

Prize Scarcity and Bidding Behavior in All-Pay Contests with Multiple Prizes

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Abstract

We compare bidding behavior in complete information all-pay contest experiments that vary in the number of prizes and number of players. We confirm the observation from many prior single prize all-pay auction experiments that overbidding relative to equilibrium predictions is common. Our primary results are that increasing the number of prizes and players proportionally does not reduce the amount of overbidding but increasing the number of prizes while holding the number of players constant eliminates overbidding. We conclude that the overbidding phenomenon is related to the scarcity of the prize.

Keywords: All-pay contest; auction; experiment; Nash-equilibrium; overbidding
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1 Introduction

All-pay contests in which players must exert costly effort or commit resources in an attempt to win a prize are a fundamental aspect of modern society. Examples of these contests include R&D contests, academic grant writing, elections, lobbying, and sales among others. A common feature of these particular examples is that these contests often award several prizes, one to each of the “best” contestants.¹ Furthermore, these prizes are often awarded deterministically. For example, in an R&D contest, rather than simply being more likely to go to the better proposals, the prizes are awarded with certainty to the most valuable innovations. Thus, these are examples of multi-prize all-pay auctions. There is a vast literature studying such contests, and significant divergence of behavior from theoretical predictions has been observed in experiments (Dechenaux et al., 2014). Despite the prominence of the aforementioned contests, however, there have not been any experimental tests of behavior in multi-prize all-pay auctions. In this paper, we provide such a test, varying both the number of players and number of prizes in an all-pay auction. In doing so, we are able to properly observe and test a novel explanation for the disparity between theory and behavior: the scarcity of the prize, that is, the proportion of prizes to players. Our experiments reveal that the scarcity of the prize is largely responsible for the amount of overbidding in contests, which is the most commonly observed behavioral phenomenon in previous experimental studies. In particular, we find that when the proportion of prizes to players is 1 in 3, there is significant overbidding, while there is significant underbidding when this proportion is 2 in 3. These results further demonstrate that overbidding is not restricted to single prize contests.

The theoretical setting on which we focus is that of an all-pay auction with multiple prizes, complete information, and a continuous strategy space. Baye et al. (1996) and Siegel

¹For example, funding agencies like NSF typically make more than one award and local elections such as school boards often have more than one winner. Multiple prizes are also common in the world of sports. For example, golf tournaments award prize money to all golfers who “make the cut” and the Olympics awards medals to the top three performers.

(2009) describe Nash equilibrium predictions for these auctions with one or more prizes. All equilibria are in mixed strategies, and multiple equilibria are common for many specifications of these auctions. While the existence of multiple equilibria typically leads to difficulty in comparing the theoretical predictions with observed predictions, these papers show that there is a revenue equivalence across all equilibria. That is, the average revenue generated by the auction is equal to the total prize value. Moreover, when players are identical, there is only one symmetric equilibrium. These facts provide two avenues via which we may compare the behavior of our subjects with the existing theory.

Our experiments are designed to compare bidding behavior in a single prize all-pay auction with behavior in multiple prize all-pay auctions with the same and with less prize scarcity. Our goal is to examine how closely bidding behavior matches with Nash equilibrium predictions and also to determine whether the well-known pattern of over-dissipation of rents persists as the number of prizes increases. We consider two ways of modifying the number of prizes. First, we increase the number of prizes while holding the number of players and the total prize value constant, thus decreasing the scarcity of the prize. Second, we increase both the number of prizes and the number of players but keeping the proportion constant, thus holding the scarcity of the prize constant. While we have no *a priori* hypothesis about whether multiple prizes will reduce over-dissipation, this treatment allows us to test whether over-bidding is intrinsically tied to the single prize format in the previous literature or whether it persists with multiple prizes.

A single prize all-pay auction with three bidders serves as our baseline treatment. Our results from these experiments confirm that over-dissipation is prevalent in single prize all-pay auctions. We also conducted experiments with three subjects bidding for two prizes, each of half the value of the baseline to maintain revenue equivalence with the baseline treatment. We find that with a reduction in prize scarcity, the over-dissipation is eliminated and average bids are lower than the Nash equilibrium predictions. Finally, we conducted

experiments with six subjects bidding for two prizes and find that over-dissipation occurs to a similar extent as in the baseline. Our primary conclusion is that over-dissipation is sensitive to the competitiveness of the auction and the scarcity of the prize. When the prize to bidder ratio is sufficiently high, over-dissipation is eliminated.

Beginning with Davis and Reilly (1998) and Potters et al. (1998), there have been a number of experiments conducted to study bidding behavior in all-pay contests with complete information. One common feature of all of the experiments in this literature is that the auctions only award a single prize to the highest bidder. Auctions with complete information and multiple prizes have been studied in experiments with Tullock contests (for example, see Sheremeta, 2011 and Shupp et al., 2013), but not in an all-pay auction framework where the highest bidders win for sure.² The all-pay auction framework is preferable for situations in which, given the actions of the other players, an agent can identify a best response strategy that wins for sure. For example, consider the allocation of concert or sports tickets to the fans who are closest to the front of the line. When concert tickets go on sale, if everyone values the concert ticket and their time equally, then the best response, given everyone else's arrival time, is to arrive at the line just before the k -th other person, assuming there are k tickets.³

Despite minor differences in experimental design, one pervasive feature of the majority of complete information all-pay auction experiments is over-dissipation of rents, meaning the revenue of the auction exceeds equilibrium predictions (Dechenaux et al., 2014). For example, Davis and Reilly (1998), Gneezy and Smorodinsky (2006), Ernst and Thoni (2013), and Lugovskyy et al. (2010) all report overbidding in some or all of their treatments.⁴ Overbid-

²See Barut et al. (2002) for a study with multiple prize all-pay auctions with incomplete information.

³On the other hand, a Tullock contest is preferable if there is an element of luck or uncertainty regarding the outcome. For example, most sports competitions involve an element of chance in addition to effort and talent and so are better modeled as Tullock contest. In war, while having a greater number of troops can increase the odds of winning, it is not necessarily the case that having more troops will ensure victory.

