Allotment in First-Price Auctions: An Experimental Investigation

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Abstract

We experimentally study the effects of allotment – the division of an item into homogeneous units – in independent private value auctions. We compare a bundling first-price auction with two equivalent treatments where allotment is implemented: a two-unit discriminatory auction and two simultaneous single-unit first-price auctions. We find that allotment in the form of a discriminatory auction generates a loss of efficiency with respect to bundling. In the allotment treatments, we observe large and persistent bid spread, and the discriminatory auction is less efficient than simultaneous auctions. We provide a unified interpretation of our results that is based on both a non-equilibrium response to the coordination problem characterizing the simultaneous auction format and a general class of behavioral preferences that also includes risk aversion, joy of winning and loser's regret as specific cases.

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Keywords: Allotment, multi-unit auction, discriminatory auction, first-price auction, laboratory experiment.

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1 Introduction

Multi-unit auctions – i.e., auctions in which several homogeneous units of the same good are sold at one go – are becoming increasingly popular in a large variety of markets. Variants of multi-unit auctions have long been used to trade electricity, treasury bills, public procurement contracts; more recently, they are being adopted to allocate emission permits,[1] and to regulate renewable energy markets[2] and many industrial purchasing relations, especially on the internet.[3]

When multiple units of the same good are involved, the market designer has to be concerned with two intimately related questions: *(i)* whether to sell the entire quantity as a single bundle or allot it into several distinct units; *(ii)* in the latter case, which particular allotment strategy to implement. Bundling units together can have obvious advantages for the auctioneer, such as synergies in production, simplicity and lower administrative costs. On the other hand, bidders will generally respond strategically to allotting if the value they attach to a specific unit depends on the number of units already acquired (or expected to be acquired) in the auction. This response will be sensitive to the allotment format chosen (see, among others, Engelbrecht-Wiggans and Kahn 1998a and 1998b). In addition, allotment might also foster entry by other (small) bidders, thus altering the degree of competition and behavior by incumbents (see, e.g., Goeree et al. 2013). Therefore, allotting may generate composite effects, that can vary widely depending on market structure and technological characteristics regarding the production, transport and distribution of goods. But, if all such structural and technological factors are properly controlled for, what effects, if any, does the exogenous decision to bundle or allot the quantity of a divisible good exert on bidders' behavior and thereby on the outcome of the auction (efficiency and revenue)?

The present paper tackles this question reporting results from a novel and intuitive experiment. In a nutshell, the experiment's details are the following. Our design includes three treatments. The first treatment corresponds to bundling and consists of a standard single-unit, first-price, independent private value auction. The other two treatments implement allotment in two different ways. In the second treatment, bidders compete in a two-unit discriminatory auction: each bidder places two bids, the two highest bids are deemed winning and the bidder(s) who placed the winning bids is (are) assigned the units and pays (pay) the amount of her (their) winning bid(s). In the third treatment, bidders participate in two simultaneous first-price auctions, each involving a single unit.

To single out the pure effect of the selling strategy chosen, we adopt the simplest possible setting such that the three treatments, according to standard theory, should be equivalent in terms of bidding behavior and efficiency: first, the units traded in the auctions do not display any complementarity or substitutability, as then comparing single-unit against multi-unit auctions would have to account for complex effects on bidders' incentives. Second, we keep constant the number of bidders and the distribution of private valuations to rule out the possibility that allotment affects the degree of competition or the thickness of the demand.

[1]See Betz et al. (2010) for the Australian systems; Lopomo et al. (2011) for the mechanism options in USA; Goeree et al. (2010) for an experimental investigation of the European Emission Trading System, the world's largest carbon trading market.

[2]For example, the number of countries that adopted renewable energy auctions increased from 9 in 2009 to at least 44 by early 2013, out of which 30 were developing countries (IRENA 2013); as for European Union, in 2013, 8 Member States result adopting renewable energy auctions (EC 2013).

[3]For business-to-business (B2B) multi-unit auctions, see Katok and Roth (2004).

Although this setup is extremely stylized, it nevertheless mimics many real markets, most evidently Treasury bill auctions and (other) primary offerings of stock and bonds. Moreover, we believe that our benchmark case of units' constant marginal values may have other existing representations in the field. For example, providers of electricity often operate at ranges of constant marginal cost in incomplete markets; a similar situation applies for "sales for re-sale" transactions, as long as sales volume remains below capacity constraints.

Our experimental evidence highlights that allotment causes behavioral responses by bidders that are not predicted by the standard theory. In particular, the main experimental results can be summarized as follows. First, allotment in the form of a discriminatory auction generates an efficiency loss and a marginal decrease in revenue with respect to bundling. Second, the allotment strategy is not neutral: even though, in both allotment formats, we detect bid spread (i.e., different bids for the two units), running two simultaneous auctions reduces inefficiency relative to the discriminatory auction. Third, in all treatments we observe overbidding (i.e., bids above the theoretical risk neutral Nash equilibrium) but bids are less aggressive in the discriminatory auction than in the other treatments.

The paper makes two contributions that are of particular interest. Our first contribution is applied. Our results suggest that bidders may behave "as if" the marginal values of the units were decreasing even though their intrinsic values appear to be constant. As shown by us, this has an impact on efficiency that should point the choice of the market designer toward bundling. When allotment has to be implemented, the simultaneous auctions format is preferable: by requiring proper bid coordination between bidders, and in the absence of elements that may facilitate successful coordination, simultaneous auctions may induce some *shaky* bidders to refrain from the (inefficient) bid spread strategy; this produces a larger total surplus relative to the discriminatory auction, where this coordination problem is absent.

Our second contribution consists in providing a description of our results in terms of a general class of behavioral motives. Mechanism design maps a set of rules and assumptions about bidders' preferences to outputs. Most of the literature in this field simply assumes risk neutrality. Our experiment provides clean evidence that this assumption does not match the behavior of many bidders, and that the actual behavior is biased in a way that renders bundling the favorable design choice, both in terms of efficiency and surplus to the auctioneer. In line with recent advances in behavioral economics, we show that risk aversion, joy of winning, and loser's regret are all valid representations of preferences to explain our experimental results. While our study does not aim at disentangling among these (and possible other) behavioral explanations, in discussing our results we identify the general features that they have in common: *(i)* bidders gain a benefit from winning the auction on top of the assigned monetary values, and *(ii)* this benefit decreases with the number of units acquired.

The rest of the paper is organized as follows. Section 2 reviews the related literature. Section 3 presents the experimental design and the theoretical predictions under the standard assumption of risk neutral bidders. Section 4 reports the results of our experiment. Section 5 provides a unified explanation of our results in terms of general behavioral features also discussing some existing hypothesis that meet these features. Finally, Section 6 concludes with some policy implications from our experimental findings.[4]

[4]The experimental instructions, a formal analysis of the testable predictions and some additional empirical results are provided in the Supplementary Material.

2 Related Literature

Considering the existing economic literature on auctions involving multiple objects, this paper adds a controlled investigation on the allotment effect *per se*. In so doing, we refer to three main strands of literature. The first concerns the effects of bundling: Palfrey (1983) theoretically shows that, with two bidders and in a second-price auction, allocating different goods as a single bundle is revenue superior (but inferior in terms of total welfare) to selling them through parallel auctions (see also Chakraborty 1999). Popkowski Leszczyc and Häubl (2010) experimentally show that, when there is complementarity between goods, a bundle auction generates higher revenue than two parallel auctions for the components of the bundle; the opposite occurs when the goods are substitutes. Differently from these papers, we do not introduce any complementarity/substitutability between goods in the aim to study the "pure" effects that allotment exerts on bidders' behavior. Moreover, we consider multi-unit auctions in which bidders place multiple bids in the same auction and we extend the analysis to "pay-as-bid" pricing rules.

Second, we contribute to the literature on multi-unit auctions that investigates the properties of the standard formats (i.e., uniform price, discriminatory and Vickrey and their open outcry counterparts). In particular, the theory on discriminatory auctions (Engelbrecht-Wiggans and Kahn 1998b) has shown that, when the units have decreasing marginal valuations, *(i)* bidders shade all bids and *(ii)* the difference between two bids placed by a bidder tends to be smaller than the difference between the corresponding valuations. Experimental analysis on multi-unit auctions (surveyed, e.g., by Kagel and Levin 2011 and Kwasnica and Sherstyuk 2013) have mainly focused on uniform-price and Vickrey auctions, while less attention has been devoted to the discriminatory format. Some relevant exceptions are: Goeree et al. (2013), who study preemptive bidding in discriminatory and ascending auctions in which entry has a negative externality on incumbent bidders; Goswami et al. (1996) and Sade et al. (2006), who investigate cooperative behavior in discriminatory and uniform-price common value auctions with pre-play communication; Engelmann and Grimm (2009), who analyze bidders' behavior and efficiency in five different multi-unit auction formats (discriminatory, uniform-price sealed-bid, uniform-price open, Vickrey and Ausubel auctions). Engelmann and Grimm (2009) find a strong evidence of overbidding and bid spreading. In a companion paper - Grimm and Engelmann (2005) - these authors advance risk aversion and joy of winning as possible explanations for this puzzling evidence, finding empirical arguments that suggest the superiority of the latter behavioral artifact. We share with Engelmann and Grimm (2009) the same setting, and we depart from it as we assess the effects of allotment on bids and efficiency in alternative pay-as-bid auction formats. To this end, we compare results from the discriminatory auction with an equivalent (in value) single-unit first-price auction. Moreover, in order to check whether results depend on the specific form of allotment, we also consider an additional treatment in which bidders participate in two identical and simultaneous single-unit first-price auctions.

Finally, our paper also relates to the literature on combinatorial auctions in which buyers can submit bids on either single units or packages. Combinatorial auctions are useful allocation mechanisms when units are characterized by the presence of synergies or when, because of their budget capacity and dimension, there are bidders interested in subsets of goods only (Cramton et al. 2006). Kagel and Levin (2005), Katok and Roth (2004) and Chernomaz and Levin (2012) investigate how the exposure problem - occurring when a bidder refrain from aggressive bidding in order to avoid exposure to losses in case she wins only a limited number of units - affects efficiency and revenue of the auction. We share with this literature the attention to the effects of introducing the possibility of allotting items. However, the comparison of our results with those from combinatorial auctions is not straightforward: indeed, in the latter, package bids compete with single-item bids in the same auction, while in our study, we compare an auction in which only package bids are allowed with two formats in which bidders can exclusively place separate bids.

