Discrete Clock Auctions: An Experimental Study

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Abstract

We analyze the implications of different pricing rules in discrete clock auctions. The two most common pricing rules are highest-rejected bid (HRB) and lowest-accepted bid (LAB). Under HRB, the winners pay the *lowest* price that clears the market; under LAB, the winners pay the *highest* price that clears the market. Both the HRB and LAB auctions maximize revenues and are fully efficient in our setting. Our experimental results indicate that the LAB auction achieves higher revenues. This also is the case in a version of the clock auction with provisional winners. This revenue result may explain the frequent use of LAB pricing. On the other hand, HRB is successful in eliciting true values of the bidders both theoretically and experimentally.

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1 Introduction

A common method to auction radio spectrum, electricity, gas, and other products is the discrete clock auction. The auctioneer names a price and each bidder responds with her desired quantity. If there is excess demand, the auctioneer then names a higher price. The process continues until there is no excess demand.

Discrete rounds are used in practice to simplify communication, make the process robust to communication failures, and mitigate tacit collusion (Ausubel and Cramton 2004). An implication of discrete rounds is that the pricing rule matters. The two most common pricing rules are lowest-accepted bid and highest-rejected bid. Another issue is whether the bidder can specify an exit bid—a price less than the current price at which the bidder desires to reduce quantity. In the limit as the size of the bid increment goes to zero, the distinction between pricing rules is irrelevant and exit bids are unnecessary. However, in practical auctions where the number of rounds often ranges from 4 to 10, discreteness matters.

In this paper, we examine bidding behavior under three versions of a discrete clock auction. In each version, after each round the bidders learn the aggregate demand. To prevent bid-sniping, an activity rule requires that a bidder's quantity demanded cannot increase at higher prices. Bidders can only maintain or reduce quantity as the price rises. The three versions differ in the pricing rule and whether bidders make exit bids to express the price at which a quantity reduction is desired.

Highest-rejected bid (HRB). If the bidder reduces quantity in a round, the bidder names a price for each quantity reduction. The price of each reduction must be greater than the prior price and less than or equal to the current price. Each exit price is interpreted as the price at which the bidder is indifferent between the higher quantity and the lower quantity. If there is no excess demand at the current price, the supply is awarded to the highest bidders, and each winner pays the highest-rejected bid for the quantity won. The clearing price is the lowest price consistent with market clearing—the price at which supply equals demand.

Lowest-accepted bid (LAB). This is the same as HRB, except that the winners pay the lowest-accepted bid for the quantity won. The clearing price is the highest price consistent with market clearing.

Lowest-accepted bid with provisional winners (LABpw). This is the same as LAB, except there are no exit bids. Instead after each round, provisional winners are determined. Those with the highest price bid are selected first, and, in the event of a tie, the remaining provisional winners are selected at random.

The clock auction is best thought of as a dynamic version of a sealed-bid uniform-price auction. In the uniform-price auction, the auctioneer collects a demand curve from each bidder, forms the aggregate demand curve, and crosses it with the supply curve to determine the market clearing price and the quantity won by each bidder. The clock auction does the same thing, but gathers the demand curves from each bidder in a sequence of discrete rounds, and bidders receive information about excess demand at the end of each round. The uniform-price auction is just a single-round clock auction. In both clock auctions and uniform-price auctions, two pricing rules are commonly used: highest-rejected bid and lowest-accepted bid. This is the motivation for our HRB and LAB treatments.

The LAB rule is used in US Treasury auctions, as well as Treasury auctions in many other countries. These are sealed-bid uniform-price auctions. In contrast, clock auctions for electricity and gas products in Europe have used the HRB rule.

Our third treatment, lowest-accepted bid with provisional winners, is a version of the simultaneous ascending auction commonly used to auction radio spectrum. The government of India used this format for its 2010 3G spectrum auction. Similar approaches have been used elsewhere, such as in Italy’s 3G spectrum auction.

At first glance, it would seem that selecting the highest clearing price (LAB) would result in greater revenue than selecting the lowest clearing price (HRB). The argument is incomplete, since the pricing rule influences behavior. LAB provides a stronger incentive for shading one’s bid below valuation. In simple cases (assuming symmetry, independence, and risk neutrality), the greater bid shading under LAB exactly offsets the revenue gain from selecting the higher clearing price. Revenue equivalence obtains, and the two pricing rules result in the same expected revenue—at least in theory when bidders seek to maximize profits.