⁴For additional experiments on complete information all-pay auctions, see Klose and Kovenock (2015), Fehr and Schmid (2014), and Chen et al. (2015).

ding has also been reported in all-pay auctions with incomplete information (Barut et al., 2002 and Noussair and Silver, 2006) and in Tullock contests (see Sheremeta, 2013 for a review).

It is interesting to note that in two instances of all-pay auctions with two bidders competing for one prize, overbidding has not been observed (Potters et al., 1998 and one treatment of Ernst and Thoni, 2013). In the experiments that do find overbidding, there are three or more bidders competing for the prize. These findings lead to a hypothesis that bidding behavior is sensitive to prize scarcity - that more people competing for the prize leads to greater over-dissipation. Our findings suggest that this hypothesis is in fact true.

The remainder of the paper proceeds as follows. In the next section, we review the theory of all-pay auctions and describe our experimental design. In Section 3, we present the results of our analysis of the experiments. Section 4 concludes.

2 Theory and Experimental Design

There are n players competing for one of $m < n$ identical prizes with common value R . All players i simultaneously submit a bid b_i , then prizes are awarded to the m players with the highest bids. Ties are resolved by distributing the contested prizes between the tied bidders uniformly at random. Given the profile of bids $b = (b_1, b_2, \dots, b_n)$, let $\#H_i(b)$ and $\#M_i(b)$ denote the number of players $j \neq i$ such that $b_j > b_i$ and $b_j = b_i$, respectively. Then the probability that player i receives a prize $P_i(b)$ is defined by

$$P_i(b) = \begin{cases} 1, & \text{if } b_i > b_j \text{ for at least } n - m \text{ players } j \neq i, \\ 0, & \text{if } b_i < b_j \text{ for at least } m \text{ players } j \neq i, \\ \frac{m - \#H_i(b)}{\#M_i(b)}, & \text{otherwise.} \end{cases}$$

Players in this contest must pay their bid regardless of whether they win a prize. The expected utility of player i is thus defined by $u_i(b) = P_i(b)R - b_i$.

All equilibria of the game described above are in mixed strategies. To see why, note that a player's best response is always to bid just above the m -th highest bid of the other players unless the m -th highest bid is the prize value in which case the best response is zero. Thus, no equilibrium in pure strategies exists. Baye et al. (1996) show that, when $m = 1$, all equilibria are such that the expected auction revenue is equal to the prize value. Siegel (2009) extends this result to $m > 1$, showing that in general the expected auction revenue is equal to the total prize value mR .

Although there can be multiple mixed strategy equilibria for any specification of the game, the "revenue equivalence" means that we can compare the behavior in our experiments with the predicted Nash equilibria by examining the auction revenue. With this in mind, we selected three variations of the all-pay auction, all of which have a unique symmetric equilibrium and multiple asymmetric equilibria. The existence of a unique symmetric equilibrium provides a natural benchmark against which we may compare the distribution of bids. The treatments differed in the number of bidders and the number of prizes. The first treatment, denoted $N3P1$, involved groups of three bidders competing for a single prize. The second treatment, denoted $N3P2$, had three bidders competing for two prizes. The third treatment, denoted $N6P2$, had six bidders competing for two prizes. We adjusted the prize value across treatments to hold the expected bid constant across all equilibria in all treatments. This design allows us to compare bidding as the number of prizes increases holding the number of players constant ($N3P1$ vs. $N3P2$) and to compare bidding as the number of prizes increases holding the the scarcity of the prize constant ($N3P1$ vs. $N6P2$).

Table 1 shows a summary of the three treatments along with average bids and revenue for each treatment. We conducted three sessions for each treatment. For the three player treatments, sessions had either 12, 15 or 18 subjects. The sessions for $N6P2$ had 18 subjects

Table 1: Summary of Treatments

Treatment	n	m	R	Number of subjects	Average Bid	Average Revenue
<i>N3P1</i>	3	1	800	39	340.73	1022.18
<i>N3P2</i>	3	2	400	45	205.29	615.86
<i>N6P2</i>	6	2	800	54	354.16	2124.99

per session. The average bid for all Nash equilibria for all three treatments is 266.67. Expected revenue is equal to the total prize: 800 for the three player treatments and 1600 for *N6P2*. Actual average bids and revenue in the experiments are shown in Table 1.

From prior experimental work, we expect to see overbidding in the one prize auction (*N3P1*) relative to the Nash equilibrium. We consider it an open question whether the overbidding will exist when we examine auctions with two prizes, as multiple prize all-pay auctions with complete information have not been studied in the literature.

Although the equilibrium average bid is held constant across all three treatments and all equilibria, there are noteworthy differences in the equilibrium bid distributions. As shown in Figure 2, the symmetric equilibrium distributions for *N3P1* and *N6P2* have most of the mass in low bids close to 0. By contrast, the symmetric equilibrium distribution for *N3P2* has most of the mass in high bids close to the prize value. In our analysis below, we will test whether bidding is consistent with the symmetric equilibrium. Further, when the distribution of bids is not consistent with the symmetric equilibrium, we will examine how the deviations from equilibrium lead to the observed over- or under-bidding.

The experiment proceeded as follows. Subjects participated in one of the three treatments described above (a between-subjects design).⁵ Subjects received printed copies of the instructions, and the instructions were read aloud. After reading the instructions, subjects

⁵Prior to the auction experiment, all subjects made a series of 10 choices between two gambles following the procedure from Holt and Laury (2002). One of the 10 choices was selected at random to be payoff relevant. Subjects were not informed of earnings from this part of the experiment until the end of the experiment.

completed a quiz that presented a hypothetical set of bids and asked subjects to identify the winner(s) and to state every player's earnings. Subjects could not proceed until they answered all questions correctly. In the event of an error, one of the session proctors helped explain the error to the subject. Following successful completion of the quiz, subjects played 40 rounds of the experiment. Since we are interested in understanding behavior in a one-shot auction, subjects were randomly re-matched in every round (a stranger design) in order to reduce the feasibility of tacit collusion.

