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An Externality-Robust Auction: Theory and Experimental Evidence

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Abstract

Behavioral robustness is essential in mechanism design. Existing papers focus on robustness as captured by dominant strategies. This paper studies the novel concept of externality-robustness, which addresses players' motives to affect other players' monetary payoffs. One example is externalities due to spite, which has been used to explain overbidding in second-price auctions. We show theoretically and experimentally that a trade-off exists between dominant-strategy implementation and externality-robust implementation. In particular, we derive the externality-robust counterpart of the second-price auction. Our experiments replicate the earlier finding of overbidding in the second-price auction, but we find that average bids equal value in the externality-robust auction. Our data also reveal that both auctions produce the same level of efficiency, suggesting that both dimensions of robustness are equally important. Our results are relevant for mechanism design in general, because the concept of externality-robustness is applicable to arbitrary mechanism design problems.

Keywords: robust mechanism design, spiteful preferences, experimental auctions

JEL Classification: C91, D03, D44, D82

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1 Introduction

The mechanism design literature has realized early on that its practical success will depend on the robustness of the mechanisms it engineers. Wilson (1987) was one of the first authors to criticize the assumption of common knowledge of many details of both the environment and the behavioral model. Mechanisms that are designed under such assumptions might be infeasible or produce unpredictable outcomes in real-world applications, where the mechanism designer or the agents typically lack substantial knowledge about the other parties involved. In the subsequent literature, robustness is often equated with more demanding equilibrium concepts such as dominant strategies.[1] However, robustness in this sense is only one dimension worth investigating. Recent work has made progress on robustness in the dimension of non-standard and possibly interdependent preferences.[2] In this paper, we study the trade-off between dominant-strategy implementation and externality-robust implementation in a simple auction environment.

The second-price sealed-bid auction (SPA) is the most prominent example of a dominant-strategy mechanism. As Vickrey (1961) has shown, in theory the SPA achieves Pareto-efficiency in private information environments without requiring strategic sophistication of the bidders. Experimental studies reveal, however, that the actual performance of the SPA can differ substantially from the theoretical prediction (e.g. Kagel, 1995): overbidding is regularly observed, such that Pareto-efficiency of the outcome is not guaranteed. Among the candidates that can explain overbidding, spiteful preferences have received much attention (e.g. Morgan et al., 2003; Brandt et al., 2007; Andreoni et al., 2007; Cooper and Fang, 2008; Nishimura et al., 2011; Kimbrough and Reiss, 2012). Spiteful bidders have an incentive to overbid in the SPA, because the own bid can affect the price that a winning opponent has to pay. In this sense, the SPA is not robust to the possibility that the bidders have interdependent preferences.

In the first part of the paper, we derive the externality-robust counterpart of the SPA, the externality-robust auction (ERA). The concept of externality-robustness works as follows. Suppose that the selfish Bayes-Nash equilibrium of a mechanism satisfies that unilateral deviations (e.g. to overbidding in an auction) leave the expected payoffs of all non-deviating agents unaf-

[1] More precisely, the prevalent robustness requirement of Bergemann and Morris (2005) is implied by implementation in ex-post equilibrium, which in turn is equivalent to implementation in dominant strategies with independent private values.

[2] The robustness concept applied in this paper is due to Bierbrauer and Netzer (2016). See Bierbrauer et al. (2015) for an extensive discussion of the different aspects of robustness that can be traced back to Wilson (1987).

fected. Then this equilibrium will continue to exist for very general preference interdependencies, because the bidders cannot manipulate each other's payoffs. In addition to spitefulness, the class of externalities for which robustness is implied also contains motives such as inequality aversion (Fehr and Schmidt, 1999; Bolton and Ockenfels, 2000), intention-based social preferences (Rabin, 1993; Dufwenberg and Kirchsteiger, 2004), altruism (Andreoni, 1989), or cross-shareholdings between firms (Ettinger, 2003; Dasgupta and Tsui, 2004; Chillemi, 2005). Given the degrees of freedom in designing ex-post transfers of Bayesian incentive-compatible mechanisms, it is possible to make any mechanism externality-robust without changing either its allocation rule or its expected revenue. The resulting ERA is a first-price auction augmented by bonus payments to elicit larger bids. Specifically, every bidder obtains a bonus that is increasing in the own bid but independent of the others' bids and the event of winning or losing the auction. The bonus schedule is designed so as to induce truthful bidding. Unilateral deviations from truthful bidding then have no effect on the other bidders' payoffs, because (*i*) their bonus payments are unaffected and (*ii*) winning the auction generates no additional rents that can be manipulated. Since the modification of transfers destroys the dominant-strategy property of the SPA, the ERA is no longer robust in this sense.

In the second part of the paper, we test the two auction formats SPA and ERA experimentally. Our goal is to evaluate the trade-off between the two different robustness concepts, i.e., the trade-off between robustness in the dimension of beliefs about other players' strategies and robustness in the dimension of payoff externalities. From the previous discussion we obtain several qualitative predictions about bidding behavior. First and foremost, we expect to find average overbidding in the SPA but not in the ERA, since spitefulness among experimental subjects can manifest itself in overbidding in the SPA but not in the ERA. Importantly, overbidding in the SPA can disrupt the efficiency of the auction outcome, as the auction winner will not necessarily be the one with the highest valuation. Second, since it is reasonable to assume that not all bidders have correct equilibrium beliefs, we expect to observe variance around the true value in bidding behavior in the ERA, which will also disrupt the efficiency of the auction outcome. Our experimental data reveal that both SPA and ERA achieve ex-post efficiency in about 90 percent of all cases. This suggests that the two notions of robustness are equally important from an efficiency perspective.

Our experimental data further show that bids are on average about 10 percent above values in the SPA. Average overbidding in the ERA, by contrast, is not different from zero. This suggests that spiteful preferences indeed affect bidding behavior in the SPA but not in the ERA. To further verify that the behavioral differences between SPA and ERA are in fact due to their different robustness properties, we conducted additional treatments where subjects interact with a computer instead of another subject. The important property of these control treatments is that interaction with a computer directly eliminates the possibility that a bidder can influence the payoff of another bidder.[3] If spitefulness is indeed the (only) reason for overbidding in the SPA, we should not observe overbidding in the SPA against the computer (SPA-C). For the ERA, in contrast, where no externalities exist by design, we should observe no change in bidding behavior when the human opponent is replaced by the computer (ERA-C). Our data show that average overbidding is significantly reduced (to about 4 percent) in the SPA-C. We also find that average overbidding remains indistinguishable from zero in the ERA-C. Even though some overbidding persists in SPA-C, these results provide clean evidence that a large part of the difference in average bidding behavior between the SPA and the ERA is driven by spitefulness and the property of externality-robustness of the ERA.

The SPA and the ERA also differ in their distributional implications. The seller benefits from overbidding at the expense of the buyers, which is reflected in average revenues that are about 12 percent larger in the SPA compared to the ERA. The fact that a mechanism may coincidentally generate high revenues for some behavioral trait to which it is not robust – such as the SPA for spiteful preferences – does only underline the importance of understanding robustness in mechanism design. For instance, seemingly desirable outcomes of a non-robust mechanism turn into undesirable outcomes when the behavioral traits happen to take other forms – such as pro-social preferences or cross-shareholdings.[4] More generally, if a mechanism designer can be sure ex-ante that a specific type of externality exists, then he will not want to rely on an externality-robust mechanism. Similarly, if he can be sure ex-ante how agents form their beliefs about the other agents' behavior, then he will not want to rely on a dominant-strategy mechanism. In either case, precise knowledge of the agents' motives can typically be exploited to improve

[3] Replacing human opponents by a computer is a standard experimental technique to eliminate social contexts, see e.g. Bohnet and Zeckhauser (2004) for a trust game and van den Bos et al. (2008) for a common value auction. Note that the SPA against the computer bidder is a variant of the Becker-DeGroot-Marschak mechanism (Becker et al., 1964), which is often used to elicit the willingness to pay of a single buyer.

[4] In several real-world auctions, bidders are firms who hold shares of their competitors (Ettinger, 2003; Dasgupta and Tsui, 2004; Chillemi, 2005; Ettinger, 2008). Such cross-shareholdings imply that firms take into account the effect of their behavior on other bidders' profits. Cross-shareholdings are predicted to lead to underbidding in the SPA, with reversed distributional consequences for sellers and buyers. An alternative approach for evaluating externality-robustness in the laboratory would be to induce such interdependencies. However, the reliance on naturally occurring externalities like spite allows us to directly compare our data to the existing experimental literature on second-price auctions.

outcomes. By contrast, robustness approaches are motivated by the idea that often we cannot be sure about the agents' deviations from a reference model.

The primary goal of our paper is to explore robustness in mechanism design, using the auction setting as a convenient testbed. However, an additional contribution of our paper is that it adds directly to a better understanding of bidding behavior in auctions in general. The discussion about the motives for overbidding in the SPA is still unsettled. In addition to spitefulness, for which our data provide evidence, alternative explanations that have been advanced include joy of winning (Cooper and Fang, 2008; Roider and Schmitz, 2012), joy of winning against human opponents (van den Bos et al., 2008), and bounded rationality (Kagel et al., 1987; Kagel and Levin, 1993; Cooper and Fang, 2008). We therefore collected a measure of the subjects' joy of winning, using a procedure due to Sheremeta (2010), where money can be invested to win a contest with no monetary prize. This measure turns out to be positively correlated with bidding in all four treatments, although significantly so only in two of the four treatments. The hypothesis of joy of winning against human opponents predicts lower bids against the computer opponent for both the SPA and the ERA, which we do not find, as explained above. Finally, we administered a Raven Advanced Progressive Matrices test (Raven et al., 2007), which measures cognitive skills. Cognitive skills have a significant impact on bidding only in the SPA, where better cognitive skills are associated with less overbidding. This is a surprising finding, because the SPA and the SPA against the computer are cognitively equally demanding. The distinguishing feature of the SPA from the other three treatments is, however, the existence of another bidder whose payoff can be manipulated. This observation lends support to the possibility that cognitive skills serve as a proxy measure for less spiteful preferences in our analysis, which is consistent with existing evidence that has documented a positive correlation between cognitive skills and pro-social behavior (e.g. Burks et al., 2009; Millet and Dewitte, 2007).