3 Experimental design and predictions

In order to assess how allotment affects bids and efficiency, we compare results from a benchmark treatment in which bidders compete for a single item with those observed in two equivalent (in terms of experimental features and potential payoff) auction formats with multiple and identical units. For each treatment, we ran three sessions. Each session included 15 periods and involved 18 participants, for a total of 162 subjects.

3.1 Treatments

The benchmark treatment, *1A1U*, consists of a single-unit, first-price, independent private value auction with two bidders. Once pairs are formed, each bidder privately observes the value of an indivisible item. In each period, values are randomly and independently drawn from the same uniform distribution with support $[0, 200]$. All the characteristics of the distribution used to generate private values are common knowledge. After observing their values, bidders simultaneously place their bids. The bidder who places the highest bid wins the item and her earnings are given by the difference between her value and her bid. The other bidder earns nothing.

In the second treatment, *1A2U*, in every period the two bidders compete in a two-unit discriminatory auction. To each bidder, the two units have the same value, which, in each period, is randomly and independently drawn from a uniform distribution with support $[0, 100]$. This implies that the distribution (in terms of mean and upper and lower bounds) of the sum of the private values in *1A2U* coincides with that used in the benchmark, *1A1U*. The rules of the auction are as follows: given her value, each bidder places two bids. Once the four bids are collected, the two units are assigned to the bidder(s) who placed the two highest bids. For any unit acquired, the bidder earns an amount given by the difference between her value and the corresponding winning bid. As in *1A1U*, if a bidder does not obtain any unit, she earns nothing.

In the third treatment, *2A1U*, allotment is introduced by letting the two bidders participate in two identical and simultaneous first-price auctions, each involving a single unit. Apart from this aspect, all other experimental features are identical to those adopted in *1A2U*. Given her value, each bidder places two bids, one in each auction. In each of the two auctions, the highest bid wins the corresponding unit. Earnings are then computed as in *1A2U*.

3.2 Procedures

Upon their arrival, subjects were randomly assigned to a computer terminal. In all sessions, instructions were distributed at the beginning of the experiment and read aloud. Before the experiment started, subjects were asked to answer a number of control questions to make sure that they understood the instructions as well as the consequences of their choices. When necessary, answers to the questions were privately checked and explained. At the beginning of the experiment, the computer randomly formed three rematching groups of six subjects each. The composition of the rematching groups was kept constant throughout the session. At the beginning of every period, subjects were randomly and anonymously divided into pairs. Pairs were randomly formed in every period within rematching groups. Subjects were told that pairs were randomly formed in such a way that they would never interact with the same opponent in two consecutive periods.[5]

In every period, subjects were presented with two consecutive screens. On the first screen, subjects were informed about their private value and were required to place their bids (one in *1A1U*, two in *1A2U* and *2A1U*). On the second screen, each subject was informed about the winning bid(s) as well as her payoff in that period. Payoffs were expressed in points and accumulated over periods. Subjects started the experiment with a balance of 300 points to cover the possibility of losses. At the end of the experiment, the number of points obtained by a subject during the experiment was converted at an exchange rate of 3 euro per 100 points and monetary earnings were paid in cash privately.

The experiment took place at the Experimental Laboratory of the University of Innsbruck in November 2011. Participants were mainly undergraduate students, recruited by using *ORSEE* (Greiner 2004). The experiment was computerized using the *z-Tree* software (Fischbacher 2007). On average, subjects earned 12.00 Euro in sessions lasting 45 minutes (including the time for instructions and payment). Before leaving the laboratory, subjects completed a short questionnaire containing questions on their socio-demographics and their perception of the experimental task.

3.3 Testable predictions: bids, spread and efficiency

In order to derive testable predictions on bidding behavior and efficiency in the three treatments, we develop a simple theoretical framework based on the assumption of risk neutral bidders with standard preferences. Although a systematic violation of risk neutrality has been extensively documented by the economic literature, it still constitutes the standard assumption in models studying the equilibrium properties of different auction formats. Moreover, as discussed in the next pages, the assumption of risk neutrality provides two very intuitive predictions in our experiment, namely equivalence (in terms of bids, total efficiency and auctioneer's revenue) across auction formats, and identical bids in the allotment treatments, *1A2U* and *2A1U*.

In *1A1U*, the item auctioned off has a value V_i for bidder i. Values are private information, but it is commonly known that they are *i.i.d.* random variables with uniform distribution over the interval $[0, \bar{V}]$. After observing her own value, bidder i places her bid, a_i. The item is assigned to the bidder who places the highest bid and the winner pays her bid. Bidder i's payoff is $V_i - a_i$ if she wins the auction and zero otherwise.

In the allotment treatments, *1A2U* and *2A1U*, the two bidders compete for two units: in *1A2U*, the two units are sold in the same auction; in *2A1U*, they are sold separately, in two identical and simultaneous auctions. In both cases, the two units have the same value, v_i,

[5] Our rematching protocol implies that, given the size of the sub-groups (six subjects), on average subjects interacted with the same opponent every 5 periods. Clearly, this is not a perfect stranger design; nevertheless, the protocol leaves very little room for developing bidding strategies over multiple periods. The rematching protocol was intended to increase the number of independent observations and perform non parametric tests to check for robustness of the main parametric results.

to bidder i. Values are private information, but it is commonly known that they are *i.i.d.* random variables with uniform distribution over the interval $[0, \bar{v} = \bar{V}/2]$. Therefore, the sum of the values of the two units, $2v_i$, is uniformly distributed over the interval $[0, \bar{V}]$, just like V_i in *1A1U*.

In *1A2U*, bidder i places two bids, $b_{i,1}$ and $b_{i,2}$, with $b_{i,1} \geq b_{i,2}$ (i.e. $b_{i,1}$ and $b_{i,2}$ are the highest and lowest bids of bidder i, respectively). Four bids are thus collected within a pair, the two highest bids win and are paid by the corresponding bidder(s). Bidder i's payoff is $2v_i - b_{i,1} - b_{i,2}$ if she wins both units, $v_i - b_{i,1}$ if she wins only one unit, and zero otherwise. Notice that $b_{i,1}$, the bidder i's high bid, competes with $b_{j,2}$, the bidder j's low bid. Bidder i wins her first unit if and only if only $b_{i,1} > b_{j,2}$; she also obtains a second unit if and only if $b_{i,2} > b_{j,1}$.

In *2A1U*, bidder i places one bid, $c_{i,1}$, in the first auction and one bid, $c_{i,2}$, in the second. In each auction, the highest bid wins the unit and the corresponding bidder pays it. If bidder i wins both auctions, her payoff is thus $2v_i - c_{i,1} - c_{i,2}$; if she wins only the first (respectively, second) auction, her payoff is $v_i - c_{i,1}$ (respectively, $v_i - c_{i,2}$); if she wins neither auction, her payoff is zero.

Under the assumption of risk neutral bidders, each of the three treatments admits a unique symmetric (Bayes-)Nash equilibrium in pure strategies, which implies the following testable predictions:

H1. **Efficiency and revenue equivalence.** *In all treatments, the units are allocated to the bidder with the highest private value. Thus, on average, the overall surplus is the same across treatments. Finally, in every treatment, the expected overall surplus is split equally between bidders and the auctioneer.*

H2. **Bid equivalence.** *In all treatments, bids are equal to half the value assigned to that unit. Thus, for given private value, bids in* 1A1U *are equal to the sum of the two bids in* 1A2U *and* 2A1U.

H3. **Zero-spread.** *In* 1A2U *and* 2A1U, *bidders place two identical bids for the two units.*

4 Experimental results

We organize our results as follows. First, we investigate differences across treatments in overall efficiency, bidders' surplus and auctioneer's revenue. Second, we compare treatments with respect to the extent of overbidding by looking at both the (sum of the) bids and the proportion of subjects that bid above the risk neutral (*RN*) equilibrium level. Third, focusing on the two treatments with allotment, *1A2U* and *2A1U*, we study bid spreading.

The non parametric tests discussed below are based on 27 independent observations (9 rematching groups per treatment). Similarly, the parametric models presented in the next subsections properly control for dependency of observations over repetitions by either clustering standard errors or introducing random effects at the rematching group level. Moreover, in order to check the robustness of our main findings to repetition effects, we replicated the parametric analysis on different subsets of 5 periods: both the sign and the magnitude of the treatment dummies remain stable across subsets of periods.[6]

[6] Results of these robustness checks are available upon request.

4.1 Efficiency and revenue

Our first result concerns the effects of allotment on the outcome of the auction in terms of total surplus and how this surplus is split between the auctioneer and the bidders.

To investigate this issue, for each pair and in every period, we construct three measures: *(i)* the *relative efficiency*, defined as the ratio between the achieved total surplus and the maximum possible surplus; *(ii)* the *relative auctioneer's revenue*, given by the ratio between the winning bid(s) and the maximum possible welfare; *(iii)* the *relative bidders' surplus*, corresponding to the ratio between the monetary payoff(s) of the winning bidder(s) and the maximum possible surplus. As shown in the previous section, under the assumption of risk neutrality, we should observe no differences in these three measures across treatments.

Table 1 shows summary statistics for the three measures in the three treatments.

[*Table 1* about here]

We observe a loss of (relative) efficiency in all treatments, with this effect being more pronounced in *1A2U*. Indeed, relative efficiency is similar in *1A1U* (0.979) and in *2A1U* (0.975), while it appears lower in *1A2U* (0.957). The efficiency loss in *1A2U* is associated with a reduction in the relative auctioneer's revenue (0.700 in *1A2U*, 0.716 in *2A1U* and 0.737 in *1A1U*), while no appreciable differences in bidders' surplus are detected across treatments.

Table 2 reports estimates from GLS random effects models to compare relative efficiency, relative auctioneer's revenue, and relative bidders' surplus in the three treatments, computed by averaging at the rematching group level.

