - B'(v) + \gamma = 0$$

Hence, taking into account the boundary condition $B(v) = 0$:

$$B(v) = \int_0^v x dF^{(1)}(x) + \gamma v.$$

For the parameters used in the experiment ($\gamma = 1/2, n = 3, F = U[0, 1]$), it follows that $B(v) = v/2 + 2v^3/3$.

A.4 Winner-only, all three auction types

The predictions for the winner-only treatments are straightforward: For the winner-pay auctions, bidders' equilibrium bids are the standard equilibrium bids in a setting without outside observer inflated by γ times the difference between the outside observer's value estimates for the winner and the losing bidders. For the all-pay sealed-bid auction, bidders' equilibrium bids are the standard equilibrium bids in a setting without outside observer inflated by γ times the same difference and also by the probability of winning. When estimating a bidder's value, the outside observer minimizes w.r.t. w :

$$\int_0^{\bar{v}} |w - v| dG(v) = \int_0^w (w - v) dG(v) + \int_w^{\bar{v}} (v - w) dG(v),$$

where G is the outside observer's belief, that is, the distribution function of the bidder's value. The FOC:

$$\int_0^w dG(v) - \int_w^{\bar{v}} dG(v) = 0 \Leftrightarrow 2G(w) - 1 = 0.$$

For the three-bidder case, with values uniformly distributed on $[0, 100]$, $G(v) = v^3/10^6$ for the winning bidder, under the assumption that bidders submit bids according to the same strictly increasing bidding curve. This implies that the outside observer's best guess equals $w = 100/\sqrt[3]{2} \approx 79$. W.r.t. the guesses for the losing bidders, $G(v) = \frac{3v}{200} - (v^3/2)/10^6$. The outside observer's optimal guess is approximately equal to 35. The difference between the estimates equals about 44, which translates to the inflation of bids by 22.

Appendix B: Estimated bidding functions for FP, SP and AP auctions

Table B.1
Estimated bidding functions for the FP auction.

	Bid	Theoretical prediction
Intercept	6.2476* (2.8823)	22
Value	0.8048*** (0.0454)	2/3
FPWP	2.1628* (1.0733)	-22
FPWPcontrol	-6.0022** (2.7355)	-22
FPWcontrol	-5.9411* (2.6659)	-22
Value*FPWP	0.0224 (0.0444)	1/3
Value*FPWPcontrol	0.0118 (0.0687)	0
Value*FPWcontrol	0.0441 (0.0485)	0
N	2518	

Notes: Clustered standard errors in parentheses. FPWP, FPWPcontrol, and FPWcontrol are dummy variables which are equal to 1 if and only if the observation involves treatments FPWP, FPWPcontrol, and FPWcontrol, respectively. FPW is the reference treatment.

* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

Table B.2
Estimated bidding functions for the SP auction.

	Bid	Theoretical prediction
Intercept	11.4418*** (2.6629)	22
Value	1.0526*** (0.06521)	1
SPWP	8.0788** (3.1726)	40.5
SPWPcontrol	-3.3336 (4.8040)	-22
SPWcontrol	-9.2593** (2.8356)	-22
Value*SPWP	-0.1781** (0.0664)	-1/2
Value*SPWPcontrol	0.0251 (0.0553)	0
Value*SPWcontrol	0.0122 (0.0966)	0
N	2509	

Notes: Clustered standard errors in parentheses. SPWP, SPWPcontrol, and SPWcontrol are dummy variables which are equal to 1 if and only if the observation involves treatments SPWP, SPWPcontrol, and SPWcontrol, respectively. SPW is the reference treatment.

* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

Table B.3
 Estimated bidding functions for the AP auction.