There are two recent papers that investigate questions related to ours. First, Fehr et al. (2015) study experimentally the performance of mechanisms for subgame-perfect implementation in environments with symmetric information. They show that these mechanisms are not robust to interdependent preferences between the agents, and consequently their performance in the laboratory falls considerably short of the theoretical prediction. They conclude that these results underscore the need for designing mechanisms which are robust with respect to interdependent preferences. Second, while we study the trade-off between the two described notions of robustness, Bierbrauer et al. (2015) combine both of them in a single mechanism (which comes at the cost that this reduces the set of implementable outcomes). They compare theoretically and experimentally optimal mechanisms that are ex-post implementable if there are no interdependent preferences, to mechanisms that are constrained optimal under the requirements of both ex-post implementability and externality-robustness.[5] In line with our findings, they report systematic deviations from predicted behavior in the former but not in the latter mechanisms.

2 Theoretical Analysis

2.1 Formal Framework

Framework and notation introduced below are a special case of the mechanism design approach in Bierbrauer and Netzer (2016).[6] The problem is to allocate one unit of an indivisible object among risk-neutral bidders with private information about their willingness to pay. The set of bidders is $I = \{1, \ldots, n\}$, $n \geq 2$. Bidder i's valuation of the object is denoted by $\theta_i \in \Theta_i$. Let $\theta = (\theta_1, \ldots, \theta_n) \in \Theta = \Theta_1 \times \ldots \times \Theta_n$ denote the profile of valuations of all bidders. The expression $\theta = (\theta_i, \theta_{-i})$ will be used when convenient. Bidder i's valuation is drawn randomly from the set $\Theta_i = \{\theta^1, \ldots, \theta^m\} \subset \mathbb{R}$, where $m \geq 2$ and $0 \leq \theta^1 < \theta^2 < \ldots < \theta^m$. Valuations are drawn independently and identically across bidders, according to strictly positive probabilities $p^1, p^2, \ldots, p^m$. Cumulated probabilities are denoted by $P^k = \sum_{j=1}^{k} p^j$, $k = 0, 1, \ldots, m$, so that $P^0 = 0$ and $P^m = 1$. Let $Q = \{(q_1, \ldots, q_n) \in [0, 1]^n | \sum_{i=1}^{n} q_i = 1\}$ be the set of possible outcome decisions, where $q = (q_1, \ldots, q_n) \in Q$ are the winning probabilities for each bidder. Let $T = \mathbb{R}^n$ be the set of all possible transfers, where $t = (t_1, \ldots, t_n) \in T$ prescribes the transfers paid to each bidder (negative transfers amount to payments made by the corresponding bidder). Altogether, $A = Q \times T$ is the set of possible allocations. Bidder i's material payoff from an allocation is given by $\pi_i(q_i, t_i, \theta_i) = q_i\theta_i + t_i$.

In this environment, a social choice function (SCF) is a mapping $f : \Theta \to A$ which assigns an allocation $f(\theta) \in A$ to every profile $\theta \in \Theta$. The notation $f = (q_1^f, \ldots, q_n^f, t_1^f, \ldots, t_n^f)$ will also be used, so that $q_i^f(\theta)$ is the winning probability and $t_i^f(\theta)$ is the transfer to bidder i under the SCF f, given valuations θ. The SCF f^{SPA} which is underlying the second-price sealed-bid

[5] Netzer and Volk (2014) study ex-post implementation for the model of intention-based social preferences.

[6] We follow the mechanism design approach to auctions, which explains some of our terminology. For instance, relying on the revelation principle, we will equate bidding spaces with type spaces, and we refer to the strategy of bidding the value as "telling the type truthfully." We do not need to make a distinction between types and bids in a truth-telling equilibrium.

auction is described as follows. For any given profile of valuations θ, let $W(\theta) \subseteq I$ be the set of bidders with maximal valuation in $\theta = (\theta_1, \ldots, \theta_n)$. Furthermore, let $s(\theta)$ be the second-largest valuation in θ. Whenever $|W(\theta)| = 1$, so that there is a single bidder with largest valuation, $s(\theta)$ is strictly smaller than this largest valuation. Whenever $|W(\theta)| > 1$, so several bidders have the same largest valuation, $s(\theta)$ is identical to this largest valuation. Now define

$$q_i^*(\theta) = \begin{cases} 1/|W(\theta)| & \text{if} \quad i \in W(\theta), \\ 0 & \text{if} \quad i \notin W(\theta), \end{cases} \tag{1}$$

which implies that the object is allocated with equal probabilities among all bidders with largest valuation. Transfers are defined by

$$t_i^{SPA}(\theta) = \begin{cases} -s(\theta)/|W(\theta)| & \text{if} \quad i \in W(\theta), \\ 0 & \text{if} \quad i \notin W(\theta), \end{cases} \tag{2}$$

which states that the winner has to pay the second-largest valuation (adjusted for randomly broken ties).[7] The direct mechanism for $f^{SPA} = (q_1^*, \ldots, q_n^*, t_1^{SPA}, \ldots, t_n^{SPA})$, where each bidder is asked for a bid from Θ_i and the outcome is determined by f^{SPA}, is called the second-price sealed-bid auction, or the Vickrey auction (Vickrey, 1961). It is a special case from the class of Vickrey-Clarke-Groves mechanisms (e.g. Mas-Colell et al., 1995, ch. 23), so that truthful bidding (making bids equal to the true value) is a weakly dominant strategy for every bidder.

2.2 Externality-Robustness

While the dominance of truthful bidding is an important advantage of the SPA, it has the disadvantage of being vulnerable to externalities. The price that the winner has to pay is the highest among the losing bids, which implies that each bidder's behavior can have a large impact on the other bidders' payoffs. This can be demonstrated in a simple example, which we will also use later on in Section 2.4 to illustrate the ERA. Assume $n = 2$ and $m = 2$. Let $\Theta_i = \{1, 2\}$ be the set of possible valuations, and write $p^1 = p$ and $p^2 = 1 - p$, where $0 < p < 1$. Assume also that bidder 2 in fact bids truthfully. It is an easy exercise to derive the ex-ante expected

[7]Expression (2) allows for two different interpretations. First, it could describe the rule that each bidder $i \in W(\theta)$ has to pay $s(\theta)/|W(\theta)|$ irrespective of which bidder in $W(\theta)$ eventually obtains the good. Second, it could describe the rule that only the winning bidder in $W(\theta)$ pays the price $s(\theta)$, in which case (2) is an ex-post expected payment. The two interpretations make no difference with risk-neutral bidders. We prefer the second interpretation, and this is also how we implemented the SPA in our experiment. The same arguments apply to the ERA below.

payoff pairs that bidder 1 can induce for herself and the opponent by varying her own strategy. Truthful bidding yields the maximal expected payoff $p(1-p)$ for bidder 1. Deviations to always bidding low (underbidding) or always bidding high (overbidding) reduce this expected payoff to $p(1-p)/2$. The effect on bidder 2 is as follows. Truthful bidding yields $p(1-p)$ also for bidder 2. If bidder 1 deviates to underbidding, however, the expected payoff of bidder 2 increases to $(1-p)$. Overbidding, on the other hand, reduces bidder 2's expected payoff to 0. Now suppose that bidder 1 is not selfish but maximizes a weighted sum of the own and the opponent's payoff, with weight α placed on the opponent. Then underbidding will be preferable to truthful bidding whenever $\alpha > [p/(1-p)]/2$. This could correspond to a case with a sufficiently large share α of holdings in the opponent firm (Ettinger, 2003; Dasgupta and Tsui, 2004; Chillemi, 2005). Overbidding, on the other hand, becomes more attractive than truth-telling whenever $\alpha < -1/2$, which could correspond to a case of sufficiently strong spitefulness (Morgan et al., 2003; Brandt et al., 2007).

The problem arises because bidder 1's strategy choice affects the payoff of bidder 2. Suppose that, in a different auction format, bidder 1 did not have the opportunity to manipulate the payoff of bidder 2 through a unilateral deviation from truthful bidding, and suppose further that truthful bidding was still a selfish best response for bidder 1. In such an auction, the incentive to bid truthfully would not be destroyed by pro- or anti-social concerns.[8] Hence we say that an SCF is externality-robust if it is (*i*) Bayesian incentive-compatible, i.e., truth-telling is a selfish Bayes-Nash equilibrium in the direct mechanism, and (*ii*) it satisfies that unilateral deviations from this equilibrium have no impact on the expected payoffs of all other agents.

Bierbrauer and Netzer (2016) show that externality-robustness is implied by an insurance property of the incentive-compatible social choice function to be implemented, i.e., the agents' payoffs have to be ex-ante insured against the randomness in the other agents' types. This property is similar to concepts of insurance in auctions with risk-averse bidders (e.g. Maskin and Riley, 1984) and with ambiguity-averse bidders (e.g. Bose et al., 2006), but it serves a different purpose here. Insurance is relevant with risk-averse bidders (albeit not generally optimal, see Matthews, 1983, and Maskin and Riley, 1984) for the conventional reasons, and it is relevant with ambiguity-averse bidders (and also optimal, see Bose et al., 2006) because providing insurance on the worst-case prior allows the seller to extract revenue from the bidders. In the present

[8]This argument applies to a large class of interdependent preference models, including essentially all the models commonly used in the literature. For a more detailed discussion see Bierbrauer and Netzer (2016) or Bierbrauer et al. (2015), and the related arguments in Segal and Sobel (2007) and Dufwenberg et al. (2011).

context, insurance is relevant because it protects an agent against other agents' attempts to manipulate her payoffs, and hence it protects the equilibrium against payoff externalities.[9]

Bierbrauer and Netzer (2016, Proposition 2) show in an abstract framework that it is possible to start from any Bayesian incentive-compatible SCF f and to construct an externality-robust SCF $\bar{f}$ that coincides with f in terms of the decision rule $(q_1^f, \ldots, q_n^f)$, the expected revenue, and the interim expected payoffs of all agents. In the next section, we apply this result to our auction setup, where the general construction of the new transfers $(t_1^{\bar{f}}, \ldots, t_n^{\bar{f}})$ reduces to

$$t_i^{\bar{f}}(\theta) = \mathbb{E}_{\theta_{-i}} \left[q_i^f(\theta_i, \theta_{-i})\, \theta_i + t_i^f(\theta_i, \theta_{-i}) \right] - q_i^f(\theta)\, \theta_i. \tag{3}$$

Bose et al. (2006) and Bodoh-Creed (2012) use an analogous construction in a model framework where bidders have ambiguous beliefs about the other bidders' values. The expectation in (3) is then taken with respect to bidder i's worst-case prior, which provides insurance to the bidder and at the same time increases revenues to the seller.