The experiment allowed each subject to enter a bid of any non-negative real number to two decimal places. A concern in the prior literature involves biases from imposing a maximum bid (Dechenaux et al., 2014). To alleviate this concern, the instructions did not mention any maximum bid. In practice, the experiment software imposed a maximum bid of 2000 tokens which is well above the prize value in all treatments.

All payments were expressed to subjects in experimental tokens, where 100 tokens was equal to \$1. Subjects were informed that they would receive a 2000 token endowment in addition to whatever they won or lost during the all-pay auction. They were also informed that we would randomly select 5 of the 40 auction rounds to pay subjects and that earnings or losses from those 5 rounds would be totaled and added to the 2000 token endowment to determine their earnings. The expected earnings in all equilibria are 0 each period, so predicted earnings for this part of the experiment are 2000 tokens, or \$20.⁶

The experiment took about one hour, and subjects were paid in cash following completion of the experiment. All subjects were undergraduate students at California Polytechnic State University in San Luis Obispo, CA. The experiments were run using the z-Tree software (Fischbacher, 2007). The full instructions provided to the subjects are available from the

⁶It was possible that losses in the five chosen rounds could exceed the 2000 token endowment, leading to a net loss in the experiment. Subjects were informed that no one would actually lose money in the experiment. In practice, only 2 of the 138 subjects had negative total earnings and they were only slightly negative, so we are not concerned that the truncated losses affected bidding behavior.

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3 Results

In this section we present two sets of empirical results. The first results pertain to analysis of aggregate bidding behavior in the experiments. The second set of results address individual subject bidding behavior.

3.1 Aggregate Results

Figure 1 shows histograms of the auction revenue for each of the three treatments with the solid red line showing the total prize value and the curve showing the predicted distribution of auction revenue for each treatment in the symmetric equilibrium. The red line showing the prize value is also the expected revenue in all equilibria: 800 in $N3P1$ and $N3P2$ and 1600 in $N6P2$. Over-dissipation is present in a large fraction of rounds in the $N3P1$ (62% of rounds) and $N6P2$ (71%) treatments while there is under-bidding in $N3P2$ where only 21% of rounds had revenue over 800 tokens.

To facilitate comparisons of aggregate bidding across treatments, we construct a variable, denoted θ , that is equal to the average auction revenue in a session divided by the total prize value for that treatment. So, $\theta = 1$ when auction revenue is equal to the total prize value and is greater than 1 when there is over-dissipation. We have three independent observations for each treatment (one per session) since we randomly re-match subjects every round. Comparing the level of over-dissipation in $N3P2$ to either $N3P1$ or $N6P2$, we note that all three values of θ in $N3P2$ are lower than all three values in $N3P1$ and $N6P2$. As a result, a Wilcoxon rank sum test (or other similar nonparametric tests) has the minimum possible p-value of 0.1 in both cases. This confirms, to the greatest extent possible with our data, that overall bidding is lower in $N3P2$ than either of the other treatments. Based on a Wilcoxon

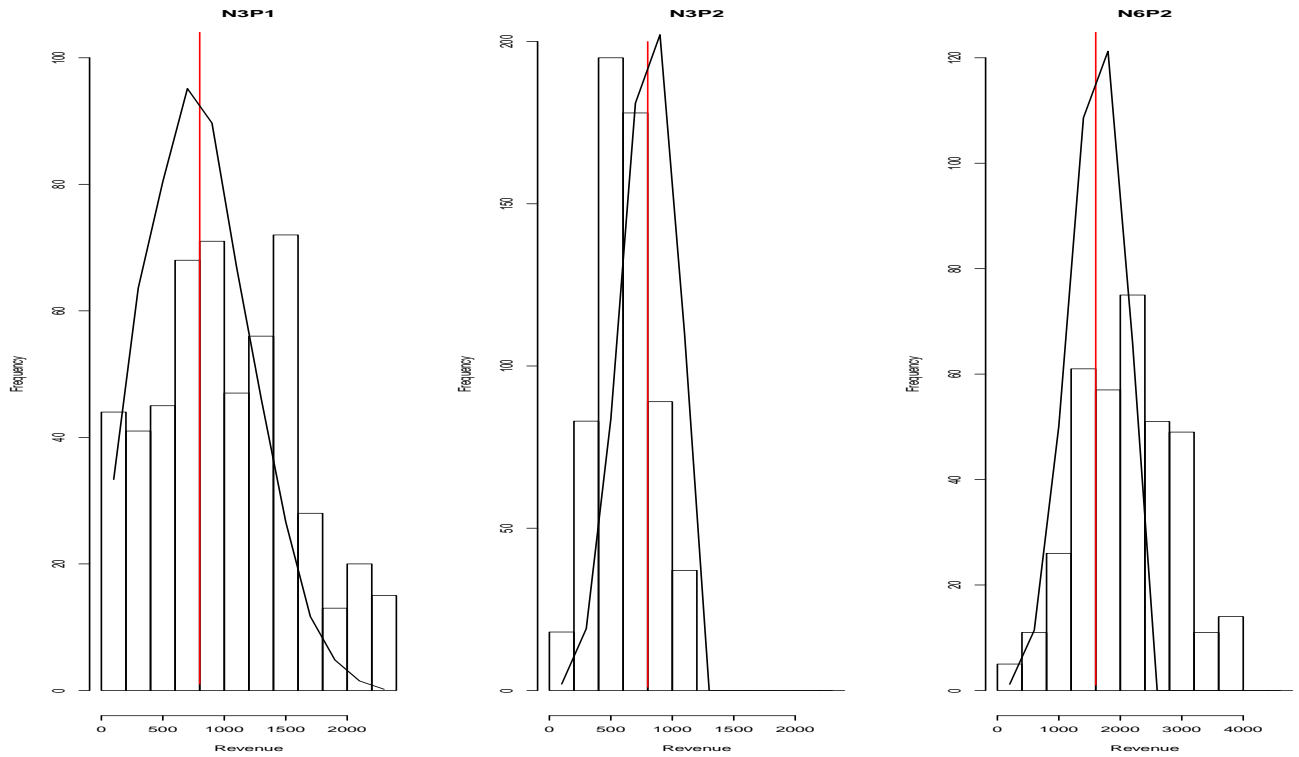


Figure 1: Auction Revenue

The histogram shows the frequency of revenue outcomes in a treatment. The vertical red line shows the equilibrium expected revenue. The black curve shows the predicted frequency of revenue outcomes in the symmetric equilibrium.

rank sum test, we cannot reject the null hypothesis that the extent of over-dissipation is the same in *N3P1* and *N6P2*.