	Bid (APWP)	Theoretical prediction		Bid (APW)	Theoretical prediction
Intercept	8.159 (4.428)	0	Intercept	6.588** (2.192)	0
Value	0.560*** (0.132)	0.5	Value ²	0.002 (0.002)	0.0022
Value ³	0.0000317* (0.000)	0.000067	Value ³	0.000051 (0.000)	0.000067
N	2520		N	2520	
	Bid (APWP)	Theoretical prediction		Bid (APW)	Theoretical prediction
Intercept	2.462** (0.758)	0	Intercept	6.093** (1.697)	0
Value ³	0.0000795*** (0.000)	0.000067	Value ³	0.0000645*** (0.000)	0.000067
N	2520		N	2520	

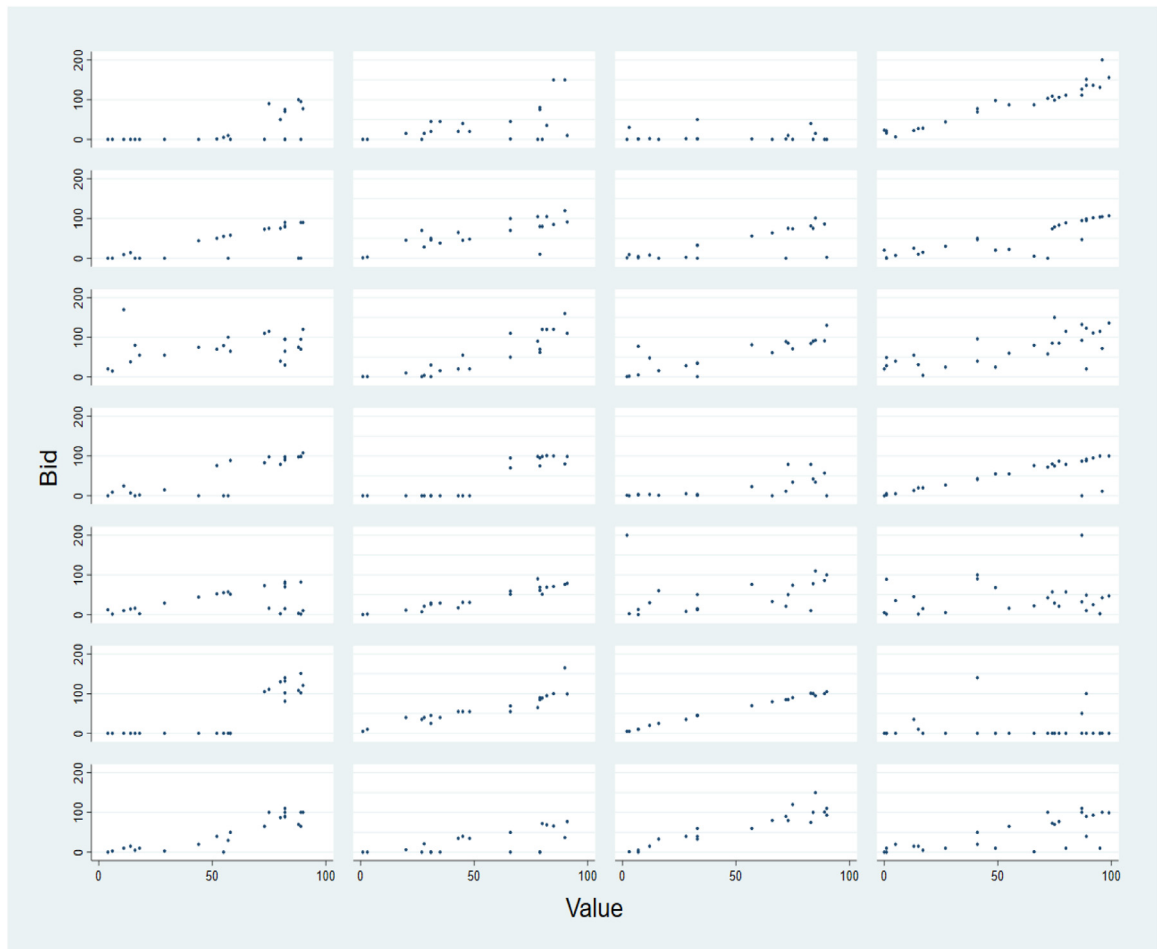
Notes: Clustered standard errors in parentheses.