2.3 The Externality-Robust Auction

We now apply the construction described in the previous section to $f = f^{SPA}$ to derive its externality-robust counterpart $\bar{f} = f^{ERA}$. Since the efficient decision rule $(q_1^*, \ldots, q_n^*)$ is adopted without modification, the following proposition describes only the modified transfers. We will illustrate the result with a simple example in Section 2.4 below.

Proposition 1. *In the externality-robust auction f^{ERA}, transfers are given by*

$$t_i^{ERA}(\theta) = B(\theta_i) + \begin{cases} -\theta_i/|W(\theta)| & \text{if} \quad i \in W(\theta), \\ 0 & \text{if} \quad i \notin W(\theta), \end{cases} \tag{4}$$

where

$$B(\theta_i) = \sum_{j=1}^{k-1} \left(P^j\right)^{n-1} \left(\theta^{j+1} - \theta^j\right) \tag{5}$$

for k such that $\theta_i = \theta^k$.

Proof. See Appendix A.1. □

[9] See Bose et al. (2006, p. 424f) for a careful discussion of the different concepts of insurance in auctions. Bellemare and Sebald (2011) apply a related invariance property to experimentally infer about belief-dependent preferences. Esö and Futo (1999) have investigated the different problem of insuring the auctioneer against randomness in the revenue (see also Börgers and Norman, 2009).

Consider the simultaneous sealed-bid auction induced by the direct mechanism for f^{ERA}. Without the additional term $B(\theta_i)$ in the transfers (4), it would correspond to a first-price auction (FPA) where bidders are required to submit bids and the winner pays the own bid. In the simple FPA, bidders would shade their bids (report less than their true valuation) with the goal of earning rents in case of winning, but the bonus function $B(\theta_i)$ defined in (5) restores incentives to report the valuation truthfully. The bonus takes a value of zero for the smallest possible bid, it is strictly increasing, and it does not depend on the opponents' bids or the event of winning or losing the auction. Externality-robustness now holds because, first, the bonus $B(\theta_i)$ received by bidder i cannot be influenced by any opponent, and, second, there are no additional rents that can be manipulated by manipulating the identity of the winner, as the true valuation is paid by the winner in equilibrium.

Three qualifications are appropriate. First, a disadvantage of the ERA is that it no longer has dominant strategies, which implies that the bidders need to know the prior distribution of values and form beliefs about equilibrium behavior of the other bidders. The same knowledge is required for the auctioneer, because the optimal bonus schedule depends on the type distribution. The SPA requires no such knowledge. As we have discussed before, this reflects the fact that there is a trade-off between the different notions of robustness of a mechanism.[10] Second, while the truthful bidding equilibrium of the ERA is robust with respect to interdependent preferences, it is not necessarily the unique equilibrium. We can show in the example in the next section that additional equilibria may exist for some prior distributions of values. The SPA has multiple equilibria as well, if one considers equilibria in weakly dominated strategies (Blume and Heidhues, 2004). Third, the literature has investigated a large range of different externalities in auctions (Jehiel and Moldovanu, 2006). Not all of them are captured by the notion of externality-robustness considered here, which eliminates externalities between bidders based on overall payoffs.[11]

[10] Segal and Sobel (2007) propose a concept which speaks to both notions of robustness at once, by requiring the opponent in a two-player game to be indifferent between the conventionally defined dominated and dominating strategy, for all own strategies. For the purpose of mechanism design, this concept appears overly demanding. Bierbrauer et al. (2015) impose externality-robustness on top of ex-post implementability, which reduces the set of implementable social choice functions.

[11] Bidders still have the discretion to manipulate the identity of the winner, which can be relevant in other applications (Jehiel et al., 1996). The same holds for externalities arising from types to the losers of an auction (Jehiel and Moldovanu, 2000) and directly from prices (Engelbrecht-Wiggans, 1994; Maasland and Onderstal, 2007) as in knockout auctions (Graham and Marshall, 1987; McAfee and McMillan, 1992) or auctions that are used to finance public goods (Goeree et al., 2005; Engers and McManus, 2007). Externalities can also arise from toeholds in takeovers (Burkart, 1995; Singh, 1998; Bulow et al., 1999; Ettinger, 2008), where bidders compete for a target firm of which they own some shares already. This creates a claim in the auction revenue for the bidders, another externality not addressed by the ERA.

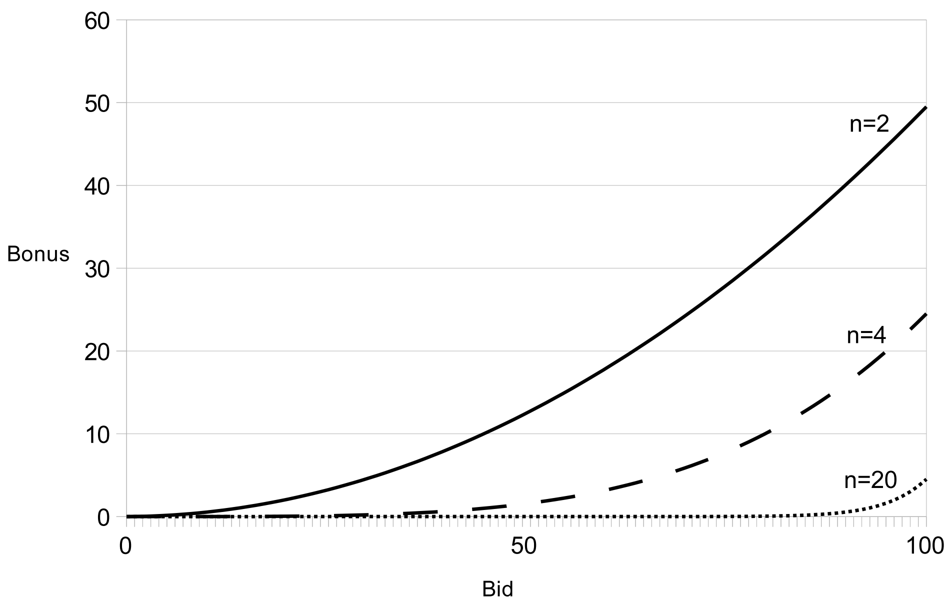
2.4 Example

To get a better understanding of the properties of $B(\theta_i)$, suppose that $\Theta_i = \{1, ..., m\}$ and that values are uniformly distributed. The bonus function can now be written as

$$B(k) = \sum_{j=1}^{k-1} \left(\frac{j}{m}\right)^{n-1},$$

which is a strictly convex function of the bid k. For $m = 100$, as in our following experiment, it is depicted in Figure 1 for the three cases of $n = 2$, $n = 4$ and $n = 20$. With two competing bidders, as in the experiment, a bid of 50, for instance, is rewarded by a bonus of 12.25, a bid of 80 is rewarded by a bonus of 31.6, and the maximal bid of 100 is rewarded by a bonus of 49.5.

Figure 1: Bonus Function



Returning to the example from Section 2.2 ($n = m = 2$, $p^1 = p$, $p^2 = 1 - p$), it follows that $B(1) = 0$ and $B(2) = p$. Table 1 compares the SPA to the ERA for this case. Each row in the table corresponds to one of the four possible profiles of values. The efficient decision rule is identical for both auctions. The table then contains the transfers of the SPA and the ERA, as well as their generated ex-post revenues. For the ERA, straightforward calculations show that, conditional on bidder 2 bidding truthfully, bidder 1 still achieves the maximal own expected payoff of $p(1-p)$ by also bidding truthfully, while both over- and underbidding reduce this payoff to $p(1-p)/2$. In contrast to the SPA, however, bidder 2 can always expect to obtain $p(1-p)$, irrespective of bidder 1's behavior.

Table 1: Comparison of SPA and ERA

θ_1	θ_2	q_1^*	q_2^*	t_1^{SPA}	t_2^{SPA}	Revenue	t_1^{ERA}	t_2^{ERA}	Revenue
1	1	1/2	1/2	$-1/2$	$-1/2$	1	$-1/2$	$-1/2$	1
1	2	0	1	0	-1	1	0	$p-2$	$2-p$
2	1	1	0	-1	0	1	$p-2$	0	$2-p$
2	2	1/2	1/2	-1	-1	2	$p-1$	$p-1$	$2(1-p)$

It can also be seen in this example that truthful bidding is no longer a dominant strategy in the ERA, and that multiple equilibria may exist: If bidder 2 always submits the bid 2, then, whenever $p \geq 1/2$, it becomes a best response of bidder 1 to always bid 2 as well.

2.5 Ex-Post Revenues

The ERA generates the same expected revenue as the SPA with selfish bidders, but their ex-post revenues differ. In particular, the ex-post revenue of the SPA is always non-negative. This is not necessarily the case for the ERA where the auctioneer makes payments to the bidders, so that ex-post deficits might become possible. It will be shown in the following that deficits remain impossible in the case with uniformly distributed values, but cannot be ruled out in some more general environments.

Recall that $B(\theta_i)$ is increasing in θ_i. To rule out deficits for all possible valuation profiles $\theta \in \Theta$, it therefore suffices to check the cases where all bidders have the same valuation: $\theta_i = \theta^k$ for some $k \in \{1, \dots, m\}$ and all $i \in I$. These are worst-case scenarios for the auctioneer, because overall bonus payments are maximal among all valuation profiles that yield a gross revenue of θ^k. Hence it suffices to check whether or not

$$n\, B(\theta^k) \leq \theta^k \tag{6}$$

holds for all $k \in \{1, \dots, m\}$, where the LHS captures the bonus sum and the RHS is gross revenue collected. As a next step, it can be shown that condition (6) is most stringent for the largest possible value θ^m, a consequence of convexity of the bonus function (see Appendix A.2). Thus, the ERA never runs a deficit if and only if

$$n\, B(\theta^m) \leq \theta^m. \tag{7}$$

For the framework introduced in Section 2.4, condition (7) can be verified (see again Appendix A.2), which shows that ex-post deficits are impossible with uniformly distributed (equidistant) values. Deficits become possible in more general frameworks, however. For instance, assume $n = 2$ and $m = 3$ within the previous framework, but deviate from the assumption of a uniform distribution. For concreteness, let $p^1 = 1 - \epsilon$, $p^2 = \epsilon/2$ and $p^3 = \epsilon/2$. It can be shown that (7) is violated whenever $\epsilon < 1/3$. If high valuations are unlikely, the bonus payments must be especially large for high bids, to ensure incentive-compatibility. Otherwise, high-value bidders would be tempted to underbid and still win with sufficiently large probability. In the (unlikely) event that several bidders simultaneously have such high valuations, this leads to a deficit.