We follow Lugovskyy et al. (2010) and Barut et al. (2002) in constructing a regression equation that allows for a convergence process in bidding behavior over the course of the experiment. This model assumes that different sessions may have different levels of over-dissipation at the start but that all sessions in the same treatment converge to the same level of over-dissipation. This regression allows us to compare the overall level of over-dissipation across treatments at the end of the experiment. The regression equation is:

$$\theta_{st} = \sum_{s=1}^9 \beta_s D_s \frac{1}{t} + \gamma_{N3P1} D_{N3P1} \frac{t-1}{t} + \gamma_{N3P2} D_{N3P2} \frac{t-1}{t} + \gamma_{N6P2} D_{N6P2} \frac{t-1}{t} + \epsilon_{st} \quad (1)$$

In the above equation, the D_s are dummy variables for each of the 9 sessions (3 for each treatment). D_{N3P1} , D_{N3P2} , and D_{N6P2} are dummy variables for the three treatments. t represents the period, ranging from 1 to 40, and ϵ_{st} is a random normal error term. This regression estimates the starting point (β_s) and ending point (γ_i) of a convergence process where each session has its own starting point but all sessions in a given treatment share a common end point.

Table 2 shows the regression results with statistical significance corresponding to a null hypothesis that each coefficient equals 1 (since $\theta = 1$ is the equilibrium prediction in all equilibria) instead of 0. In both *N3P1* and *N6P2*, all sessions begin with overbidding. The extent of overbidding declines by the end of the session but is still significant. In contrast, by the end of the sessions in *N3P2*, we observe statistically significant underbidding relative to the equilibrium prediction. Comparing the treatments to each other, γ_{N3P2} is significantly lower than the other two treatments at a 1% level and γ_{N6P2} is slightly greater than γ_{N3P1} , significant at 5% level.

Table 2: Convergence of Aggregate Dissipation Over Time

	Dependent Variable θ		
$\beta_1, \beta_2, \beta_3$	2.212*** (0.189)	1.284 (0.210)	2.065*** (0.210)
$\beta_4, \beta_5, \beta_6$	0.884 (0.209)	0.711* (0.172)	0.287*** (0.188)
$\beta_7, \beta_8, \beta_9$	1.561** (0.243)	1.815*** (0.243)	1.429* (0.243)
γ_{N3P1}	1.205*** (0.0270)		
γ_{N3P2}	0.788*** (0.0251)		
γ_{N6P2}	1.295*** (0.0325)		
Observations	1480		
R-sq	0.823		

Standard errors in parentheses

Coefficient is significantly different than 1:

**** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$*

N3P1 includes sessions 1, 2, and 3.

N3P2 includes sessions 4, 5, and 6.

N6P2 includes sessions 7, 8, and 9.

To summarize our results on aggregate bidding, we confirm results from prior studies that there is over-dissipation in a one prize three bidder all-pay auction. We further show that similar amounts of over-dissipation occur when the number of prizes and bidders are increased proportionally. Most noteworthy is that we instead observe under-dissipation when the number of prizes is increased, holding the number of players constant.

3.2 Individual Results

Figures 2 and 3 show a histogram of bidding behavior for each of the three treatments for all rounds and for the final 10 rounds, respectively. The solid red line shows the average bid in all equilibria, equal to 266.67 in all three treatments. The curve shows the expected distribution of bids in the symmetric equilibrium for each treatment. Similar to what has been found in the prior literature (see Dechenaux et al., 2014), we observe bimodal bidding in the one prize treatment with many bids at or close to 0 and many bids close to the prize value. The histograms shed some light into the causes of overbidding in the $N3P1$ and $N6P2$ treatments. In both cases, it is the large number of bids close to the prize value (over 700 tokens) that is the cause of the overbidding phenomenon.

As a further illustration, consider the number of bids within 5% of the prize value. In $N3P1$ and $N6P2$, there were 266 (17%) and 559 (26%) bids greater than 760 tokens, respectively. In the symmetric equilibrium, we expect only 3% of bids in $N3P1$ to be that high and only 7% of bids in $N6P2$. By contrast, consider the $N3P2$ treatment. Here the symmetric equilibrium puts greater mass on bids near the prize value relative to the other treatments. Based on equilibrium predictions, we would expect 22% of bids to be over 380 tokens. Instead, we observe only 85 (5%) bids that high.

Figures 4 and 5 show the empirical CDF for each of the three treatments for all rounds and for the last 10 rounds, respectively. The solid line in each panel is the symmetric equilibrium distribution. These figures corroborates the pattern of overbidding in $N3P1$ and