[*Table 2* about here]

In line with our preliminary observations, the first column of *Table 2* shows that relative efficiency is significantly higher in *1A1U* than in the two allotment treatments, but the second column clarifies that this difference has to be ascribed to the discriminatory auction: relative efficiency is significantly lower in *1A2U* than in *1A1U*, while no significant difference is recorded between the *1A1U* and *2A1U*. The difference in relative efficiency between *1A2U* and *2A1U* is highly significant ($\chi^2(1) = 8.19$, $p < 0.01$).[7] Column (2) also shows that the welfare loss is significant in all treatments. The relative efficiency in *1A1U* (as measured by the constant term) is significantly smaller than one ($\chi^2(1) = 28.43$, $p < 0.01$). Similarly, the measures of relative efficiency in *1A2U* and *2A1U* – expressed by the linear combination of the constant term with the corresponding treatment dummy – are significantly lower than one (in *1A2U*: $\chi^2(1) = 79.58$, $p < 0.01$; in *2A1U*: $\chi^2(1) = 35.95$, $p < 0.01$). The loss in efficiency in all treatments is due to allocative inefficiency: the percentage of winning bids placed by subjects with the lowest private value is 10.67% in *1A1U*, 29.85% in *1A2U*, and 18.04% in *2A1U*.

Moving to the relative auctioneer's revenue, we do not find significant differences between *1A1U* and the two allotment treatments (column (3)). However, when we replace the allotment dummy, *1A2U*&*2A1U*, with two separate treatment dummies, we find both have

[7] In line with these findings, a (two-sided) Mann-Whitney rank-sum test rejects the null hypothesis that the relative efficiency in *1A1U* is the same as that in the two allotment treatments ($z = 2.057$, $p < 0.05$). Similarly, the test detects a significant difference in relative efficiency between *1A2U* and *2A1U* ($z = -2.693$, $p < 0.01$) as well as between *1A1U* and *1A2U* ($z = 2.517$, $p < 0.05$). No significant differences are observed between *1A1U* and *2A1U* ($z = 1.015$, $p = 0.310$).

a negative coefficient, but only that of *1A2U* is significant (column (4)).[8] No statistical difference is detected between *2A1U* and *1A1U* as well as between *2A1U* and *1A2U*.

We find no significant differences in terms of relative bidders' surplus across treatments, either in the regressions (both the coefficients of *1A2U* and *2A1U* in column (6) as well as the estimate of *1A2U&2A1U* in column (5) are not significant; the difference between the coefficients of *1A2U* and *2A1U* in column (6) is not significant: $\chi^2(1) = 0.00$, $p = 0.992$), or by using non parametric tests (according to a two-sided Mann-Whitney rank-sum test, the difference in the relative bidders' surplus between *1A1U* and the treatments with allotment is not significant: $z = -0.463$, $p = 0.643$; similarly, the difference between *1A2U* and *2A1U* is not significant: $z = 0.044, p = 0.965$).

Finally, because of overbidding (see next subsection), in all treatments the relative auctioneer's revenue is greater than the relative bidders' surplus: the null hypothesis that they are equal is always rejected by a (two-sided) Wilcoxon signed-rank test ($z = 2.667$, $p < 0.01$).

R1. **Differences in efficiency and revenue.** *(i) While we observe allocative inefficiency in all treatments, efficiency is higher in* 1A1U *and* 2A1U *than in* 1A2U*. (ii) The auctioneer's revenue is higher in* 1A1U *than in* 1A2U*. (iii) Treatments do not significantly differ in terms of bidders' surplus. (iv) In all treatments the auctioneer's revenue is higher than the bidders' surplus.*

4.2 Overbidding

Figure 1 shows scatterplots of all submitted bids in all periods in the three treatments (for the allotment treatments, the sum of the two bids is reported). The dashed line denotes the theoretical *RN* Nash equilibrium level of (the sum of) the bid(s), while the solid line is the 45° line (bid = value).

[*Figure 1* about here]

We observe overbidding in all treatments. In particular, the proportion of bids above the *RN* level is 89.14% in *1A1U*, 79.38% in *1A2U*, and 83.46% in *2A1U*. A (two-sided) Mann-Whitney rank-sum test rejects the null hypothesis that the average number of periods in which a subject overbids in *1A1U* is the same as in the two treatments with allotments ($z = 2.160$, $p < 0.05$). The previous finding is mainly driven by the comparison between *1A1U* and *1A2U* ($z = 2.075$, $p < 0.05$), whereas the difference between the benchmark and *2A1U* is not significant ($z = 1.634$, $p = 0.102$).

Table 3 reports the probit marginal effect estimates for the probability of overbidding in the three treatments.

[*Table 3* about here]

As shown in column (4), allotment reduces the probability of overbidding. Indeed, the coefficient of *1A2U&2A1U* is negative and highly significant. Column (5) reveals that, compared with *1A1U*, the probability of overbidding in *1A2U* is significantly lower. The treatment effect remains negative, although not significant (according to a two-sided test) in *2A1U*. Finally,

[8] A (two-sided) Mann-Whitney rank-sum test confirms this result as it rejects the null hypothesis that the relative auctioneer's revenues in *1A1U* and *1A2U* are equal ($z = 1.810$, $p = 0.070$).

the difference between the coefficients of *1A2U* and *2A1U* is not significant ($\chi^2(1) = 1.57$, $p = 0.210$).

Moving to the magnitude of overbidding, *Table 4* reports results from parametric panel regressions to study the determinants of the (sum of the) bids in the three treatments.

[*Table 4* about here]

By looking at the first three columns of *Table 4*, the coefficient of *Value* is significantly greater than 0.5 in *1A1U* ($\chi^2(1) = 422.73$, $p < 0.01$), in *1A2U* ($\chi^2(1) = 166.89$, $p < 0.01$) and in *2A1U* ($\chi^2(1) = 317.41$, $p < 0.01$).[9] As indicated by the coefficient of *1A2U&2A1U* in column (4), after controlling for the private value and the linear time trend, allotment significantly decreases the (sum of the) bids. Moreover, when we replace *1A2U&2A1U* with two distinct treatment dummies, we find that both *1A2U* and *2A1U* have the same sign, although (according to a two-sided test) it is significant in *1A2U* only. The difference between the coefficients of *1A2U* and *2A1U* in column (5) is not significant ($\chi^2(1) = 0.38$, $p = 0.539$).[10] As a final observation, the (sum of the) bids significantly decrease(s) over periods as indicated by the coefficient of *Period*.[11] We summarize the previous findings as follows.

R2. **Overbidding.** *(i) In all treatments, subjects bid above the RN equilibrium level. (ii) Bids in* 1A1U *are greater than the sum of the two bids in* 1A2U *and* 2A1U*. This effect is stronger when* 1A1U *is compared with* 1A2U*.*

The above parametric results are robust to different specifications of the econometric model. In particular, results (available upon request) from a Tobit regression (with standard errors clustered at the rematching group level) confirm sign and magnitude of the coefficients reported in *Table 4*.

4.3 Bid spread in *1A2U* and *2A1U*

In contrast with what is predicted by risk neutrality, we find that 84.32% and 75.31% of bids in *1A2U* and *2A1U*, respectively, display bid spread. *Figure 2* illustrates the difference between bids per value in *1A2U* and *2A1U*.

[*Figure 2* about here]

Over all periods, relative to the *RN* level, the magnitude of bid spread is 30.33% in *1A2U* and 29.57% in *2A1U*. In both treatments, the relative spread is significantly greater than 0 according to a (two-sided) Wilcoxon signed-rank test (in both treatments, $z = 2.667$, $p < 0.01$). Moreover, the relative spread exceeds 40% in 29.88% and 30.00% of the offers

[9] This result is confirmed by a (two-sided) Wilcoxon signed-rank test, which rejects the null hypothesis that bids are equal to the *RN* level in the three treatments ($z = 2.666$, $p < 0.01$).

[10] In line with the previous results, a (two-sided) Mann-Whitney rank-sum test strongly rejects the null hypothesis that the average bid in *1A1U* is the same as in the allotment treatments ($z = 2.160$, $p = 0.031$). Again, the negative effect of allotment on bids is stronger when *1A1U* is compared to *1A2U* ($z = 2.075$, $p = 0.038$), rather than when it is compared to *2A1U* ($z = 1.634$, $p = 0.102$ for the two-sided test). We do not find any significant difference between *1A2U* and *2A1U* ($z = -0.574$, $p = 0.566$).

[11] In order to disentangle the intercepts from the effects of repetition, we imposed the linear trend to start from 0 in the first period.

made in *1A2U* and *2A1U*, respectively. Finally, as *Figure 2* makes it clear, the size of the bid spread increases with the bidder's value.

In *Table 5*, we parametrically investigate the determinants of both the size and the probability of bid spread in the two allotment treatments.

[*Table 5* about here]

There is a positive and highly significant correlation between the size of bid spread and the bidder's private value. Interestingly, as shown by the coefficient of *Period* in columns (1), (3) and (5), the size of bid spread either remains stable or increases over periods. This confirms that rather than converging to the level predicted under the assumption of risk neutrality, subjects persistently and intentionally choose to place different bids. As indicated by the coefficient of *2A1U* in column (5), we do not observe significant differences in the size of bid spread between *1A2U* and *2A1U*.[12] By looking at the probit marginal effect estimates in columns (2), (4) and (6), we find that the probability of bid spread positively depends on the assigned value and increases over periods. Finally, column (6) shows that bid spread is more likely to occur in *1A2U* than in *2A1U*.

R3. **Bid spread.** *(i) In the allotment treatments,* 1A2U *and* 2A1U*, we observe a persistent and large-in-size bid spread. The size of bid spread is the same in the two treatments. (ii) The probability of bid spread is higher in* 1A2U *than in* 2A1U*.*

Given the results about overbidding and bid spread, in *Table 6* we look at the size of the two bids in the allotment treatments.