2.6 Existing Auction Formats

To illustrate revenue equivalence beyond the usual class of auctions, Riley and Samuelson (1981) describe, among other examples, a "Santa Claus auction." It turns out that the ERA corresponds to this auction format. However, Riley and Samuelson do not examine the Santa Claus auction any further and, in particular, they do not describe its desirable properties in the presence of externalities, which is the focus in our paper.[12] Bose et al. (2006, p. 422) describe an analogous auction with a bonus schedule that depends on the degree of ambiguity, and which converges to the Santa Claus auction as ambiguity vanishes. Also related, Matthews (1983) describes an auction where a bonus is paid to high bidders, while low bidders have to make payments to the auctioneer.

The distinguishing feature of the ERA is that bonus payments are made to all bidders. In this regard it is also related to several real-world auction formats in which the transfers to non-winning bidders are different from zero.[13] First, this also holds in all-pay auctions (Goeree et al., 2005), albeit with opposite sign. There, non-winning bidders have to pay their bid, while they receive a payment related to their bid in the ERA. Second, in some auctions a share of the revenue is distributed back to the bidders (Graham and Marshall, 1987; McAfee and McMillan, 1992; Engelbrecht-Wiggans, 1994; Maasland and Onderstal, 2007). Engelbrecht-Wiggans (1994), for instance, describes how the heirs bid for an estate and divide the winner's payment among themselves. In such auctions, however, the transfer to an unsuccessful bidder depends on the

[12] Technical differences are the reserve price and the continuous valuations in their paper. The bonus function for $n = 2$ in Riley and Samuelson (1981, p. 387) is $\int_{v_*}^{b} F(v)dv$, where b is the bid, v_* is the reserve price, and F is the cdf of the valuations. Riley and Samuelson (1979) contains the generalization to $n \geq 2$ bidders.

[13] The literature has also investigated bonus auctions in which an individual-specific bonus is awarded only to the winner, in form of a discount on the price that has to be paid (Mares and Swinkels, 2011).

winning bid instead of the own bid, which reinforces the opportunity to affect each others' payoffs by over- or underbidding. Finally, the literature has investigated premium auctions such as the different versions of the Amsterdam auction (Goeree and Offerman, 2004; Hu et al., 2011). They are closely related to the ERA because they reward a premium to a non-winning bidder with the goal of raising equilibrium bids. In the first-price Amsterdam auction, for instance, the highest bidders wins and pays the own bid, while both winner and second-highest bidder receive a premium that is increasing in the second-highest bid.[14] There are two main differences to the ERA. First, not all bidders obtain the premium, and, second, the size of the premium does not depend on the own bid alone. Unilateral deviations from equilibrium behavior will therefore influence the payoffs of the other bidders in the Amsterdam auction.

2.7 Alternative Explanations of Overbidding

Before turning to our experiment, in this section we briefly discuss alternative explanations for overbidding in auctions that are not based on externalities like spite. This is important as each of these explanations might affect the SPA and the ERA in different ways, thus generating obfuscating effects in our empirical analysis.

The most common explanations for overbidding in the SPA have already been discussed before: joy of winning (Cooper and Fang, 2008; Roider and Schmitz, 2012), joy of winning against human opponents (van den Bos et al., 2008), and bounded rationality (Kagel et al., 1987; Kagel and Levin, 1993; Cooper and Fang, 2008). These explanations predict deviations from truthful bidding also in the ERA, so we take care to control for them in our experiment.

The literature has also proposed a range of explanations for overbidding in the first-price auction that do not predict overbidding in the second-price auction (because of its dominant-strategy property). First and foremost, this includes risk aversion (Cox et al., 1988) or loss aversion (Lange and Ratan, 2010).[15] An interesting consequence of the insurance property of the ERA is that, aside from addressing payoff externalities, it also neutralizes behavioral effects of risk- or loss-aversion. Put differently, truth-telling remains an equilibrium of the ERA even if bidders are averse to uncertainty. The reason is that – conditional on truth-telling of the

[14] More precisely, an elimination stage takes place first, where the price increases until only two bidders are left. An FPA is then conducted among these two bidders, where the premium depends linearly on the difference between the second-highest bid and the price at which the first stage concluded. There also exists a second-price version of the Amsterdam auction. See Goeree and Offerman (2004) for more details and a formal analysis.

[15] Lange and Ratan (2010) propose a model of loss aversion that can generate over- or underbidding in second-price auctions in the field (where commodities are sold) but predicts truthful bidding in the laboratory (where money is sold).

other bidders – the expected payoff of each type of each bidder is (*i*) maximized by truth-telling and (*ii*) becomes deterministic. Deviations from truth-telling can therefore only decrease the expected value of the payoff and increase its uncertainty. Hence the possibility that the subjects in our experiment are averse to risk or losses should not distort our comparison of the SPA and the ERA. Other explanations for overbidding in the FPA are regret (Filiz-Ozbay and Ozbay, 2007), level-k thinking (Crawford and Iriberri, 2007; Crawford et al., 2009), quantal response equilibrium (Goeree et al., 2002), impulse balance equilibrium (Ockenfels and Selten, 2005), or interim rationalizability (Battigalli and Siniscalchi, 2003). A complete analysis of equilibrium bidding in the ERA for each of these models is beyond the scope of this paper. However, to the extent that several of these explanations rely on cognitive limitations on the side of the bidders, they are addressed by our control for cognitive skills in the experiment. Furthermore, the comparison between our basic treatments and the treatments where subjects play against the computer will provide evidence for spite as the main driver of our findings.

3 Experimental Design

We conducted four different treatments, a second-price auction, an externality-robust auction, and two corresponding auction formats in which subjects interacted with a computer instead of interacting with another subject.

3.1 Second-Price Auction (SPA)

Treatment SPA is a standard second-price auction, repeated for 24 rounds. Subjects are anonymously and randomly rematched in two-person groups in each round.[16] Each bidder first observes her private value but not the value of the matched bidder. Values are drawn independently across bidders and rounds according to a uniform distribution from $\Theta_i = \{1, \ldots, 100\}$, which is common knowledge. Both bidders in a group then simultaneously submit their bids, which can be any value from Θ_i. The bidder who submits the higher bid wins the auction. She receives her private value and pays the bid of the losing bidder. The payoff of the losing bidder is zero. Ties are resolved randomly with equal probability. Feedback is given at the end of each round, where each bidder is reminded of her own valuation, the own bid, the bid of the competing bidder, and the resulting own payoff in the period. Then the next round begins.

[16]Since we had between 30 and 36 subjects per session, repeated game effects should be absent.

3.2 Second-Price Auction against the Computer (SPA-C)

Subjects in treatment SPA-C face a single-agent decision problem. In contrast to treatment SPA, bidders are not matched in two-person groups but interact with the computer that draws numbers from $\Theta_i = \{1, \ldots, 100\}$. Otherwise, the two treatments are identical. If the bid of a subject exceeds the drawn number, the subject wins the auction. She receives her private value and pays a price that equals the drawn number. The subject's payoff is zero if her bid falls short of the drawn number. Ties are resolved randomly with equal probability. Bidders are informed in the beginning that the numbers drawn by the computer correspond to the bids of subjects in a past auction that was identical except for the fact that two bidders competed for winning. Indeed, we conducted one session of SPA-C for each session of SPA with the exact same realization of own values and others' bids. That is, for each subject in SPA-C there is a subject in SPA who had the same sequence of values in the 24 rounds. Moreover, the subject in SPA-C receives a sequence of numbers from the computer that equals the sequence of bids that the corresponding subject in SPA received from the respective other bidders.

3.3 Externality-Robust Auction (ERA)

Treatment ERA is an implementation of the externality-robust auction that we derived in Section 2.3. As in SPA, the auction is repeated with random rematching for 24 rounds, and values are drawn independently and uniformly from $\Theta_i = \{1, \ldots, 100\}$. The only difference between SPA and ERA are the auction rules that determine the payoffs. In ERA, the bidder with the highest bid wins and receives her private value as in SPA, but now she pays her own bid and receives the bonus that corresponds to her own bid as given in (5). The bidder with the lower bid also receives the bonus that corresponds to her own bid.

3.4 Externality-Robust Auction against the Computer (ERA-C)

Subjects in treatment ERA-C again face a single-agent decision problem because they interact with the computer. The treatments ERA and ERA-C are identical otherwise, so that the relation between ERA and ERA-C is the same as the relation between SPA and SPA-C.

3.5 Additional Measurements

In each session we elicited two additional individual characteristics after the 24 rounds of the respective auction format were completed. To measure a subject's "joy of winning," we conducted a short treatment in which the subject could win a contest against the computer. Each subject received an additional endowment of 20 points that could be spent to win the contest. After the subject's decision how many points to spend, the computer draws an integer from $\{0, \ldots, 20\}$ according to a uniform distribution. The subject wins the contest if the number of points spent exceeds the randomly drawn integer. Ties are randomly resolved with equal probability. Importantly, winning is merely symbolic, i.e., it does not carry a financial gain. A subject's payoff is thus given by 20 points minus the number of invested points, irrespective of the outcome of the contest. We take the number of points spent to win as a measure of the subject's joy of winning. This approach of measuring joy of winning follows Sheremeta (2010).[17]

To measure the subjects' "cognitive skills," we administered a computerized 12-item Raven Advanced Progressive Matrices test (Raven et al., 2007). The Raven test is a widely used IQ test, based on problems the solutions to which neither depend on knowledge nor on verbal skills. Each item presents a 3×3 matrix of abstract figures, where one figure is missing. Subjects have to determine the missing figure out of eight given solution possibilities. Identifying the correct solution requires reasoning about patterns across both rows and columns. The problems become more difficult over the course of the 12 items. Before the subjects could start working on the test, they first had to correctly solve two practice items to ensure the understanding of the test. After a subject correctly solved the two test items, she had 12 minutes to complete the 12 main items. Feedback for the main items was given only in the end. The performance in the Raven test and the measure of joy of winning serve as control variables in our analysis of the subjects' bidding behavior.