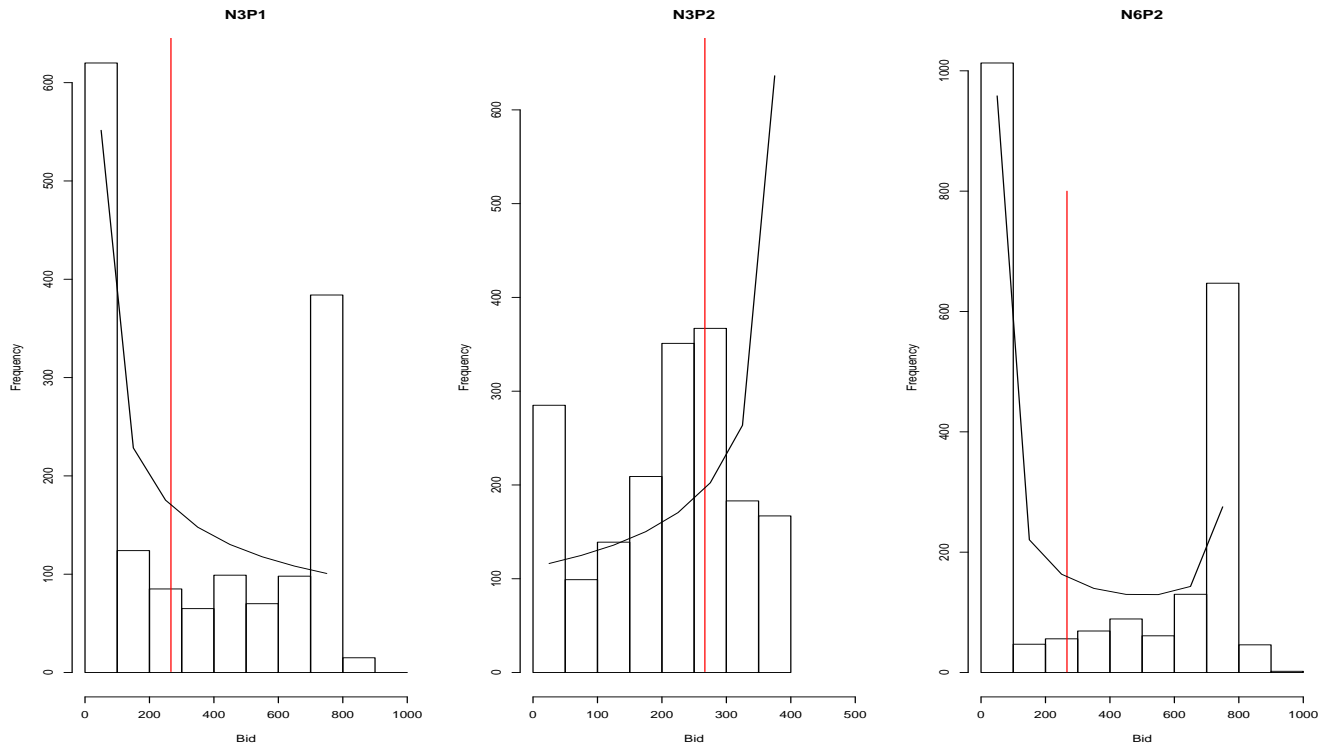


Figure 2: Individual Bidding Behavior - All Periods

The histogram shows the frequency of bids in a treatment. The vertical red line shows the equilibrium average bid, 266.67 in all treatments. The black curve shows the predicted frequency of bids in the symmetric equilibrium.

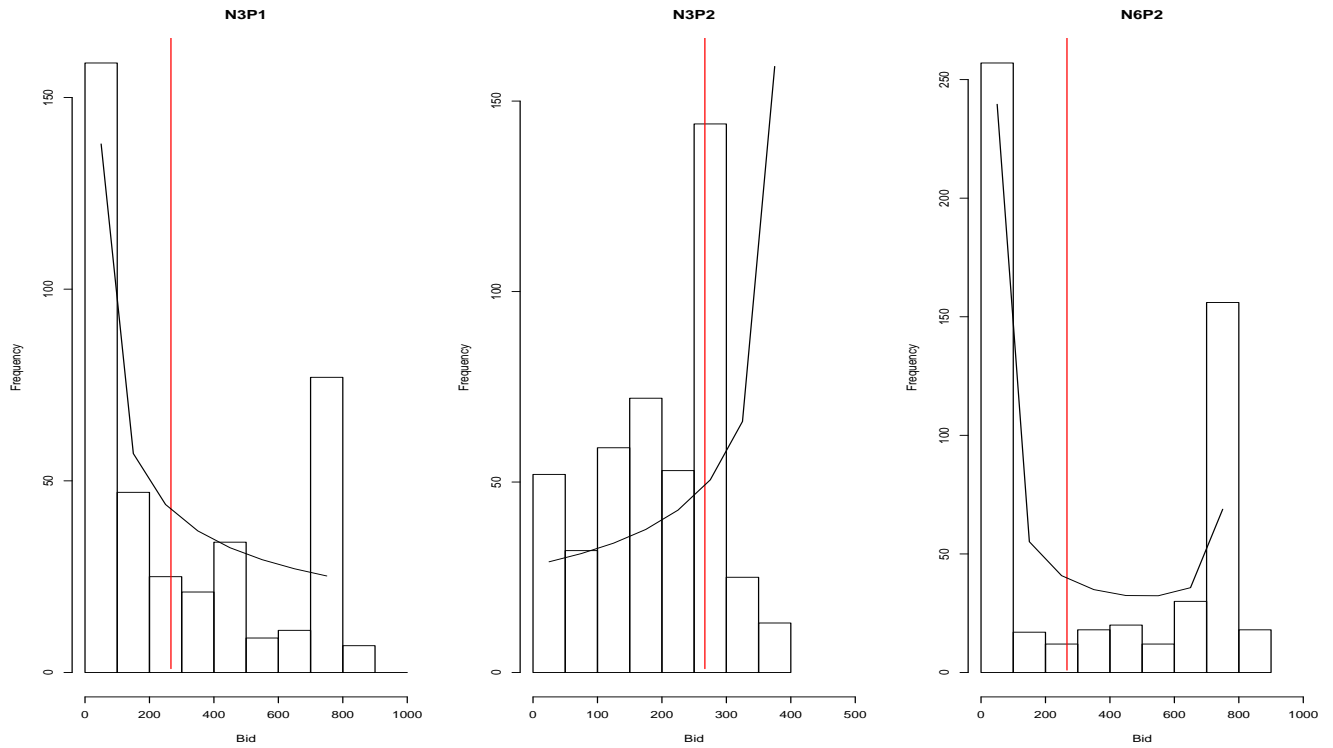


Figure 3: Individual Bidding Behavior - Final 10 Periods

The histogram shows the frequency of bids in a treatment. The vertical red line shows the equilibrium average bid, 266.67 in all treatments. The black curve shows the predicted frequency of bids in the symmetric equilibrium.