[*Table 6* about here]

Both the highest and the lowest bids observed in *1A2U* and *2A1U* are associated with overbidding. The coefficient of *Value* in columns (1)-(4) is always significantly greater than 0.5 (for the highest bid: $\chi^2(1) = 372.00$, $p < 0.01$ in *1A2U*; $\chi^2(1) = 610.64$, $p < 0.01$ in *2A1U*; for the lowest bid: $\chi^2(1) = 30.39$, $p < 0.01$ in *1A2U*; $\chi^2(1) = 77.52$, $p < 0.01$ in *2A1U*). A (two-sided) Wilcoxon signed-rank test rejects the null hypothesis that the two bids in both treatments are equal to the *RN* level (for the highest and lowest bids in *1A2U* as well the highest bid in *2A1U*: $z = 2.667$, $p < 0.01$; for the lowest bid in *2A1U*: $z = 2.547$, $p = 0.011$). Moreover, by looking at columns (5) and (6), we do not find any significant difference between treatments in both the highest and the lowest bids.

The coefficients of *Value* in the regressions reported in *Table 6* account for the differences in overall bids across auction formats (result *R2*). Indeed, while the coefficients of *Value* in the regressions based on the highest bids in *1A2U* and *2A1U* (columns (1) and (3)) are similar in magnitude to those attached to *Value* in *1A1U* (see *Table 4*, column (1)), the corresponding coefficients in the regressions based on the lowest bids (columns (2) and (4)) are substantially smaller. In other words, in the allotment treatments, subjects make two different bids, both greater than those under risk neutrality; moreover, relative to the value

[12] This result is confirmed by non parametric tests: a (two-sided) Mann-Whitney rank-sum test does not reject the null hypothesis that bid spread in *1A2U* is the same as in *2A1U* ($z = 0.751$, $p = 453$).

of the unit, the size of overbidding associated with the highest bid is similar to that observed in *1A1U*, while the size of overbidding associated with the lowest bid is significantly smaller.[13]

Again, the previous results are robust to different specifications of the econometric model. In particular, Tobit regressions (with standard errors clustered at the rematching group level) produce estimates that are equivalent to those reported in *Table 6*.

The finding that subjects in *1A2U* overbid with both bids represents a remarkable difference with the results of Engelmann and Grimm (2009): in a discriminatory auction similar to our *1A2U*, they find that the lowest bid is, on average, below the *RN* level (underbidding). This discrepancy in results can be due to the different (re)matching protocol used in the two experiments. While the partner matching used in Engelmann and Grimm (2009) can induce subjects to collude over periods and thus to lower bids, the random rematching protocol implemented in our experiment makes collusion (virtually) impossible.

It might be argued that differences in bidding behavior across treatments are due to the fact that *1A2U* and *2A1U* impose an extra cognitive load,[14] as they require subjects to make an additional bid relative to *1A1U*. We formally investigate this issue by using information on the response time spent by subjects to make their choices in each period. In particular, we follow a two-step analysis. First, we parametrically assess the existence of differences in response times across treatments. In this respect, following the same econometric strategy as in *Table 4*, we regress time response on the treatment dummies and a linear time trend. We find that time responses are significantly lower in *1A1U* than in the other two treatments. Moreover, when focusing on the allotment treatments, time responses are higher in *1A2U* than in *2A1U*. This evidence is in line with the idea that choosing bids is more complex in the allotment treatments than in *1A1U*. Second, we replicate the parametric analysis of *Tables 3-5* on pooled data by including the time response as additional determinant of the (sum of the) bids and bid spread. We find that both the size and the probability of bid spread are significantly and positively associated with the response time. Thus, in the allotment treatments, calibrating two different bids requires significantly more time than choosing the same bid for the two units. Nevertheless, the inclusion of the response times as additional determinant of the bidding behavior leaves the coefficients of the treatment dummies virtually unchanged.[15]

[13]We run two additional panel regressions (with clustered standard errors). The dependent variable in the first (second) regression is equal to the unique bid in *1A1U* and to the highest (lowest) bid in the two allotment treatments, *1A2U* and *2A1U*. As controls, both regressions include the allotment dummy, *1A2U&2A1U*, the value of one item and the time trend. The estimate of *1A2U&2A1U* is not significant in the first regression, while it is negative and significant at the 1% level in the second regression.

[14]See Rubinstein (2007) and Piovesan and Wengström (2009) for references on the relationship between response times and economic behaviors.

[15]In an effort to reduce overbidding and bid spread, bidders could be given the option to reconsider their bids in a second stage (see, for instance, Güth et al. 2003, and Porter et al. 2003, for experiments introducing the reconsider option in different contexts). We thank an anonymous referee for addressing this issue. From what we have seen in our analysis, it is not clear whether such an option would be effective. First, our results suggest that cognitive costs are not able to account for the observed treatment effects (see our analysis regarding response time in the Supplementary Material). Second, as mentioned in the paper, we find no indication of learning, as overbidding and bid spread are very similar in early and late periods of the experiment.

5 Discussion

The experimental evidence analyzed in the previous section and summarized by results *R1-R3* clearly contrasts the theoretical predictions derived from the standard model of Nash Equilibrium with risk neutral bidders (see subsection 3.3). What alternative behavioral assumptions are needed to rationalize our evidence? It turns out that it is possible to accommodate all of our experimental results by extending the standard model in three respects:

(A1) bidders' preferences are such that the ratio between the marginal benefit of a higher bid and its marginal cost is, *ceteris paribus*, greater than under risk neutrality;

(A2) bidders' preferences are such that, in the allotment treatments, for equal bids, the marginal utility from winning is strictly decreasing in successive units;

(A3) when an auction has a unique Nash Equilibrium, bidders play their equilibrium strategies; when, instead, an auction has multiple Nash Equilibria, two types of behaviors are possible: *(i)* either a bidder adopts an equilibrium strategy ("equilibrium" bidding), or *(ii)* a bidder believes that the opponent is going to play any of her equilibrium strategies with equal probability and best responds to this belief ("shaky" bidding).

The first two assumptions concern bidders' preferences. The third assumption allows a small departure from equilibrium reasoning when a multiplicity of equilibria exists; as will be discussed later, this departure seems particularly reasonable when coordination is difficult.

Let us first analyze the implications of assumptions (A1) and (A2) on Nash Equilibrium bids. It is straightforward to see that, in equilibrium, assumption (A1) generates overbidding (result *R2*, point *(i)*): equilibrium bids under risk neutrality are such that the ratio between marginal benefit and marginal cost of a higher bid equals one; now, if this ratio is actually greater than one, each bidder will find it worthwhile to bid more aggressively, i.e. to overbid.

Given that, under risk neutrality, overall surplus is maximized and is split equally between bidders and the auctioneer, overbidding has the obvious consequence that, in equilibrium, revenue will be higher than bidders' surplus (result *R1*, point *(iv)*).

Assumption (A2) implies bid spread in the allotment treatments (result *R3*, point *(i)*). To see this, consider *1A2U* first: notice that, in this treatment, if a bidder makes two different bids, her low bid can be winning only if her high bid is winning as well. Therefore, the low bid is intended to win a second additional unit; now, if assumption (A2) holds, this second additional unit has lower marginal benefit than the first; hence, it is optimal to bid less for it. Consider, now, *2A1U*: it can be shown that, if one bidder places a high bid in the first auction and a low in the second, the opponent will find it optimal to do the opposite; but then, the high bid of one bidder will compete with the low bid of the other, which is exactly what happens in *1A2U*. As a consequence, equilibrium bids will be the same in the two treatments with allotment; hence, bidders will make bid spread also in *2A1U* and bid spread will be equal in the two treatments.

Bid spread also explains why efficiency is lower in *1A2U* than in *1A1U* (result *R1*, point *(i)*): in fact, because of bid spread, it is possible that the high bid placed by the bidder with the lowest private value exceeds the low bid of the bidder with the highest private value; in this case, an inefficient allocation will be realized; this is clearly not possible in *1A1U*, where, given that equilibrium bids are increasing, the winner will always be the bidder with highest private value.

The fact that, in the allotment treatments, bidders make bid spread destroys the equivalence between *1A1U* on the one hand and the treatments with allotment on the other. In particular, bids in *1A1U* are, on average, greater than the sum of the two bids in the allotment treatments (result *R2*, point *(ii)*). The intuition is that, under assumption (A2), allotment reduces competition between bidders, very much like unbundling for a monopolist reduces competition across consumers when their willingness to pay for the goods are negatively correlated. This is because in the allotment treatments, the high bid of one bidder, which is intended to get the first unit with a larger marginal benefit, competes with the low bid of the other, which is intended to get the second unit with a smaller marginal benefits. As a consequence, a high bid that is less aggressive would still give a satisfactory probability of winning the (highly valuable) first unit. This anticompetitive effect is absent in *1A1U*.

Result *R2*, point *(ii)* has the obvious implication that the revenue in *1A1U* will be higher than in *1A2U* (result *R1*, point *(ii)*).

As explained above, under assumptions (A1) and (A2), *1A2U* and *2A1U* should be equivalent *in equilibrium* in terms of bids (and bid spread), revenue and efficiency. However, our experimental results indicate that *1A2U* and *2A1U* are not fully equivalent in two respects: first, even though there is no statistical difference in the size of bid spread, the probability of bid spread is lower in *2A1U* (result *R3*, point *(ii)*); second, efficiency is higher in *2A1U* than in *1A2U* (result *R1*, point *(i)*).