3.6 General Procedures

We conducted two sessions for each of the four treatments, with 272 subjects in total. 70 subjects participated in treatment SPA, 70 subjects participated in treatment ERA, and 64 and 68 subjects participated in the respective computer treatments. In each session of SPA or ERA, we implemented three matching groups of size 10 to 12, depending of the number of subjects in a session, which varied due to no-shows between 30 and 36. The experiment was computerized with the software z-Tree (Fischbacher, 2007) and took place at the decision laboratory of the Department of Economics at the University of Zurich in 2013. Subjects were mainly students

[17]In Sheremeta (2010), two subjects compete with each other to win a contest with no monetary reward. We implemented a contest against the computer to separate our measure of joy of winning from more complicated motives, such as spiteful attempts to interfere with another subject's joy of winning.

from the University of Zurich and the Swiss Federal Institute of Technology in Zurich. Students majoring in economics or psychology were excluded. The recruited was done with the software hroot (Bock et al., 2014). Each subject participated in only one session, which lasted about 90 minutes.

The instructions for the auctions were handed out to the subjects. They included comprehension questions that had to be answered correctly before the experiment could begin. Moreover, a summary of the instructions was read aloud before the experiment started. The bonus function of the externality-robust auction was presented to the subjects on a supplementary information sheet, both in form of a table and as a diagram. The original German instructions and an English translation for all four treatments can be found in the Online Appendix, which is available on the journal's web pages. The instructions for the two measurement tasks were provided directly on the computer screens. Payoffs from the auctions, denominated in "points," were converted into money at the rate of 4 points to CHF 1 (about $ 1.05 at the time of the experiments). Four rounds were randomly selected for payment at the end of the experiment. In the joy of winning task, points were converted into CHF at a rate of 10 to 1. We incentivized the Raven test by paying CHF 1 for each correctly solved item, in order not to confound our measure of cognitive skills with a subject's intrinsic motivation to participate in the test. On average, subjects earned CHF 33.30 in total, which includes a show-up fee of CHF 10.[18]

4 Hypotheses

If spiteful preferences are one (or the only) reason for overbidding in the SPA, we should observe less (or no) overbidding in the ERA, which is designed to be robust with respect to externalities like spite. This observation gives rise to our main hypothesis:

Hypothesis 1. *There is less overbidding in ERA than in SPA.*

To test whether potential behavioral differences between the two auction formats are indeed due to their different robustness properties, the subjects face non-strategic decision-making problems in the treatments in which they play against a computer. Spiteful preferences should not affect their behavior in these treatments because a competing player is absent. This gives rise to the following two hypotheses:

Hypothesis 2. *There is less overbidding in SPA-C than in SPA.*

[18]One participant made an overall loss of CHF 2.50 and paid her dues at the end of the experiment.

Hypothesis 3. *There is no difference in bidding behavior between ERA-C and ERA.*

Overbidding can also be explained by a joy of winning motive. If subjects derive utility from the mere event of winning, then their optimal bids should be increased irrespective of the specific treatment:

Hypothesis 4. *Higher joy of winning is associated with larger bids in all treatments.*

Better cognitive skills might be expected to lead to bidding behavior that is closer to optimal. However, optimality is determined by the subjects' preferences, and the direction of deviation from optimality due to lack of cognitive skills in the different auction formats is not obvious. We thus have no ex-ante hypothesis about the effect of cognitive skills.

5 Experimental Results

5.1 Bidding Behavior

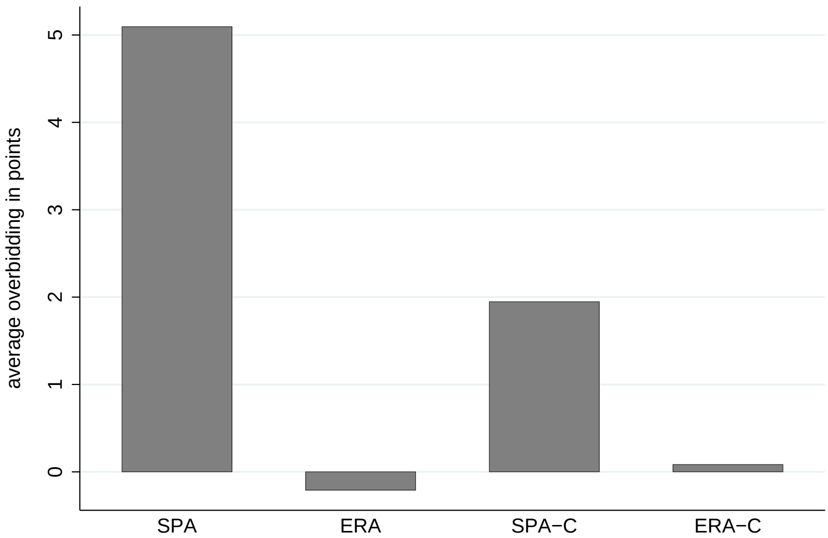
Figure 2 shows the average overbidding ($bid - value$ in points) in our four treatments. The leftmost bar indicates that we replicate the well-documented finding that subjects overbid in second-price auctions (Kagel, 1995). On average, our subjects' bids exceed their valuations by 5.1 points in SPA, which corresponds to about 10 percent given that the expected valuation is 50.5. This amount of overbidding is in line with earlier results. Kagel et al. (1987), for example, find 11 percent average overbidding.

In line with Hypothesis 1, Figure 2 also shows that there is no overbidding on average in ERA. Indeed, on average subjects bid 0.2 points less than their valuation. A Wilcoxon rank-sum test on matching group averages rejects the null hypothesis that average overbidding is the same in SPA and in ERA ($p = 0.0043$, one-sided).

Result 1. *Average overbidding is significantly lower in ERA than in SPA. On average, there is no overbidding in ERA, while bids are about 10 percent above valuations in SPA.*

Result 1 confirms Hypothesis 1 and is consistent with the idea that spiteful preferences are a reason for overbidding in the SPA. To test more directly for the contribution of spiteful preferences to overbidding, we conducted the control treatment SPA-C. Figure 2 reveals that overbidding amounts to only 1.9 points (about 4 percent) on average in SPA-C. A Wilcoxon rank-sum test comparing matching group averages in SPA and individual averages in SPA-C rejects

Figure 2: Average Overbidding



the null hypothesis that average overbidding is the same in SPA and in SPA-C ($p = 0.0044$, one-sided).[19]

Result 2. *Average overbidding is significantly lower in SPA-C than in SPA. On average, bids are only about 4 percent above valuations in SPA-C.*

Result 2 confirms Hypothesis 2 and corroborates the idea that spiteful preferences are a reason for overbidding in the SPA. It also shows that some overbidding persists in SPA-C, even though bidders do not interact with other bidders in this treatment. This reveals that spite cannot be the only reason for overbidding.[20]

We also conducted the control treatment ERA-C. In line with Hypothesis 3, Figure 2 shows that average bids in ERA-C are very similar to average bids in ERA. Average overbidding amounts to 0.08 points in ERA-C. A Wilcoxon rank-sum test comparing matching group averages in ERA and individual averages in ERA-C does not reject the null hypothesis that average

[19]Recall that for each bidder in SPA-C we have a bidder in SPA with an identical sequence of values and opponent bids. We are thus able to group participants in SPA-C into the corresponding "matching groups." Assigning matching groups in SPA-C is artificial as there is no interaction between subjects, but it provides for an additional test. A Wilcoxon rank-sum test comparing (artificial) matching group averages in SPA and SPA-C yields $p = 0.0076$, one-sided.

[20]Kagel et al. (1987) speculate that bidding above one's value in the SPA "is likely based on the illusion that it improves the probability of winning with no real cost to the bidder as the second-high-bid price is paid" (p. 1299). The same reasoning applies to subjects in SPA-C, which might explain the remaining overbidding. Our data suggests that a larger part of the overbidding in standard second-price auctions is explained by spite – an argument missing in Kagel et al. (1987). Moreover, our design provides a clean comparison of the performance of the Becker-DeGroot-Marschak (BDM) mechanism (SPA-C) and the SPA. Existing experimental work comparing both mechanisms, e.g. Rutström (1998) and Lusk et al. (2004), also find lower bids in the BDM mechanism than in the SPA but employ items of home grown value such that over- or underbidding cannot be identified.

overbidding is the same in ERA and in ERA-C ($p = 0.9526$, two-sided).[21]

Result 3. *Average overbidding does not differ between ERA-C and ERA.*

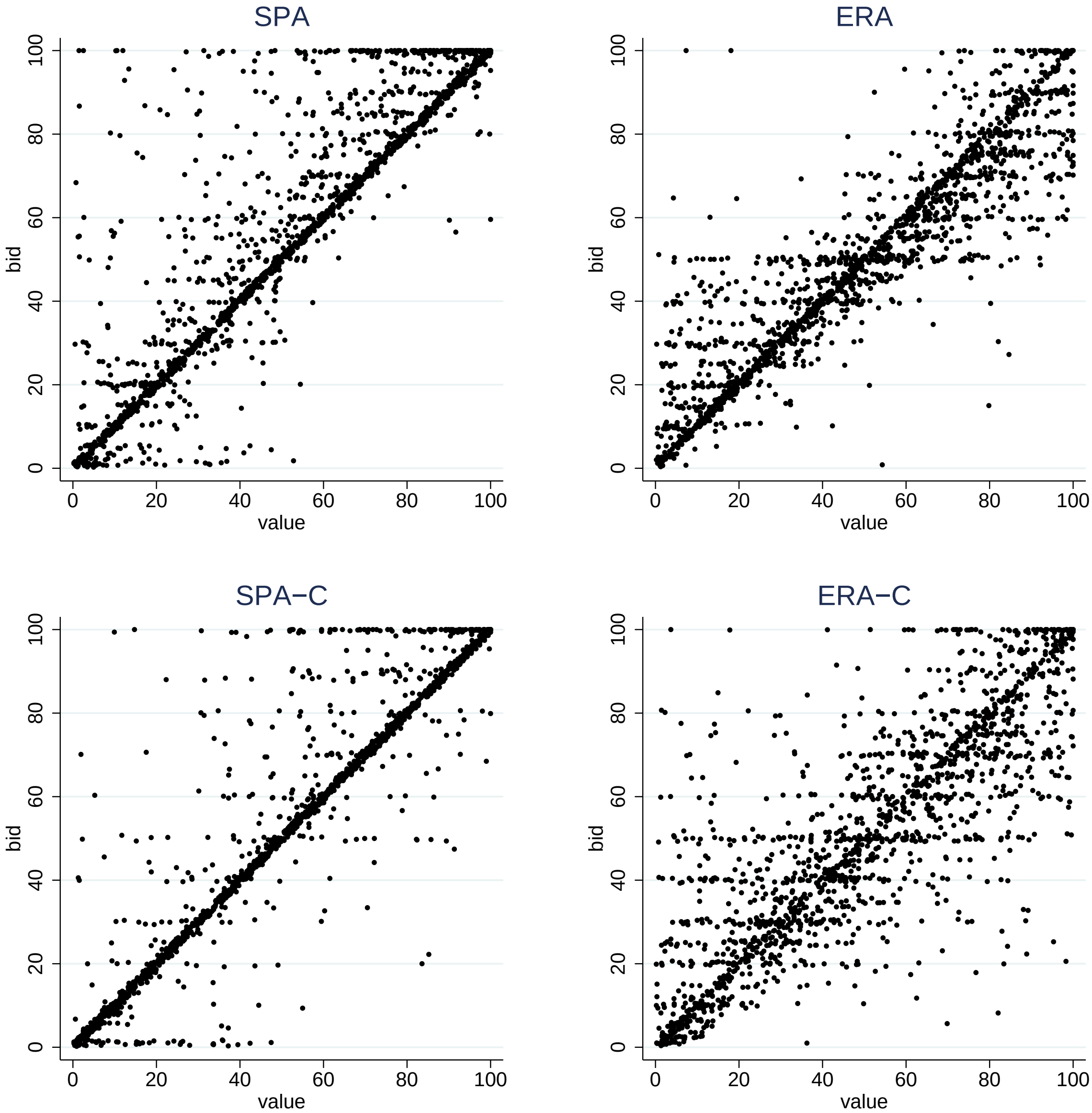
While Figure 2 illustrates our main results in a clear way, it hides a considerable variance and heterogeneity in the subjects' behavior. Figure 3 provides scatter plots showing all individual bids that were submitted for given values in our four treatments. Dots on the 45-degree line indicate cases where a bidder submitted a bid that equals her valuation. Dots above (below) the 45-degree line indicate instances of overbidding (underbidding). While bids equal the true value on average in treatments ERA and ERA-C, the scatter plots reveal that bids often deviate from the underlying value. In treatments SPA and SPA-C, by contrast, there is a larger fraction of bids that equal the underlying value, while the deviating bids tend to accumulate above the 45-degree line.