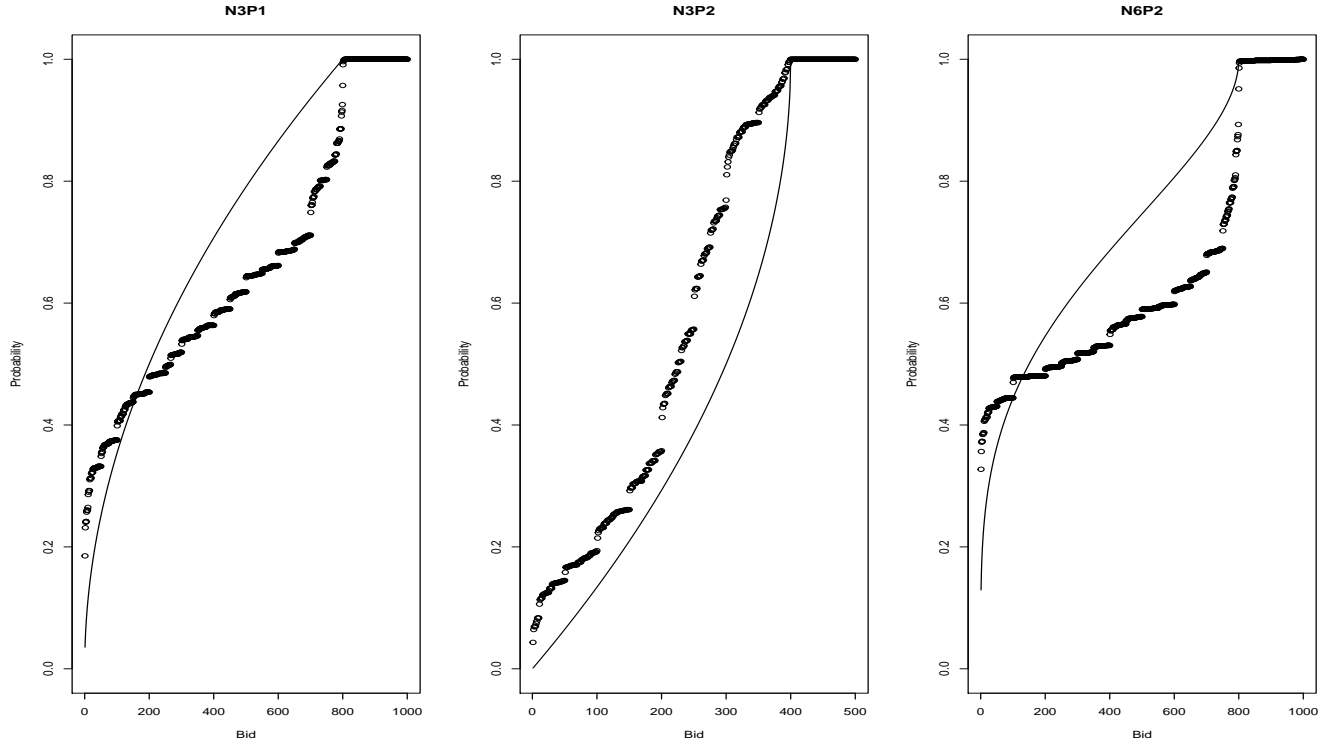


Figure 4: CDF of Actual Bids and Symmetric Equilibrium Bids - All Periods

N6P2 observed in Figures 2 and 3, that it is the result of too many bids close to the prize value. These figures also show that there are too many zero bids in these treatments, though this behavior may be induced by the large number of bids near the prize value. We also note that there is a small movement towards the equilibrium distribution when looking just at the final 10 rounds, but for the most part, the distribution of bids is similar in both figures.

Figure 6 shows box plots of each individual's distribution of bids, organized by treatment and session. At the individual level, we note that most players in *N3P1* and *N6P2* mix over almost the entire range of bids between 0 and the prize value. 72% of subjects in *N3P1* and 81% of subjects in *N6P2* have at least one bid below 40 and at least one bid above 760. In a few instances, subjects bid greater than the prize values (individual over-dissipation). In *N3P1*, 4 out of 39 subjects bid over the prize value at least once and this extreme overbidding