By adding assumption (A3), the observed discrepancies between *1A2U* and *2A1U* can be rationalized. Notice that, while *1A1U* and *1A2U* have a unique Nash Equilibrium, in *2A1U* two specular Nash Equilibria exist: one in which the first bidder places a high bid in the first auction and a low bid in the second, and the second bidder makes the opposite; one in which the first bidder places a low bid in the first auction and a high bid in the second, and the second bidder makes the opposite. In other words, bidders have to properly coordinate their bids on one of the two equilibria in a way that, in each auction, the high bid of one bidder competes with the low bid of the other. Assumption (A3) states that, in a situation like this, bidders do not necessarily try to coordinate on one of the equilibria. Rather, shaky bidding is also possible: a shaky bidder is one who believes that there is equal probability that the opponent will play one or the other of her two equilibrium strategies; stated elsewhere, a shaky bidder believes that the opponent is indeed going to play a mixed strategy, in which the pure equilibrium strategies “high bid in the first auction, low bid in the second” and “low bid in the first auction, high bid in the second” are played with equal probabilities. It turns out that the rational response to such a belief is to place the same bid in the two auctions (zero-spread): this common bid will clearly be intermediate between the high and the low bids of the opponent. Hence, the fact that we observe a lower probability of bid spread in *2A1U* than in *1A2U* (result *R3*, point *(ii)*) may be ascribed to the presence in our sample of a (limited but) significant fraction of shaky bidders who respond to the coordination problem in *2A1U* by placing two identical bids.[16]

[16] It is worth emphasizing that shaky bidding behavior in *2A1U* explains the non-equivalence between *1A2U* and *2A1U* in terms of probability of bid spread, not the mere fact that we observe a fraction of zero-spread bids in *2A1U*. In fact, a limited number of zero-spread bids in *2A1U* (and in *1A2U*) is still compatible with Nash Equilibrium. Notice that the claim that, under (A2), Nash Equilibrium bids in *1A2U* and *2A1U* are always characterized by bid spread, holds only when the strategy space is continuous. In a setting like ours, where the space of admissible bids is discrete, equilibrium bids can display zero-spread for low types. In fact, consider a bidder with a very low valuation: in a continuous domain, this bidder will find it optimal to make a positive but small bid spread; but in a discrete domain, this bidder is artificially forced either to make a

The coordination problem in *2A1U* and the shaky bidding behavior that this coordination problem might trigger, can also explain the observed difference between *1A2U* and *2A1U* in terms of efficiency (result *R1*, point *(i)*). To see this, notice that an inefficient allocation emerges whenever the two units are split between the two bidders; this potential situation is magnified in equilibrium, as the high bid of one bidder competes with the low bid of the other. In *2A1U*, however, the possibility that either two equilibrium bidders fail to coordinate (placing their high bids in the same auction) or an equilibrium bidder faces a shaky bidder (who places one common intermediate bid in the two auctions) reduces the probability of an inefficient outcome to emerge. Therefore, the higher efficiency of *2A1U* relative to *1A2U* may be a direct or indirect consequence of the coordination problem in the former treatment.

Finally, it has to be noticed that, according to our experimental results, while we find the auctioneer's revenue to be higher in *1A1U* than in *1A2U*, the level in *2A1U* seems to be in between (although the difference between the treatments is not statistically significant). Shaky bidding behavior could also explain this result. The optimal common bid placed by a shaky bidder in *2A1U*, which is intermediate between the high and the low bid of an equilibrium bidder, will be larger than the average of the two bids. To see this, consider a shaky bidder with a low private value: this bidder will not find it worthwhile to effectively compete with the high bid of the opponent (wherever it is placed), as it would require bidding too aggressively. Hence, this bidder competes only against her opponent's low bid. But the best response to the (equilibrium) low bid of the opponent is essentially a high (equilibrium) bid. Now consider a shaky bidder with a high private value: by placing a bid which is intermediate between the high and low bids, this bidder will have a large (but less than one) probability of winning one unit and a much lower probability of winning both; however, a relatively small increase of her common bid is sufficient to make this bidder win both units. This option would be profitable if the marginal utility from winning the second unit is not too small relative to the marginal utility of winning the first. Therefore, the common bid by the shaky bidder will be closer to the high than to the low bid of the equilibrium bidder; consequently, when a shaky bidder faces an equilibrium bidder, the expected revenue will be larger than when two equilibrium bidders meet. This would explain why the revenue in *2A1U*, where the presence of shaky bidders is significant, may be larger than in *1A2U*.

The experimental evidence supports the hypothesis of shaky bidding behavior as a possible explanation of the difference in efficiency and revenue between *1A2U* and *2A1U*. First, the first two columns of *Table 7* show that bid spread behavior significantly reduces the sum of the bids in *2A1U* (but not in *1A2U*). This confirms the fact that, in *2A1U*, equilibrium bidders (who make bid spread) bid on average less than shaky bidders (who place the same bid in the two auctions).

[*Table 7* about here]

Second, column (3) of *Table 7* shows that the (average) spread reduces the auctioneer's revenue and accounts for the difference between *1A2U* and *1A1U* detected in *Table 2*. Finally, as shown by the last column of *Table 7*, controlling for the (average) spread in the two treatments with allotment also accounts for the difference in relative efficiency observed in

large bid spread or to make no spread at all, and may opt for the latter. *Table 5* confirms that the probability of making zero-spread bids is larger for low valuation bidders. In other words, bid spread signals equilibrium behavior; zero-spread, instead, is consistent both with equilibrium (but only for low valuation bidders) and with shaky bidding behavior.

Table 2 across *1A1U*, *1A2U* and *2A1U* (after controlling for the spread, the difference in relative efficiency between *1A2U* and *2A1U* is not significant, $\chi^2(1) = 0.11$, $p = 0.739$).

Having showed that assumptions (A1)-(A3) are able to rationalize our experimental findings, we finally discuss how reasonable and realistic these assumptions are.

Assumption (A3) admits the possibility that a bidder responds to the coordination problem arising from the presence of multiple equilibria by believing that the opponent is going to play any of her two equilibrium strategies with the same probability. This behavioral hypothesis seems particularly sensible in games in which no element exists that may help bidders coordinate successfully, which is exactly the case in our *2A1U* auction. Notice that traditional payoff-based equilibrium selection criteria like Pareto dominance and risk dominance (see Harsanyi and Selten 1988) are not applicable in our context: in fact, the two equilibria in *2A1U* are characterized by identical payoffs and also deviation costs from one or the other equilibrium are symmetric. In addition, non-payoff-based equilibrium selection criteria do not apply here: there is no reason why one equilibrium of *2A1U* should be more focal than the other. Besides that, the absence of prior communication and the stranger rematching protocol prevents bidders' expectations from converging on one particular equilibrium. Therefore, given the absence of elements that may facilitate successful coordination on one equilibrium or the other, it seems reasonable that a bidder may refrain from trying to coordinate on one particular equilibrium and opt for the strategy that gives her the largest payoff *on average*, should the other bidder play one or the other of her equilibrium strategies.[17]

To substantiate the intuition behind assumption (A3), we analyze shaky bidding behavior in *2A1U* in greater detail. Recall that, while bid spread signals equilibrium behavior, zero-spread is consistent both with equilibrium (but only for low valuation bidders) and with shaky bidding behavior. The first thing to observe is that, in our experiment, a typical bidder places two equal bids in some periods and makes bid spread in others. Indeed, no subject in our experiment placed two equal bids in all 15 periods. On the other hand, the large majority of subjects (78%) did place two equal bids in at least one period. In light of this, one question naturally arises: is there anything in the game that affects the decision of an individual to turn from bid spread to zero-spread bids? The idea behind assumption (A3) is that a shaky bidder is one who intentionally decides to place two equal bids in order to avoid the risk of a coordination failure. Therefore, this type of behavior should arguably arise especially when a bidder has just experienced the negative consequences (in terms of payoffs) of a mis-coordination.

[*Table 8* about here]

Table 8 shows that this intuition appears correct. Columns (1) and (3) focus on those bidders who placed two equal bids in at least 7 out of 15 periods: these are bidders who are likely to be shaky bidders, having chosen the zero-spread strategy with high frequency. Now, the first column shows that the probability of switching from bid spread in one period

[17] The idea behind shaky bidding is thus close to the one behind the concepts of risk dominance. However, while risk dominance is an equilibrium selection criterion, i.e., a player adopts this criterion to choose among her *equilibrium* strategies, shaky bidding behavior applies to *all* the strategies of a player, including strategies that are not part of any Nash Equilibrium. Hence, shaky bidding is a non-equilibrium choice model, similar in spirit to a level-k thinking model (see, e.g., Nagel 1995): in fact, a shaky bidder can be thought of as a level-1 bidder who picks the strategy that is the best response to a (level-0) bidder who randomizes only over bids that are part of a Nash Equilibrium. In the Supplementary Material, we provide a simple 3×3 example to illustrate the workings of the shaky bidding assumption as opposed to traditional equilibrium selection criteria.

to zero-spread in the next increases significantly immediately after a coordination failure: the coefficient of *Mis-coord(t-1)* is positive and significant at the 0.01 level. Interestingly, as revealed by the third column, this effect is mainly driven by those bidders who, because of mis-coordination, lost both items in the previous period. In fact, when we split *Mis-coord(t-1)* in two distinct variables, *Mis-coord(t-1)*lost both* and *Mis-coord(t-1)*won at least one*, only the coefficient of the former is positive and highly significant ($p < 0.01$). This suggests that a bidder will typically turn from equilibrium behavior (bid spread) to shaky bidding (zero-spread) behavior when she experiences the negative consequences of mis-coordination on her payoffs (losing units that could have been obtained otherwise), a conclusion that is in line with the intuition behind our shaky bidding story.

Columns (2) and (4) perform the same analysis but with reference to those bidders who placed two identical bids only occasionally, i.e., in fewer than 7 periods. Notice that, in this subsample, the variables that capture mis-coordination in the previous period are no longer significant; instead, *Value* is highly significant and negative. One possible interpretation of this result is that this subsample does not capture genuinely shaky bidding behavior, but rather, it actually involves equilibrium bidders who place a common bid in the two auctions simply because they have a low valuation.[18]

Are assumptions (A1) and (A2) reasonable and realistic? It turns out that three simple and popular hypotheses proposed by the literature on experimental auctions, although based on different behavioral motives, do indeed satisfy both assumptions: risk aversion, joy of winning and loser's regret.[19]

Risk aversion.[20] (A1) A higher bid increases the probability of winning the object and thus insures the bidder herself against the possibility of losing. For a risk averse bidder, this insurance effect is valuable while it is valueless for a risk neutral one. As a consequence, the ratio between the marginal benefit of a higher bid and its marginal cost is, *ceteris paribus*,

[18]An anonymous referee has proposed the Quantal Response Equilibrium (QRE) has an alternative behavioral assumption to account for the observed difference between *1A2U* and *2A1U*. In fact, despite the fact that *1A2U* and *2A1U* are equivalent in the Nash Equilibrium, out-of-equilibrium payoffs differ across these treatments and this may lead to different QRE. In particular, the coordination risk characterizing *2A1U* would reflect large payoff losses associated with mis-coordinated outcomes, justifying the larger probability of playing the conservative zero-spread strategy. We recognize the sensibleness of this intuition; unfortunately, due to the large dimensionality of our experimental setting, fitting a QRE model to our data is technically unfeasible. We thus keep this idea as a potential subject for future research. It is worth noticing that the QRE concept is a completely different behavioral hypothesis with respect to our shaky bidding story (assumption A3). While QRE keeps the equilibrium condition but relaxes the rationality assumption by admitting that players may play also suboptimal strategies, assumption (A3) retains rationality (shaky bidders do best respond to their beliefs) but relaxes the equilibrium condition (shaky bidders' beliefs, though sensible, are incorrect). Notice also that the evidence presented in *Table 8*, which, in our view, sheds light on the motives underlying shaky bidding behavior, would hardly be reconciled with a pure QRE hypothesis.