Figure 4 shows that the average absolute deviation of bid from value is virtually identical in SPA and ERA (7.21 and 7.24, respectively), but it is lower in SPA-C (4.71) and higher in ERA-C (10.70). Figure 5 is a histogram of the individual subjects' average overbidding. It confirms that a larger fraction of subjects bids on average the underlying value in SPA than in ERA. The deviations of subjects who do not bid their value on average, however, are systematically biased towards overbidding in SPA, and rather symmetrically distributed around truthful bidding in ERA. In particular, a group of about 20 percent of subjects bids on average 14 or more points above their true values in treatment SPA. Consistent with the idea that some bidders have spiteful preferences, this group largely vanishes in treatment SPA-C, while the fraction of subjects who bid truthfully on average increases by about 20 percent.

Battigalli and Siniscalchi (2003) apply the concept of interim rationalizability to auctions. Rationalizability rests on the assumption of common knowledge of rationality but not of correct equilibrium beliefs. They show that, while only truthful bidding is rationalizable in the SPA, bids both above and below the Bayes-Nash equilibrium are rationalizable in the FPA. In combination with the hypothesis that some subjects are selfish and others are spiteful, the concept of rationalizability might also explain some of the noise patterns in our data. In the SPA, beliefs are irrelevant for selfish subjects, so we expect them to bid truthfully. Spiteful subjects will overbid, and heterogeneity in beliefs among these subjects should generate some noise in their behavior. By contrast, the distinction between selfish and spiteful agents becomes irrelevant in

[21] The same result again prevails if we consider averages in the artificial matching groups in ERA-C and compare them to the matching group averages in ERA (Wilcoxon rank-sum test, $p = 0.9372$, two-sided).

Figure 3: Individual Bidding



the ERA, where heterogeneous beliefs should thus contribute to more symmetric noise around the equilibrium behavior. These patterns are roughly in line with Figure 5.[22]

5.2 Efficiency

A main goal of this paper is to study the trade-off between robustness in the dimension of beliefs about other players' strategies, which the SPA satisfies, and robustness in the dimension of payoff externalities, which the ERA satisfies. The existence of subjects whose behavior deviates

[22]The scatter plots in Figure 3 also reveal a tendency of more overbidding for small values and more underbidding for large values in treatment ERA and, to a lesser extent, also in ERA-C. We have no simple explanation for this observation, but it would be interesting to see if it is consistent with or even predicted by rationalizability. Deriving the rationalizable bidding strategies for the ERA is, however, beyond the scope of this paper.

Figure 4: Average Absolute Deviation

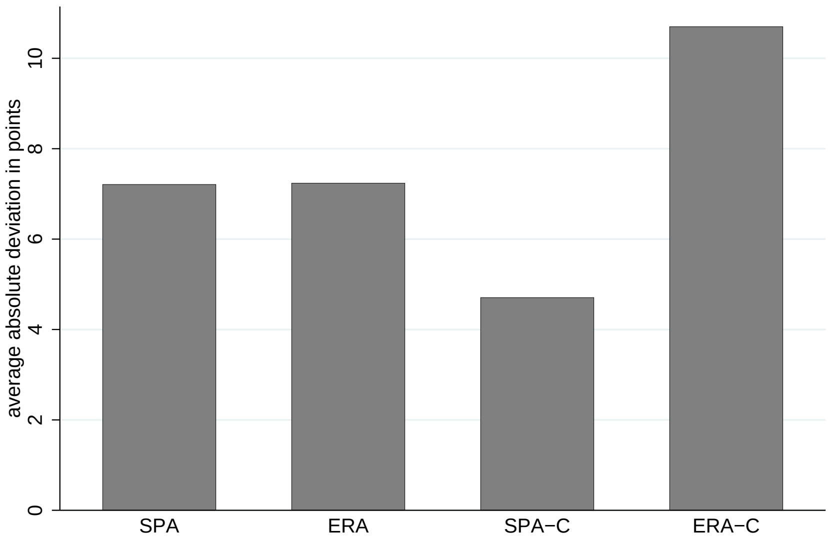
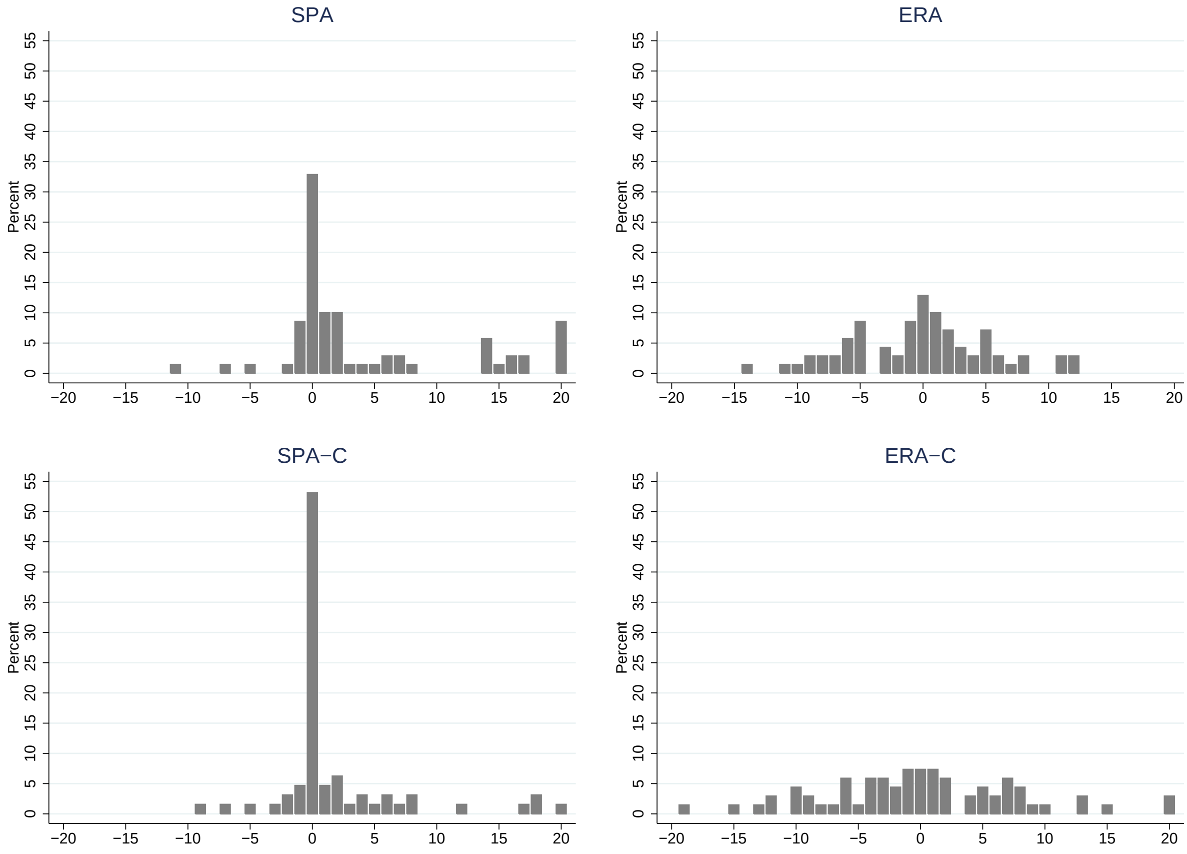


Figure 5: Distribution of Individual Average Overbidding



Notes: Each subject's average overbidding is rounded to integers. Category 20 contains subjects who overbid by 20 point or more (6, 1, and 2 subjects in SPA, SPA-C, and ERA-C).

from the reference model, due to non-equilibrium beliefs or spitful preferences, will disrupt the intended outcome of the respective non-robust mechanism but not of the robust mechanism. Hence, to obtain a measure of the relative importance of both robustness dimensions, we compare the efficiency of the SPA and the ERA. The data reveal that the allocation is ex-post efficient (i.e., the bidder with the highest valuation receives the good) in 89.3 percent of the cases (750 out of 840) in SPA and in 90.1 percent of the cases (757 out of 840) in ERA. A Wilcoxon rank-sum test on matching group averages reveals that the null hypothesis that the efficiency is the same in SPA and ERA cannot be rejected ($p = 0.5745$, two-sided).