* $p < 0.1$.

** $p < 0.05$.

*** $p < 0.01$.

Appendix C: Individual bidding behaviour in APWP



Appendix D: Instructions for treatment FPWP

WELCOME

You are about to participate in an economic experiment. The instructions are simple. If you follow them carefully, you may make a substantial amount of money. Your earnings will be paid to you in euros at the end of the experiment. This will be done confidentially, one participant at a time.

Earnings in the experiment will be denoted by 'francs'. At the end of the experiment, francs will be exchanged for euros. The exchange rate is 1 euro for every 70 francs. Your starting capital equals 490 francs (or 7 euros).

These instructions consist of seven pages like this. You may page back and forth by using your mouse to click on 'previous page' or 'next page' at the bottom of your screen. At the bottom of your screen, you will see the button 'ready'. You can click this when you have completely finished with all pages of the instructions.

AUCTION

In today's experiment, you will participate in auctions. In these auctions, three bidders bid to obtain a fictitious good. The bidders are observed by an outside observer. In the remainder of these instructions we will explain the way in which the auction is organized and the rules you must follow.

ROUNDS

Today's experiment consists of 30 rounds. In each round, a fictitious good is auctioned.

In the experiment, you will be member of a group. This group consists of you and three other participants. It is unknown to you and to the other participants who is in which group. The four group members remain in the same group throughout the experiment. Thus, you will meet the same three participants in each of the 30 rounds.

In every round, one group member is randomly chosen by the computer to play the role of outside observer. The remaining three group members are the bidders in the auction.

THE VALUE OF THE AUCTIONED GOOD

The value of the fictitious good will typically differ from one bidder to the next. To be more precise, in every round, the computer will draw a new value for every bidder. Values are drawn from the set $\{1,2,3,\dots,100\}$.

Note the following about the value for the objects:

1. The value for a bidder is determined independently of the values for the other two bidders;
2. Any value in the set $\{1,2,3,\dots,100\}$ is equally likely;
3. Each bidder only learns her own value, not the value of the other bidders;
4. The outside observer is not informed about the values of any of the three bidders.

THE AUCTION

In the auction, each of the three bidders independently submit a bid for the fictitious good. Bids must be chosen from the set $\{0,1,2,\dots,200\}$. The bidder with the highest bid gets the good and pays his bid. If two or three bidders submit the same (highest) bid, the computer will randomly determine which one obtains the good.

THE OUTSIDE OBSERVER

After the auction, the participant playing the role of outside observer is asked to guess the values of each of the three bidders. Before she does so, she obtains information about the outcome of the auction. In particular, she is informed about which bidder won the auction and how much the winner paid.

The payoffs of the outside observer depend on the precision of her estimates. Once she has entered value estimates for all bidders, the computer draws one of the three bidders at random. If the outside observer's estimate for this bidder is exactly correct, she obtains 40 points. The further her estimate is away from the actual value, the lower is her payoff. Specifically, if her estimate deviates x points for the actual value, her payoff is equal to $40 - x$. In words: the outside observer loses one point for every unit her estimate is further away from the actual value.

EARNINGS FOR THE BIDDERS

The payoffs for the bidders are dependent on both the outcome of the auction and the estimate of the outside observer. If a bidder does not win the object, his earnings in a round only depend on the value the outside observer estimated this bidder to have:

$$(\text{Earnings}) = (\text{The outside observer's value estimate})/2$$

So, a bidder earns half a franc for every franc in the outside observer's value estimate. A bidder's earnings do not depend on the outside observer's estimated values for the other two bidders.

If a bidder wins the object, his earnings in a round will depend on both his profits in the auction and the outside observer's value estimate:

$$(\text{Earnings}) = (\text{Value for the good}) - (\text{Winning bid}) + (\text{The outside observer's value estimate})/2$$

Note that a bidder gets the same payoffs from the outside observer's estimate, win or lose.

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