[19]For a formal discussion, see the Supplementary Material, where we characterize equilibrium bids under risk aversion, joy of winning and loser's regret. We also provide empirical insight on the relevance of the hypothesis of risk aversion and joy of winning/loser's regret by combining subjects' bids with the information collected through the post-experiment questionnaire. Results show that the proportions of subjects that either reported to be risk averse or gave importance to winning increase with overbidding, thus confirming that the behavioral hypothesis considered may indeed be relevant.

[20]The vast experimental literature on auctions (for an overview, see Kagel 1995; Kagel and Levin 2011) shows that risk aversion is undoubtedly an important factor in explaining deviations from the theoretical *RN* equilibrium; at the same time, it is clear that other behavioral elements may play a role. Kirchkamp et al. (2010), using a novel experimental design that manipulates bidders' risk preferences through the number of income-relevant auctions, show that risk preferences explain overbidding by about 50%.

greater for the former. (A2) Risk aversion implies that the utility function is strictly concave; hence, in the allotment treatments, for equal bids, the marginal utility of winning an additional second unit is strictly lower than the marginal utility from winning the first unit.

Joy of winning. The joy of winning hypothesis states that bidders get a positive benefit from the mere fact of winning.[21] (A1) For a bidder who enjoys winning, the actual benefit from winning any item is greater than the simple difference between value and bid as it incorporates the extra-benefit from winning. Hence, with respect to a risk neutral bidder, the marginal benefit of a higher bid is larger. (A2) In the allotment treatments, if the extra-benefit from winning is decreasing in successive units (see Grimm and Engelmann 2005), the actual value that a bidder attaches to the first unit is higher than the actual value of the second.[22]

Loser's regret. Loser's regret (or missed-opportunity-to-win regret) is based on the idea that a losing bidder who discovers that the winning bid was indeed below her valuation for the good will realize that she could have won the auction at a profitable price and thus will regret not having bid higher.[23] (A1) For a bidder with loser's regret, the actual benefit from winning any item is greater than the simple difference between value and bid as it avoids the loss of utility (regret) possibly associated with losing. Hence, with respect to a risk neutral bidder, the marginal benefit of a higher bid is larger. (A2) In the allotment treatments, it is reasonable to assume that the regret associated with missing the opportunity to win one unit is larger when no other unit has been won than when another unit has been obtained anyway. In this case, the marginal benefit from winning the second unit would be lower, since a second unit can be won only when a first unit has already been won.[24]

Clearly, the three behavioral hypothesis considered above are not the only ones who fit assumptions (A1) and (A2). Consider, for example, social preferences in the form of fairness and inequity aversion (Fehr and Schmidt 1999; Bolton and Ockenfels 2000). For a bidder who is inequity averse, in the allotment treatments winning one unit only would minimize the utility loss caused by an unfair outcome; hence, the marginal utility from winning would be

[21]Cox et al. (1988), Goeree et al. (2002), Grimm and Engelmann (2005), Cooper and Fang (2008), among others, argue that joy of winning may explain deviations from the RN equilibrium in experimental auctions. Joy of winning has also found increasing support from recent studies in neuroscience and psychology, according to which placing subjects into competitive environments can trigger a desire to win (see Delgado et al. 2008, and Malhotra 2010, both adopting an auction setup). In the literature, joy of winning has sometimes been modeled as a fixed extra-benefit that, upon winning the auction, adds to the difference between value and price (see, e.g., Cooper and Fang 2008, and Roider and Schmitz 2012), sometimes as a bonus proportional to the value of the object won (see Grimm and Engelmann 2005). In the Supplementary Material, where we formally analyze a joy of winning model, we follow the former, more popular, modeling strategy.

[22]Notice that, even though in our *2A1U*, two auctions take place, they are run simultaneously: hence, a bidder views them as a single auction game where two units are sold. Notice also that assuming that, *within* an auction game where two units are sold, the joy of winning is decreasing in successive units, does not imply that it decreases from one auction game to the next. Rather, our idea is that, when a bidder enters a new auction game, the extra-value of winning jumps back to the initial value, even though that bidder won some units in the previous periods.

[23]Engelbrecht-Wiggans and Katok (2008, 2009) and Filiz-Ozbay and Ozbay (2007) show that loser's regret induce bidders to overbid to prevent regret in case they do not win the auction. Recently, Roider and Schmitz (2012) show that joy of winning and loser's regret (which they call "disutility of losing") together are able to rationalize much of the existing experimental evidence on single-unit auctions.

[24]The literature has identified a second type of regret in auctions, called winner's (or money-left-on-the-table) regret: this occurs when the winner in an auction realizes he could have won anyway with a lower bid. Notice that this second type of regret does not fit into the class of preferences identified by assumptions (A1) and (A2) as it surely violates the first.

strictly decreasing in successive units (assumption (A2)). Moreover, if the utility loss associated with an unfair outcome is larger when the individual is behind than when she is ahead, a higher bid would, *ceteris paribus*, be associated with a larger marginal benefit/marginal cost ratio than under risk neutrality as it reduces the probability of suffering the (largest) efficiency loss associated with winning nothing (assumption (A1)). Similarly, consider preferences characterized by loss aversion with reference dependence and suppose, in the spirit of Köszegi and Rabin (2006), that the reference point reflects an expectation of the bidder about the likely outcome of the auction. In the allotment treatments, where two units are sold, a bidder could reasonably expect to part with the auction with one unit. But then, again, the marginal utility from winning the first unit would be larger than the second as it would avoid losses (assumption (A2)). Moreover, if the bidder expects to obtain an "average" win also in *1A1U*, a higher bid would, *ceteris paribus*, be associated with a larger marginal benefit/marginal cost ratio than under risk neutrality as it reduces the probability of suffering a loss (assumption (A1)).[25]

It might be questioned whether risk aversion, joy of winning and loser's regret, which are indeed credible explanations within the lab, are still relevant in real-world large-stake auctions, like those for the sale of high-valued assets (licenses, treasury bills) or for the procurement of works. That even firms may display a risk averse behavior has been shown empirically by Athey and Levin (2001) in an auction setting and by Kawasaki and McMillan (1987), Asanuma and Kikutani (1992), Yun (1999) in subcontracting relations. In a recent experimental paper, List and Mason (2011) show that CEOs exhibit risk aversion.

As far as joy of winning and loser's regret is concerned, one should abstract away from their literal meaning and interpret these hypothesis in light of assumptions (A1) and (A2) above. These two conditions, applied to joy of winning and loser's regret, can be rephrased as follows: (A1) there is a latent factor which, upon winning the auction, increases the actual payoff of a bidder (beyond the simple difference between value and price) or, upon losing the auction, generates a strictly negative payoff; (A2) when the auction involves multiple units, the marginal relevance of this factor decreases in the number of units obtained by the bidder. In light of this more general interpretation, we can imagine several unobservable factors that may have the above effects also in large-stake real world auctions. For example, winning a license or obtaining an important procurement contract may have a positive reputation effect on the firm, that can translate into higher profits in the future or in other markets in which the firm is operating. Also, it can increase the bargaining power of the firm or generating a learning by doing effect or increase the probability of accessing to future business opportunities. Similarly, losing a procurement contract may generate (opportunity) costs in terms of excess capacity. These effects are likely to become less relevant as more and more licenses/contracts are obtained by the firm.

6 Conclusion

Although economists and practitioners have long recognized the pro-entry effects of allotment in auctions, how bidders actually respond to the presence of multiple units remains a not fully

[25]We thank two anonymous referees for pointing out these two additional behavioral hypothesis. In the Supplementary Material, we formally show that simple models incorporating these hypothesis generate the same predictions as those obtained under joy of winning and loser's regret. Notice, however, that, if the bidder's reference point were the status quo, loss aversion would never bite and assumptions (A1) and (A2) would not be satisfied.

addressed question.

This paper reports results from a laboratory experiment designed to shed light on the effects of allotment – moving from a single-unit to multiple-unit auctions – on bidders' behavior, efficiency and revenue. To this end, we compared three treatments: a first-price auction in which two units are sold as a single bundle; a two-unit discriminatory auction; two simultaneous first-price single-unit auctions. The experiment has been designed so that the standard theory of risk neutral bidders gives the same equilibrium predictions in the three treatments: allotment (and the allotment format chosen) should play no role.

Our main result is, however, that allotment in the form of a discriminatory auction produces, relative to bundling, a substantial loss in efficiency and revenue. This effect has to be ascribed to a persistent tendency of subjects to place different bids for the two units auctioned. This tendency is prevalent also when the two units are sold through simultaneous auctions; however, in this format, a significant fraction of bidders makes the same bid in the two auctions, and this reduces the efficiency loss relative to the bundle auction.