Result 4. *SPA and ERA are equally efficient. The bidder with the highest valuation receives the good in about 90 percent of cases in both action formats.*

Result 4 suggests that both dimensions of robustness are equally important, because the same level of ex-post efficiency is reached in both auction formats.

5.3 Revenue

We can also compare the revenue in SPA and in ERA. We find that a seller receives 38.04 on average in SPA (average price paid by the winning bidder), while a seller receives only 34.04 in ERA (average price paid by the winning bidder minus bonus payments to both bidders). A Wilcoxon rank-sum test on matching group averages rejects the null hypothesis that the revenue is the same in SPA and in ERA with marginal significance ($p = 0.0547$, two-sided). The higher revenue in SPA than in ERA reflects the fact that subjects overbid on average in SPA but not in ERA.

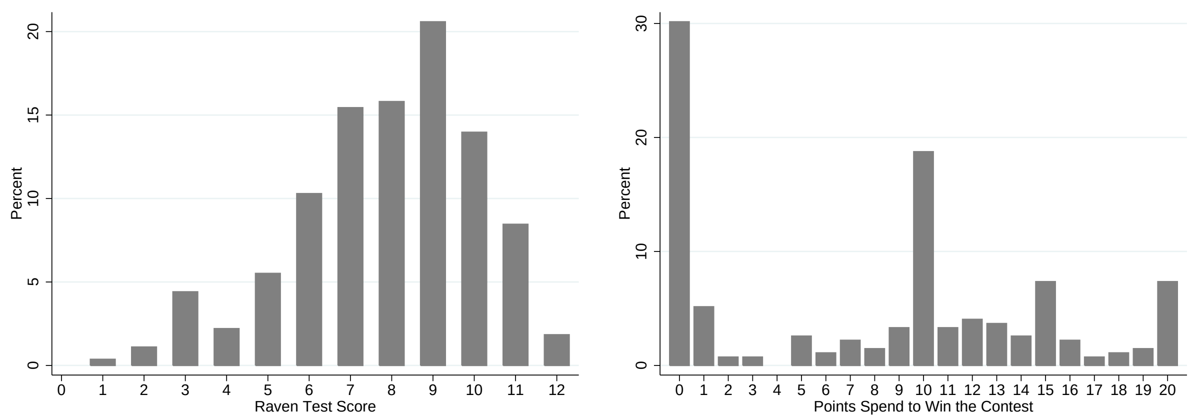
The seller benefits from spite at the cost of the buyers in the SPA. The opposite would hold in settings where bidders are pro-social or cross-shareholdings exist. However, neither the SPA nor the ERA is revenue optimal if the exact nature of externalities between bidders is known. An auction tailored to the situation can always achieve larger revenues in this case.[23] Our robustness approach applies to situations where such information requirements are excessive, for instance due to unobserved heterogeneity in the bidders' interdependent preferences, or firm ownership structures that are hard to disentangle or unobservable to the outsider.

[23]See Chillemi (2005) and Loyola (2007) for optimal auctions with known cross-shareholdings, Lu (2012) for general financial externalities, and Tang and Sandholm (2012) for spiteful bidders.

5.4 Individual Determinants of Bidding Behavior

Finally, in order to better understand the individual heterogeneity in bidding behavior documented in Figure 5, we rely on our measures of joy of winning and cognitive skills. Figure 6 shows the distribution of these two measures averaged over all four treatments. The left panel shows the distribution of the Raven test scores. On average subjects solved 7.9 puzzles, the modal value is 9. Very few subjects could solve all twelve puzzles (5 out of 272 subjects). The right panel reveals that, while subjects spent about 8 points on average to win the contest without a prize, about 30 percent of the subjects spent nothing. Almost 20 percent of the subjects spent 10 points and about 7 percent spent all 20 points. We cannot exclude that some of these decisions are due to a lack of understanding of the contest. The two measures are in fact negatively correlated: subjects who score higher in the cognitive skill task spend less money to win the contest against the computer. The correlation is not very strong ($\rho = -0.17$) but highly significant ($p = 0.005$).

Figure 6: Distribution of Individual Characteristics



We elicited a measure of joy of winning because it is one explanation for overbidding discussed in the literature. Regression (1) in Table 2 includes all observations from SPA and SPA-C and reports a fully interacted random effects regression of overbidding on period, joy of winning, and cognitive skills. We also control for value, value squared, value cubed, and the respective interactions with the computer treatment, because the deviation of a bid from value can depend on the underlying value. The regression shows that our measure of joy of winning is positively associated with overbidding in SPA. While the size of the coefficient is large (a subject who spends all 20 points in the joy of winning contest is predicted to overbid 4.72 points more than a subject who spends no points), it is not significant. An F-test however rejects the hypothesis that the sum of the coefficients "Joy" and "Joy x C" is zero, i.e., joy of winning has a significant impact on overbidding in SPA-C ($p = 0.0323$). Model (4) provides the equivalent regression for ERA and ERA-C. Again, both coefficients of the joy of winning measure are positive, but small in ERA and large and significant only in ERA-C (F-test on the hypothesis that "Joy" plus "Joy x C" equal zero, $p = 0.0025$). In sum, our data provide weak support for Hypothesis 4 according to which joy of winning is associated with higher bids.

Result 5. *Joy of winning is positively correlated with overbidding in all four treatments, but the effect is significant only in SPA-C and ERA-C.*

Table 2: Regression Analysis

	SP			ER		
Dep. Variable	(1) Over-bidding	(2) Positive deviation	(3) Negative deviation	(4) Over-bidding	(5) Positive deviation	(6) Negative deviation
Joy	0.236	0.207	-0.029	0.012	0.020	0.008
	(0.182)	(0.177)	(0.046)	(0.123)	(0.058)	(0.079)
Joy x C	0.018	0.087	0.070	0.363**	0.355***	-0.008
	(0.217)	(0.213)	(0.070)	(0.175)	(0.098)	(0.111)
Cog. Skills	-1.683**	-1.821**	-0.138	0.083	0.023	-0.060
	(0.748)	(0.773)	(0.137)	(0.392)	(0.221)	(0.266)
Cog. Skills x C	1.405*	1.350*	-0.055	0.066	-0.137	-0.203
	(0.786)	(0.817)	(0.193)	(0.559)	(0.312)	(0.379)
Period	0.021	-0.012	-0.034***	-0.037	-0.070***	-0.033
	(0.025)	(0.024)	(0.008)	(0.033)	(0.027)	(0.027)
Period x C	0.045	-0.019	-0.064*	0.090	0.067	-0.023
	(0.053)	(0.038)	(0.035)	(0.079)	(0.056)	(0.054)
Constant	19.347***	20.537***	1.216	12.151***	13.257***	1.099
	(6.710)	(7.064)	(1.440)	(4.497)	(2.873)	(2.702)
Constant x C	-17.972**	-16.464**	1.483	-3.106	-0.624	2.490
	(7.512)	(7.815)	(2.091)	(5.884)	(3.935)	(3.515)
Contr. for value	yes	yes	yes	yes	yes	yes
R-squared	0.21	0.23	0.04	0.17	0.26	0.10
No. Obs.	3216	3216	3216	3312	3312	3312
No. Clusters	70	70	70	74	74	74

Notes: The table reports random effects regressions, with subject random effect. Standard errors in parentheses control for clustering at the matching group level in SPA and ERA (6 clusters each) and at the subject level in SPA-C (64 clusters) and ERA-C (68 clusters). Recall that no interaction between subjects occurs in the computer treatments. The omitted category is SPA in regressions (1)-(3) and ERA in (4)-(6), and the interaction is with the respective computer treatment, denoted by "C." *, ** and *** denote significance at 10%, 5% and 1%.

In a common value auction experiment, van den Bos et al. (2008) find that overbidding and the winner's curse disappear when subjects play against the computer instead of human bidders. They explain this finding with the hypothesis that subjects experience joy of winning only when winning against human bidders. The results of our private value auction experiment are not consistent with this hypothesis. With joy of winning against humans but not against the computer, we should expect to find a difference in overbidding between ERA and ERA-C, similar to the difference that we find between SPA and SPA-C. Since this is not the case, the difference in average overbidding between SPA and SPA-C cannot be explained by the hypothesis that joy of winning depends on the existence of a human opponent, but is consistent with the hypothesis of spiteful preferences.

Regressions (1) and (4) also control for a subject's cognitive skills, because overbidding in second-price auctions (and other auction formats) is often attributed to bounded rationality. Regression (1) confirms that cognitive skills are a significant predictor of bidding behavior in SPA: subjects who score higher in the Raven test show less overbidding. The size of the effect is large. Each additionally solved puzzle is associated with a reduction in overbidding by about 1.7 points. For SPA-C we find that cognitive skills are much less associated with overbidding, which can be seen by the positive and significant interaction term of cognitive skills and the computer treatment. An F-test cannot reject the hypothesis that the sum of the coefficients "Cog. Skills" and "Cog. Skills x C" is zero ($p = 0.2500$). The much smaller association of cognitive skills with overbidding is, at first sight, a surprising finding, because there is no apparent reason why SPA-C should be cognitively less demanding than SPA. Moreover, regression (4) shows that cognitive skills are not significantly associated with overbidding in ERA and ERA-C either (an F-test cannot reject that the sum of "Cog. Skills" and "Cog. Skills x C" equals zero, $p = 0.7094$). Again, there is no apparent reason why these auctions should be cognitively less demanding than SPA.

Interestingly, prior research documented a relation between cognitive skills measured by the Raven test and different forms of pro-social behavior. Burks et al. (2009) find a positive relationship between Raven test scores and cooperative behavior in a sequential prisoners' dilemma game. Similarly, Millet and Dewitte (2007) find that cognitive skills measured by the Raven test are positively correlated with altruistic behavior in public goods and dictator games.[24] Our

[24]Using different measures of cognitive skills, James (2011) reports a positive relationship between cognitive skills and charitable giving. Segal and Hershberger (1999) find that IQ is positively correlated with cooperation among twins in the repeated prisoners' dilemma. The meta study by Jones (2008) reveals that cooperation rates in the repeated prisoners' dilemma are higher at universities whose students score higher in standardized cognitive tests. It should be noted, however, that there is also evidence linking higher cognitive skills to less pro-social behavior. For example, Ben-Ner et al. (2004) find a negative relationship between their measure of cognitive skills and dictator game giving (but only for women). Finally, Brandstätter and Güth (2002) find no effect of

finding that cognitive skills are significantly and negatively associated with overbidding in SPA (where spiteful preferences predict overbidding) but not in SPA-C, ERA, and ERA-C (where spiteful preferences do not predict overbidding), together with the existing empirical results linking low cognitive skills to less pro-social behavior, suggests that low cognitive skills are not necessarily the ultimate reason for overbidding in SPA. Rather, they might instead serve as a proxy for spiteful preferences (which can be classified as non-cooperative and non-altruistic) in our analysis.