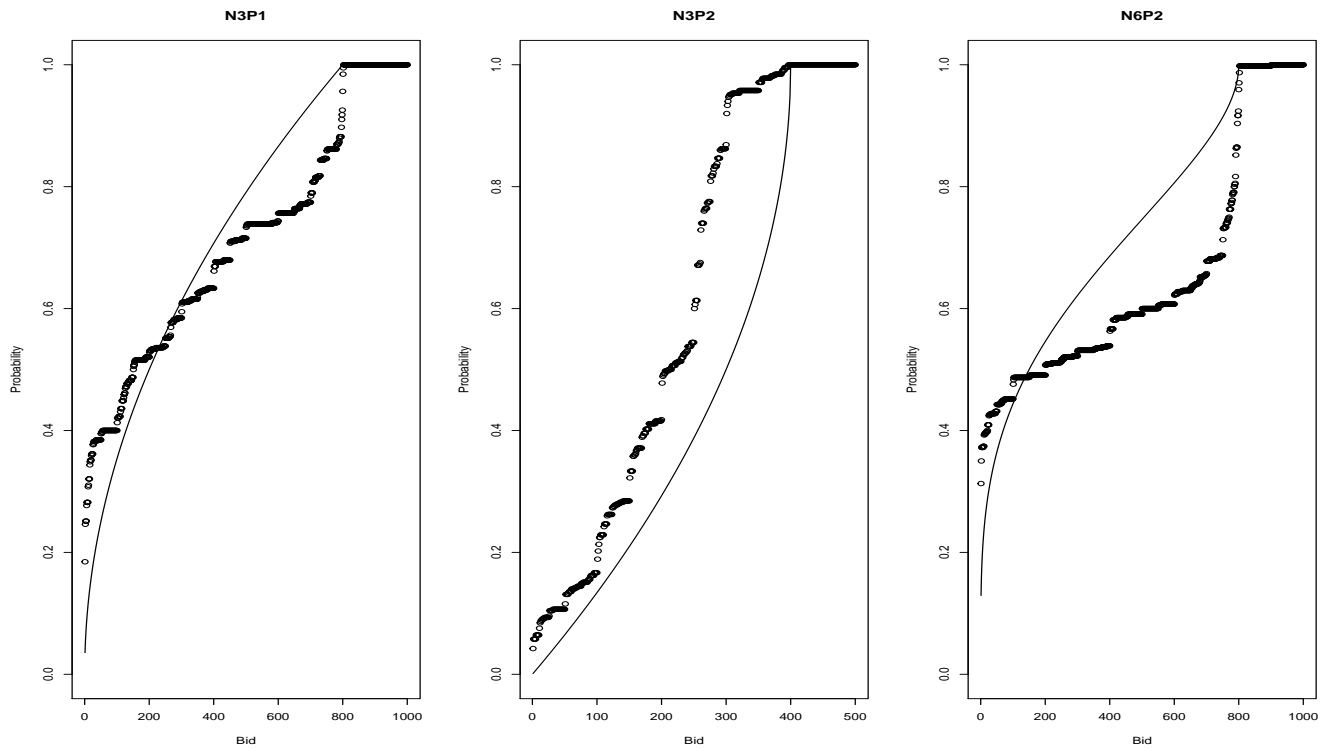


Figure 5: CDF of Actual Bids and Symmetric Equilibrium Bids - Final 10 Periods

occurs in 15 out of 1560 choice opportunities. In *N6P2*, 8 out of 54 subjects bid over the prize value at least once and this extreme bidding occurs in 48 out of 2160 choice opportunities. No subjects ever bid above the prize value in *N3P2*.

Very few subjects make the same bids throughout the session. No subjects in *N3P1* and *N3P2* have all bids within a 20 tokens range. In *N6P2*, there are four subjects who choose not to participate, bidding less than one token in all 40 periods. These subjects guarantee themselves a payoff of \$20.00, exactly equal to the equilibrium expected payoff. Given the overbidding observed in *N6P2*, these subjects' earnings are well above the average payoff (\$15.11) for their treatment.

Figure 7 shows box plots using only the final 10 rounds of the experiment. It is interesting to note that although the overall distribution of bids from all rounds in Figure 3 is similar to that from the final 10 rounds in Figure 2, at the individual level there are notable differences in bidding between the beginning and end of the experiment. In the final 10 rounds, there are many subjects who make close to the same bid in each round. The percentage of subjects who make all bids in the last 10 rounds within a 20 token range is 15%, 9%, and 26% in *N3P1*, *N3P2*, and *N6P2*, respectively. Some of these subjects focus on bids close to the prize value, some have opted out and bid close to zero, and a few bid in the middle. The remainder of subjects continue to mix over wide ranges of bids.

We use a Kolmogorov-Smirnov test to compare the distribution of bids in each treatment to the symmetric equilibrium under the assumption that individual bids are independent across rounds (as would be true if subjects played a mixed strategy equilibrium). In all cases, we reject the null hypothesis at a 1% significance level that subjects play the symmetric equilibrium strategy. This is true when looking at all data or the final 10 rounds.

The differences in bidding behavior translate into different earnings across the three treatments. Since each subject was given a \$20.00 endowment and expected earnings in the all-pay auction are zero in all equilibria, we expect average earnings to be \$20.00. By