Our experimental results strongly reject the prediction of perfect equivalence of the three treatments implied by the standard model of Nash Equilibrium with risk neutral bidders. By simply extending the risk neutrality hypothesis in two respects – namely that *(i)* bidders gain a benefit from winning the auction on top of the assigned monetary values, and *(ii)* this benefit decreases with the number of units acquired – and by identifying a rational but non-equilibrium response by bidders to the coordination problem arising when two simultaneous auctions are run in parallel, we were able to successfully rationalize our experimental evidence. Interestingly, we identified three popular behavioral explanations – risk aversion, joy of winning and loser's regret – that are built on these general features of bidders' preferences; disentangling across such alternative behavioral explanations surely represents a promising field for future research.

The interpretation of our results in terms of general preference features provides relevant insight that can be extended to other market design settings. In particular, one of the main implications of these features is that allotment uncovers a tendency of bidders to differentiate their bids, making it possible an outcome in which the units are split across bidders. In settings, like ours, where this outcome is not desirable, auction formats that inhibit the possibility (e.g., a bundle auction) or limit the successfulness (e.g., running simultaneous auctions) of a bid spread strategy are preferable. When, instead, a splitted allocation of the units across bidders is to be pursued, the choice of the market designer should favor those formats (e.g., a discriminatory auction) that support the tendency of differentiating bids. Consider, for example, a situation in which valuations are strictly decreasing. In this case, splitting units across bidders is often the efficient allocation. This outcome is prevented in a bundle auction and, therefore, a discriminatory auction would be preferable. However, under risk neutrality, even the discriminatory auction is not fully efficient, as the difference between the bids placed by a bidder is smaller than the difference between the corresponding valuations (see Engelbrecht-Wiggans and Kahn 1998b); in other words, there is less bid spread than it is optimal. The tendency of differentiating bids identified in this paper should amplify the spread with respect to risk neutrality, thus making the discriminatory auction very close to achieve full efficiency. Investigating different market settings would represent a natural strategy to test the validity of our preference-based explanation of bidders' response to allotment.

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A Figures and Tables

Table 1. Relative efficiency: summary statistics

	RE	*RAR*	*RBS*
1A1U	0.979	0.737	0.241
	(0.046)	(0.123)	(0.133)
1A2U	0.957	0.700	0.257
	(0.054)	(0.092)	(0.112)
2A1U	0.975	0.716	0.256
	(0.041)	(0.097)	(0.102)
Obs.	405	405	405

Notes. This table reports summary statistics (mean and - in parentheses - standard deviations) at the rematching group level in the three treatments.

Table 2. Relative efficiency in *1A1U*, *1A2U* and *2A1U*

	RE		*RAR*		*RBS*	
	(1)	(2)	(3)	(4)	(5)	(6)
1A2U&2A1U	-0.013^{**}		-0.029		0.012	
	(0.006)		(0.018)		(0.018)	
1A2U		-0.022^{***}		-0.037^{*}		0.016
		(0.006)		(0.022)		(0.021)
2A1U		-0.004		-0.021		0.008
		(0.006)		(0.021)		(0.021)
Period	0.002^{***}	0.002^{***}	-0.005^{***}	-0.005^{***}	-0.006^{***}	-0.006^{***}
	(0.001)	(0.001)	$(7.3 * 10^{-4})$	$(7.3 * 10^{-4})$	$(8.0 * 10^{-4})$	$(8.0 * 10^{-4})$
Constant	0.968^{***}	0.968^{***}	0.768^{***}	0.768^{***}	0.211^{***}	0.212^{***}
	(0.006)	(0.006)	(0.016)	(0.016)	(0.016)	(0.016)
$Wald - \chi^2$	12.70	22.17	54.93	55.10	55.15	55.32
$p > \chi^2$	0.002	0.000	0.000	0.000	0.000	0.000
Obs.	405	405	405	405	405	405

Notes. This table reports coefficient estimates from GLS models - with weights in columns (3 - 6) - that include random effects at the rematching group level. The dependent variable in columns (1) and (2), is the mean of the relative efficiency of the rematching group in the period. The dependent variable in columns (3) and (4), is the mean of the relative auctioneer's revenue of the rematching group in the period. The dependent variable in columns (5) and (6), is the mean of the relative bidders' surplus of the rematching group in the period. *Period* is a linear time trend that starts from 0 in the first period of the experiment. *1A2U* and *2A1U* are treatment dummies. *1A2U&2A1U* is a dummy that takes value of 1 if the treatment is either *1A2U* or *2A1U*.

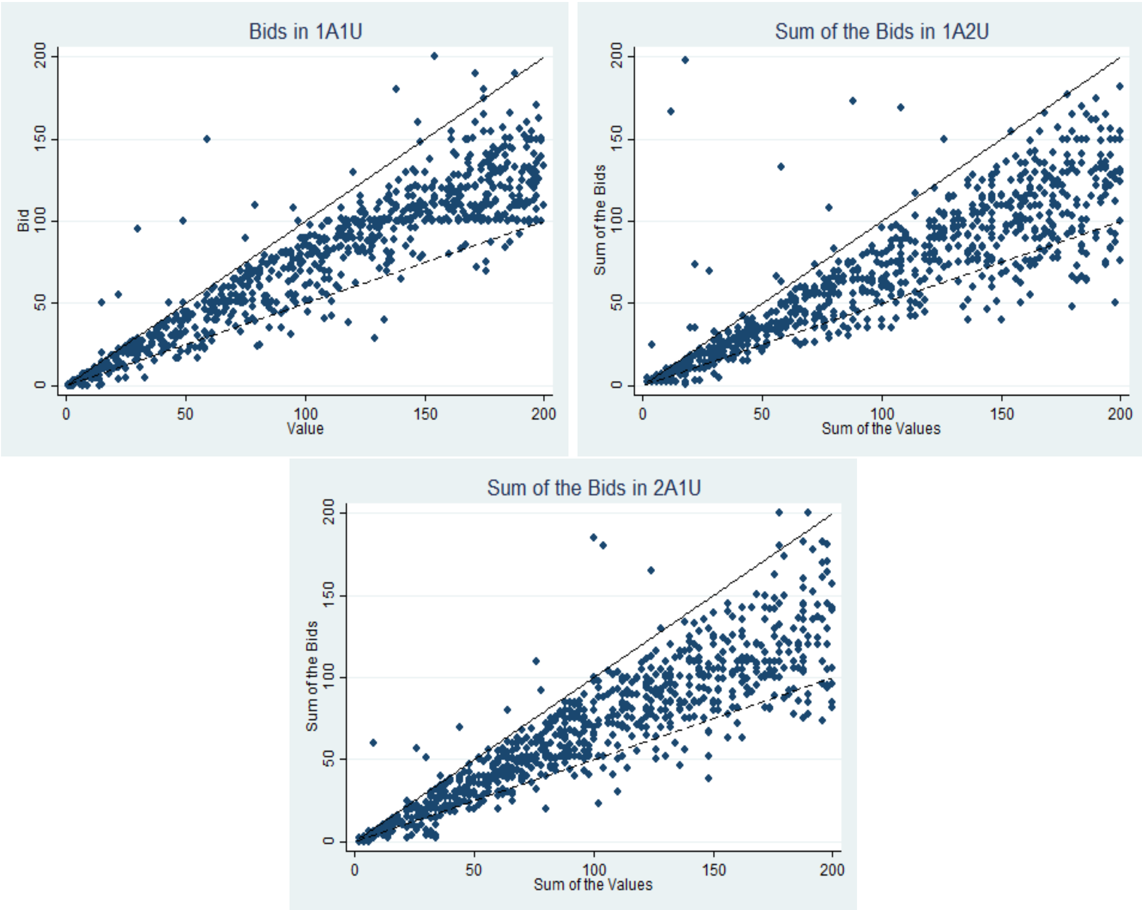

Figure 1 – (Sum of the) bids in *1A1U*, *1A2U* and *2A1U*.

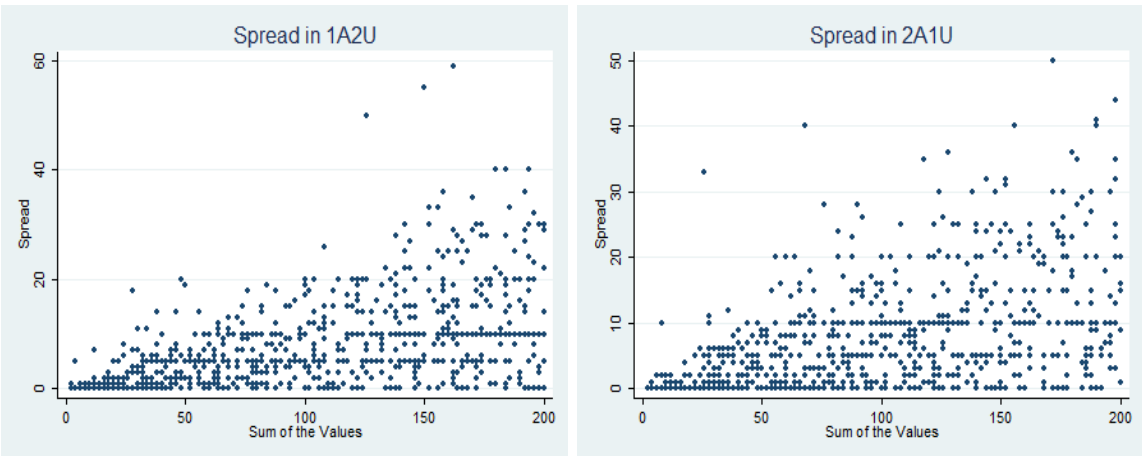

Figure 2 – Bid spread in *1A2U* and *2A1U*.