Further support for this possibility is provided by regressions (2) and (3), were the dependent variables are "positive deviation" and "negative deviation," respectively. Positive deviation equals overbidding if overbidding is positive, and is zero otherwise. Negative deviation equals the absolute value of overbidding if overbidding is negative, and is zero otherwise. These regressions provide two interesting observations. First, cognitive skills are negatively and significantly associated with positive deviations of bids from value but not with negative deviations in SPA. This is consistent with the idea that cognitive skills are a proxy for spiteful preferences, while a bounded rationality argument might predict that low cognitive skills are associated with both positive and negative deviations of bids from value. Second, the significant negative coefficient of "Period" reveals that negative deviations decline over time in SPA. This suggests that subjects learn to some extent not to underbid. Positive deviations, in contrast, do not decline over time. This is again consistent with a preference explanation for overbidding.[25]

6 Conclusions

Robustness has always been considered as an important property in mechanism design theory. The existing literature focusses on dominant-strategy implementation. However, a mechanism can be robust or non-robust in several different dimensions, and the literature has only recently started to explore novel directions, such as robustness with respect to interdependent preferences. In this paper, we have shown theoretically and experimentally that there is a trade-off between dominant-strategy-robustness and externality-robustness, and that both concepts are equally important, measured by the efficiency of the outcomes. From a broader perspective,

cognitive skills on behavior in dictator and ultimatum games.

[25]In SPA-C, the effect of period is qualitatively the same as in SPA, with a significant decrease of negative deviations over time (F-test, $p = 0.0049$) but no significant effect on positive deviations (F-test, $p = 0.3010$). Regressions (5) and (6) are the equivalent regressions for the externality-robust auction. Positive deviations of bids from value decline significantly over time in ERA. The effect is not significant in ERA-C (F-test, $p = 0.9502$). There is no significant effect of period on negative deviations in either treatment (F-test for ERA-C, $p = 0.2347$).

our results contribute to the emerging field of behavioral mechanism design theory (e.g. Glazer and Rubinstein, 1998; Eliaz, 2002; Cabrales and Serrano, 2011; de Clippel, 2014; Bierbrauer and Netzer, 2016), which studies the implications of behavioral phenomena for the design of economic institutions.

The externality-robust auction can also be seen as an experimental tool, as it eliminates the channel through which spiteful preferences manifest themselves in equilibrium behavior. In particular, our experimental evidence corroborates the idea that spiteful preferences are an important determinant of overbidding in the second-price auction.

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A Appendix

A.1 Proof of Proposition 1

We prove the proposition in three steps, fixing a bidder $i \in I$ with valuation $\theta_i = \theta^k$ for some $k \in \{1, \dots, m\}$ throughout. First, we derive an expression for $V_i^*(\theta_i) := \mathbb{E}_{\theta_{-i}}\left[q_i^*(\theta_i, \theta_{-i})\,\theta_i\right]$, followed by an analogous expression for $T_i^{SPA}(\theta_i) := \mathbb{E}_{\theta_{-i}}\left[t_i^{SPA}(\theta_i, \theta_{-i})\right]$. Finally, these results will be combined to derive $t_i^{ERA}(\theta) = V_i^*(\theta_i) + T_i^{SPA}(\theta_i) - q_i^*(\theta)\,\theta_i$ according to (3).

Step 1. Given $\theta_i = \theta^k$, the probability that exactly x other bidders also have valuation θ^k, while all remaining bidders have a strictly smaller valuation, so that $i \in W(\theta)$ and $|W(\theta)| = x+1$, is given by

$$\binom{n-1}{x} \left(p^k\right)^x \left(P^{k-1}\right)^{n-1-x}$$

for any $0 \leq x \leq n-1$.[26] According to (1), $q_i^*(\theta)$ is non-zero only when $i \in W(\theta)$, so that

$$V_i^*(\theta_i) = \sum_{x=0}^{n-1} \binom{n-1}{x} \left(p^k\right)^x \left(P^{k-1}\right)^{n-1-x} \left(\frac{\theta^k}{x+1}\right). \tag{8}$$

Step 2. Similarly, the transfers (2) for bidder i are non-zero only when $i \in W(\theta)$. In that case, observe that $s(\theta) = \theta^k$ when $|W(\theta)| > 1$ and $s(\theta) < \theta^k$ when $|W(\theta)| = 1$. Thus

$$T_i^{SPA}(\theta_i) = -\left(P^{k-1}\right)^{n-1} S^k - \sum_{x=1}^{n-1} \binom{n-1}{x} \left(p^k\right)^x \left(P^{k-1}\right)^{n-1-x} \left(\frac{\theta^k}{x+1}\right),$$

where S^k denotes the expected largest valuation among all $n-1$ other bidders, conditional on all of them remaining strictly below θ^k. The first term captures the case where i is the unique bidder with largest valuation, while the second term captures the possibility that $x \in \{1, \dots, n-1\}$ other bidders might have the same largest valuation. An expression for S^k will be derived next. Denote by $\hat{P}^j = P^j / P^{k-1}$ the cumulated probabilities of the distribution truncated at θ^{k-1}, for $j \in \{0, 1, \dots, k-1\}$.[27] Conditional on remaining strictly below θ^k, each bidder's valuation is distributed according to the cumulated probabilities $\hat{P}^j$, and the largest valuation among $n-1$ bidders is distributed according to the cumulated probabilities $(\hat{P}^j)^{n-1}$ (see e.g. Arnold et al., 2008, p. 12). Thus the probability that the largest valuation among the $n-1$ other bidders is

[26] With the convention $0^0 = 1$ this expression is also applicable to the case of $x = n-1$ and $k = 1$.

[27] With the convention $0/0 = 0$ this expression is also applicable to the case of $k = 1$.

equal to θ^j, conditional on all their valuations being strictly below θ^k, is given by

$$\left(\hat{P}^j\right)^{n-1} - \left(\hat{P}^{j-1}\right)^{n-1} = \frac{\left(P^j\right)^{n-1} - \left(P^{j-1}\right)^{n-1}}{\left(P^{k-1}\right)^{n-1}}.$$

Hence it is possible to write

$$S^k = \sum_{j=1}^{k-1} \left[\frac{\left(P^j\right)^{n-1} - \left(P^{j-1}\right)^{n-1}}{\left(P^{k-1}\right)^{n-1}} \right] \theta^j.$$

Collecting results, we obtain

$$T_i^{SPA}(\theta_i) = \\ -\sum_{j=1}^{k-1} \left[\left(P^j\right)^{n-1} - \left(P^{j-1}\right)^{n-1} \right] \theta^j - \sum_{x=1}^{n-1} \binom{n-1}{x} \left(p^k\right)^x \left(P^{k-1}\right)^{n-1-x} \left(\frac{\theta^k}{x+1}\right). \quad (9)$$

Step 3. Adding (8) and (9) yields

$$B(\theta_i) := V_i^*(\theta_i) + T_i^{SPA}(\theta_i) = \left(P^{k-1}\right)^{n-1} \theta^k - \sum_{j=1}^{k-1} \left[\left(P^j\right)^{n-1} - \left(P^{j-1}\right)^{n-1} \right] \theta^j.$$

The function $B(\theta_i)$ can be simplified using a recursive formulation. When $\theta_i = \theta^1$, so that $k = 1$, it follows immediately that $B(\theta^1) = 0$. Furthermore, for any $l \in \{1, \ldots, m-1\}$ it follows that

$$B(\theta^{l+1}) - B(\theta^l) = \left(P^l\right)^{n-1} \theta^{l+1} - \left[\left(P^l\right)^{n-1} - \left(P^{l-1}\right)^{n-1} \right] \theta^l - \left(P^{l-1}\right)^{n-1} \theta^l,$$

which reduces to

$$B(\theta^{l+1}) - B(\theta^l) = \left(P^l\right)^{n-1} \left(\theta^{l+1} - \theta^l\right).$$

Thus, for $\theta_i = \theta^k$ it is possible to write

$$B(\theta_i) = \sum_{j=1}^{k-1} \left(P^j\right)^{n-1} \left(\theta^{j+1} - \theta^j\right),$$

which is expression (5) in Proposition 1. It now follows that

$$t_i^{ERA}(\theta) = V_i^*(\theta_i) + T_i^{SPA}(\theta_i) - q_i^*(\theta)\,\theta_i = B(\theta_i) - q_i^*(\theta)\,\theta_i.$$

Using (1), this becomes expression (4) in the proposition.

A.2 Ex-Post Revenues in the ERA

Condition (6) is most stringent for θ^m. Consider revenue $\theta^k - nB(\theta^k)$. Straightforward calculations reveal that an increase from k to $k+1$ changes this expression by $[1-n(P^k)^{n-1}](\theta^{k+1}-\theta^k)$, the sign of which is equal to the sign of $[1 - n(P^k)^{n-1}]$. This latter expression is strictly decreasing in k, so whenever revenue has become smaller in response to an increased k, further increases in k will continue to reduce the revenue. Now observe that (6) is satisfied for $k = 1$, because $B(\theta^1) = 0$. Therefore, whenever a deficit occurs for some larger k – which requires that revenue has eventually decreased – then a deficit also occurs for all $k' > k$. To rule out deficits, it is therefore enough to check condition (6) for the largest value θ^m.

Condition (7) holds in the framework of Section 2.4. In this case, (7) can be rearranged to

$$n \sum_{j=1}^{m-1} (j)^{n-1} \leq m^n. \tag{10}$$

Fix arbitrary values of $n \geq 2$ and $m \geq 2$ and assume that (10) is satisfied. Then it must also be satisfied for all values $m' > m$, holding n fixed. Indeed, increasing m by one increases the LHS of the inequality by $n\,(m)^{n-1}$ and the RHS by $(m+1)^n - m^n$. An immediate application of the binomial theorem reveals that $(m+1)^n - m^n = n\,(m)^{n-1} + \gamma$, where γ summarizes all remaining terms and is positive. Hence increasing m slackens (10). For the smallest possible value $m = 2$, (10) simplifies to $n \leq 2^n$, which is satisfied for all $n \geq 2$.