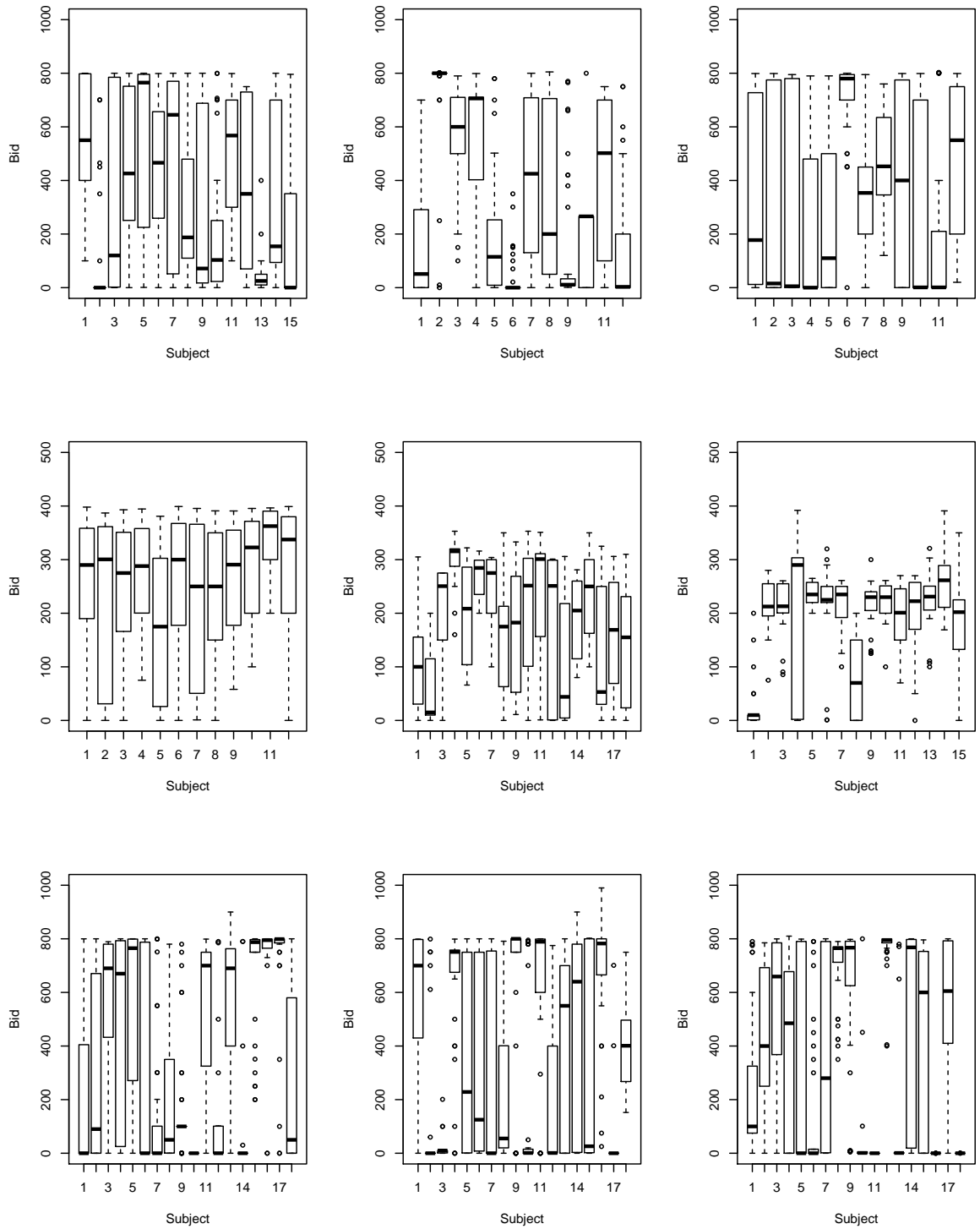


Figure 6: Box Plots of Individual Bidding Behavior - All Periods

Top Panel: N3P1

Middle Panel: N3P2

Bottom Panel: N6P2

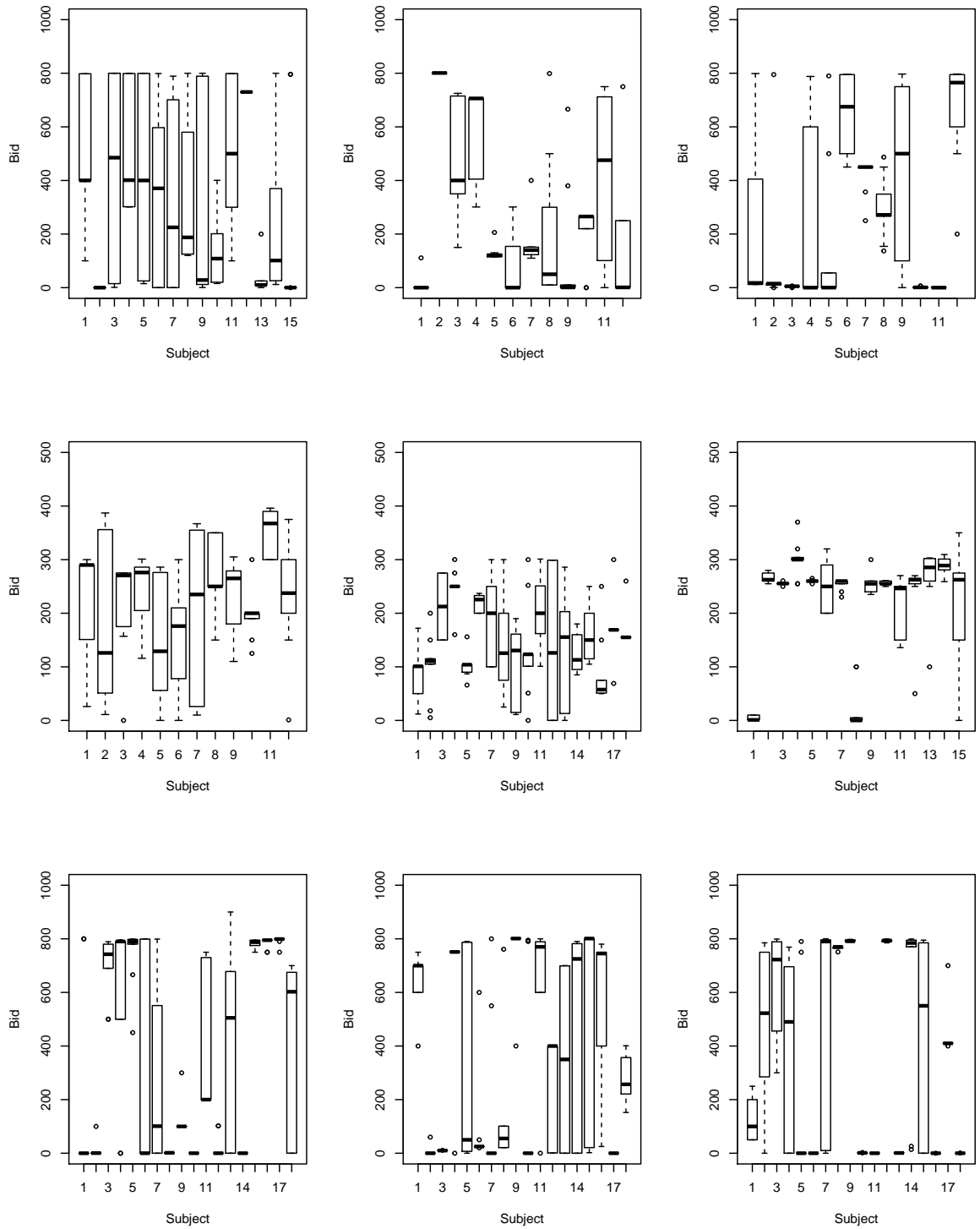


Figure 7: Box Plots of Individual Bidding Behavior - Final 10 Periods

Top Panel: N3P1

Middle Panel: N3P2

Bottom Panel: N6P2

overbidding, subjects in *N3P1* and *N6P2* earned considerably less money than those in *N3P2*. The average earnings were \$15.88 and \$15.11, respectively, in *N3P1* and *N6P2*, while in *N3P2*, average earnings were \$23.36.

4 Conclusion

Many examples of all-pay auctions actually have more than one prize awarded, yet prior experiments have focused on the one prize case. We ran experiments on all-pay auctions with complete information where we varied the number of prizes and players to examine how multiple prizes affects bidding. We find that decreasing the scarcity of the prize dramatically lowers the average bid and eliminates the over-dissipation phenomenon found in many prior studies. On the other hand, we find that increasing the number of prizes while holding scarcity constant has little effect on aggregate bidding. We conclude that over-dissipation is linked to prize scarcity; if subjects perceive they have a high enough chance to win a prize, then over-bidding disappears.

In our game, the number of players is exogenous. In a real world scenario in which the number of players is fixed, our results suggest that increasing the number of prizes will reduce aggregate bids. On the other hand, in some real world cases, the number of players is determined endogenously. In this case, if the presence of multiple prizes attracts more bidders, then over-dissipation is likely to persist.

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