Table 3. Probability of overbidding in *1A1U*, *1A2U* and *2A1U*

	1A1U	*1A2U*	*2A1U*	*Pooled*	
	(1)	(2)	(3)	(4)	(5)
Value	0.001^{***}	0.001	0.001^{***}	0.001^{***}	0.001^{***}
	$(1.8 \cdot 10^{-4})$	(0.001)	$(1.8 \cdot 10^{-4})$	$(2.2 \cdot 10^{-4})$	$(2.2 \cdot 10^{-4})$
Period	-0.002	$1.7 \cdot 10^{-4}$	-0.003	-0.002	-0.002
	(0.003)	(0.004)	(0.002)	(0.002)	
1A2U&2A1U				-0.076^{***}	
				(0.028)	
1A2U					-0.109^{***}
					(0.032)
2A1U					-0.062
					(0.046)
lpl	-245.882	-407.405	-350.385	-1016.305	-1013.195
$Wald - \chi^2$	41.42	2.92	61.14	36.22	46.69
$p > \chi^2$	0.000	0.232	0.000	0.000	0.000
Obs.	810	810	810	2430	2430

Notes. This table reports probit marginal effect estimates (robust standard errors clustered at the rematching group level in parentheses) over all periods. Columns (1)-(3) consider the three treatments, separately. Regressions in columns (4) and (5) are based on pooled data. The dependent variable is a dummy that takes a value of 1 if the (sum of the) bid(s) of the subject in the period is associated with over-bidding. *Value* is the (sum of the) private value(s) assigned to the subject in the period. *Period* is a linear time trend that starts from 0 in the first period of the experiment. *1A2U* and *2A1U* are treatment dummies. *1A2U&2A1U* is a dummy that takes value of 1 if the treatment is either *1A2U* or *2A1U*. Estimates remain unchanged when *Period* is excluded from the regressions. Significance levels are denoted as follows: $^{*}: p < 0.1$; $^{**}: p < 0.05$; $^{***}: p < 0.01$.

Table 4. (Sum of the) Bids in *1A1U*, *1A2U* and *2A1U*

	1A1U	*1A2U*	*2A1U*	*Pooled*	
	(1)	(2)	(3)	(4)	(5)
Value	0.681^{***}	0.633^{***}	0.659^{***}	0.658^{***}	0.658^{***}
	(0.009)	(0.010)	(0.009)	(0.005)	(0.005)
Period	-0.494^{***}	-0.640^{***}	-0.800^{***}	-0.649^{***}	-0.649^{***}
	(0.117)	(0.135)	(0.111)	(0.070)	(0.070)
1A2U&2A1U				-4.367^{***}	
				(2.120)	
1A2U					-5.128^{**}
					(2.478)
2A1U					-3.606
					(2.479)
Constant	7.689^{***}	8.496^{***}	8.423^{***}	11.145^{***}	11.141^{***}
	(2.248)	(2.316)	(2.180)	(1.884)	(1.904)
lrl	-3361.717	-3488.945	-3333.645	-10208.017	-10206.006
$Wald - \chi^2$	6014.09	3784.23	5430.88	14722.16	14721.77
$p > \chi^2$	0.000	0.000	0.000	0.000	0.000
Obs.	810	810	810	2430	2430

Notes. This table reports coefficient estimates (standard errors in parentheses) from two-way linear random effects models over all periods accounting for both potential individual dependency over repetitions and dependency within rematching group. The dependent variable is the (the sum of the) bid(s) placed by the subject in the period. The other remarks of *Table 3* apply.

Table 5. Bid spread in *1A2U* and *2A1U*

	1A2U		*2A1U*		*Pooled*	
	Size	*Prob.*	*Size*	*Prob.*	*Size*	*Prob.*
	(1)	(2)	(3)	(4)	(5)	(6)
Value	0.071^{***}	0.002^{***}	0.068^{***}	0.003^{***}	0.070^{***}	0.002^{***}
	(0.004)	$(2.6 \cdot 10^{-4})$	(0.004)	$(3.5 \cdot 10^{-4})$	(0.003)	$(2.1 \cdot 10^{-4})$
Period	0.055^{***}	0.007^{***}	0.117^{***}	0.008^{***}	0.086^{***}	0.007^{***}
	(0.049)	(0.003)	(0.050)	(0.003)	(0.035)	(0.002)
2A1U					-0.101	-0.084^{**}
					(0.794)	(0.036)
Constant	0.096		-0.215		-0.012	
	(0.726)		(0.853)		(0.663)	
lrl (lpl)	-2653.633	-314.564	-2678.307	-401.947	-5327.147	-716.958
$Wald - \chi^2$	367.03	27.59	294.99	109.54	659.62	96.19
$p > \chi^2$	0.000	0.000	0.000	0.000	0.000	0.000
Obs.	810	810	810	810	1620	1620

Notes. Columns (1), (3) and (5) report coefficient estimates (standard errors in parentheses) from two-way linear random effects models over all periods accounting for both potential individual dependency over repetitions and dependency within rematching group. The dependent variable in these regression is the absolute value of the difference of the two bids placed by the subject in the period. Columns (2), (4) and (5) report Probit marginal effect estimates (robust standard errors clustered at the rematching group level in parentheses) over all periods. The dependent variable is a dummy that takes a value of 1 if the subject places two different bids in the period. The other remarks of *Table 3* apply.

Table 6. Highest and lowest bids in *1A2U* and *2A1U*

	1A2U		*2A1U*		*Pooled*	
	Highest	*Lowest*	*Highest*	*Lowest*	*Highest*	*Lowest*
	(1)	(2)	(3)	(4)	(5)	(6)
Value (1 unit)	0.704***	0.562***	0.728***	0.592***	0.715***	0.576***
	(0.011)	(0.011)	(0.009)	(0.010)	(0.007)	(0.008)
Period	−0.292***	−0.348***	−0.342***	−0.459***	−0.317***	−0.403***
	(0.069)	(0.074)	(0.057)	(0.064)	(0.045)	(0.049)
2A1U					0.683	0.785
					(1.206)	(1.401)
Constant	4.304***	4.195***	4.110***	4.311***	3.885***	3.887***
	(1.133)	(1.289)	(1.071)	(1.309)	(0.973)	(1.116)
lrl	−2945.333	−3006.303	−2795.9459	−2891.461	−5752.116	−5903.973
$Wald - \chi^2$	4444.91	2475.37	6213.57	3261.75	10314.65	5610.32
$p > \chi^2$	0.000	0.000	0.000	0.000	0.000	0.000
Obs.	810	810	810	810	1620	1620

Notes. This table reports report coefficient estimates (standard errors in parentheses) from both two-way linear random effects model over all periods accounting for both potential individual dependency over repetitions and dependency within rematching group. The dependent variable in columns (1), (3) and (5) is the highest bid of the subject in the period. The dependent variable in columns (2), (4) and (6) is the lowest bid of the subject in the period. *Value (1 unit)* refers to the private value assigned to one unit, only. All other remarks of *Table 3* apply.

Table 7. Bid spread and efficiency

	Sum of Bids		*RAR*	*RE*
	1A2U	*2A1U*		
	(1)	(2)	(3)	(4)
Spread dummy	1.297	-2.545^{*}		
	(1.921)	(1.409)		
1A2U			-0.010	0.001
			(0.026)	(0.011)
2A1U			0.019	-0.004
			(0.026)	(0.010)
*1A2U*Spread_avg*			-0.004^{**}	-0.003^{**}
			(0.002)	(0.001)
*2A1U*Spread_avg*			-0.005^{***}	$-0.45 * 10^{-4}$
			(0.002)	(0.001)
Value	0.631^{***}	0.666^{***}		
	(0.011)	(0.010)		
Period	-0.649^{***}	-0.783^{***}	-0.005^{***}	0.002^{***}
	(0.136)	(0.111)	(0.001)	(0.001)
Constant	7.684^{***}	9.596^{***}	0.768^{***}	0.968^{***}
	(2.611)	(2.266)	(0.016)	(0.006)
lrl	-3487.146	-3330.756		
$Wald - \chi^2$	3782.20	5453.32	66.47	31.27
$p > \chi^2$	0.000	0.000	0.000	0.000
Obs.	810	810	405	405

Notes. Columns (1) and (2) perform the same econometric approach as in *Table 2* to analyze the determinants of the sum of the bids in *1A2U* and *2A1U*. Column (3) and (4) perform the same econometric approach as in *Table 5* to analyze the determinants of relative auctioneer's revenue and relative efficiency in the three treatments. *Spread dummy* is a dummy that takes value equal to 1 if the subject places two different bids in the period. *1A2U*Spread_avg* (*2A1U*Spread_avg*) is the interaction between *1A2U* (*2A1U*) and the average spread of the rematching group in the period. All other remarks of *Table 2* and *Table 5* apply.

Table 8. Shaky bidding and mis-coordination in *2A1U*

	(1)	(2)	(3)	(4)
	0-spr. ≥ 7	*0-spr.* < 7	*0-spr.* ≥ 7	*0-spr.* < 7
Value	-0.001^{*}	-0.001^{***}	-0.001^{*}	-0.001^{***}
	(0.001)	$(2.4 * 10^{-4})$	(0.001)	$(2.3 * 10^{-4})$
Period	0.009^{**}	-0.002	0.009^{**}	-0.002
	(0.004)	(0.002)	(0.004)	(0.002)
Mis-coord(t-1)	0.199^{***}	0.030		
	(0.060)	(0.033)		
*Mis-coord(t-1)*lost both(t-1)*			0.368^{***}	0.001
			(0.104)	(0.048)
*Mis-coord(t-1)*won at least one(t-1)*			0.053	0.055
			(0.136)	(0.034)
lpl	-70.075	-159.369	-69.039	-158.411
$Wald - \chi^2$	21.50	24.54	41.21	31.30
$p > \chi^2$	0.000	0.000	0.000	0.000
Obs.	168	588	168	588

Notes. This table reports probit marginal effect estimates (robust standard errors clustered at the rematching group level in parentheses) over all periods to analyze the determinants of zero-spread bidding in *2A1U*. The dependent variable is a dummy that equals 1 if *(i)* that bidder made zero-spread bids in period *t*, and *(ii)* that bidder made bid spread in period *t-1*. *Mis-coord(t-1)* is a dummy that equals 1 if, in period *t-1*, *(i)* that bidder and her opponent made bid spread, but *(ii)* they mis-coordinated their bids. *Mis-coord(t-1)*lost both(t-1)* (*Mis-coord(t-1)*won at least one(t-1)*) is obtained by interacting *Mis-coord(t-1)* with a dummy that equals 1 if, in period *t-1*, that bidder lost both items (won at least one item). Regressions reported in columns (1) and (3) (columns (2) and (4) are performed on the subsample of subjects who made zero-spread bids in at least (less than) 7 periods. All other remarks of *Table 3* apply.