It is a robust and puzzling finding of the experimental literature that in second-price sealed-bid auctions subjects bid more than their value although they bid truthfully in its dynamic counterpart, the English auction (Cooper and Fang 2008; Coppinger et al. 1980; Kagel et al. 1987, Kagel and Levin 1993). The HRB auction is somewhere between the English and second-price auctions and these two are the limit cases of HRB. HRB converges to the English auction (continuous clock) when the number of rounds approaches to infinity. When there is only one round, HRB is the same as the second price auction. The exit bid decision in HRB requires similar strategic thinking as in a second-price sealed-bid auction. On the other hand, whether to stay in the auction is the same binary decision as in the English auction. Harstad (2000) finds that experience with the English auction leads to less overbidding in second-price auctions. Moreover, he argues that the binary choice aspect of English auctions explains an important part of this learning. The HRB format allows subjects to make that kind of binary choice for early price increments and when they come to the price interval when they want to exit, they have this experience. In this respect, studying discrete clock auctions helps us understand what makes subjects overbid in second-price auctions and bid truthfully in English auctions.

Since we find experimentally that subjects do not deviate from the straightforward bidding strategy in HRB, it is confirmed that dynamic formats make it easier for the bidders to recognize equilibrium strategies. Having a discrete clock makes HRB more practical than the English auction, and yet it still is successful in eliciting the true values in our experiment.

The LAB pricing rule is analogous to a first-price sealed-bid auction. In particular, if there is only one round and one good, the LAB and first price auctions are the same. Another robust finding of the experimental literature is that bidders of a first-price auction overbid compared to the risk-neutral Nash equilibrium prediction (see Cox, et al. 1982, 1988, as the seminal papers;

Kagel and Levin 2008 for detailed survey).[2] Therefore, we expect to see some sort of overbidding in LAB auction.

The purpose of this paper is to examine the bidding behavior and outcomes, especially efficiency and revenue, under the three different formats experimentally. Our main hypothesis is that subjects will overbid under lowest-accepted bid, consistent with the first-price sealed-bid auction; whereas, under highest-rejected bid, bidders will bid truthfully. Thus, revenues under LAB will be higher than revenues under HRB. However, efficiency will be higher under HRB, as a result of the truthful bidding. Although the formats apply to the general case of auctioning many units of multiple products, for simplicity we restrict attention to the case of auctioning a single good.

Our results indicate that revenues under both LAB and LABpw are significantly higher than under HRB. Thus, in settings where revenue is the predominant objective, the seller may favor LAB, but in settings where both efficiency and simplicity are of greater concern, then the seller may favor HRB.

There are a number of experimental papers that use clock auctions. Some of these papers use a continuous clock (Kagel and Levin 2001). Others use a discrete clock, and compare a sealed-bid auction with a particular discrete clock (Ausubel et al. 2009). This paper aims to understand the implications of different pricing rules in discrete clock auctions.

In Section 2, we begin with a presentation of the theory. Equilibrium bidding strategies for the three versions of the discrete clock auction are characterized in Cramton and Sujarittanonta (2010). Here we summarize the results, and provide the equilibrium for bidding strategies for our experimental setting. The experimental design and the results are discussed in Sections 3 and 4. Section 5 concludes.

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[2] Risk aversion offers one explanation, but this has proven inadequate (see Kagel 1995). Several papers explain the overbidding phenomena with behavioral motives (for example, Goeree et al. 2002, Crawford and Iriberri 2007; Delgado et al. 2008; Filiz-Ozbay and Ozbay 2007; Lange and Ratan 2009).

2 Theory

There is one indivisible good for sale to $N > 1$ risk neutral bidders. Bidder i's private value for the good is v_i where each v_i is independently drawn from a commonly know distribution F. Bidder i's payoff if she wins the good at a price p is $v_i - p$. Otherwise, it is equal to 0. The seller values the good at 0.

Before the auction starts, the seller announces a vector of bid levels, $P = (P_0, P_1, \dots, P_{T-1})$ where P_t is the price at round t and T is the number of bid levels. The clock price increases every round so that $\underline{v} = P_0 < P_1 < \cdots < P_{T-1} = \overline{v}$. The auction begins in round one at a price P_1.

In each round t, each bidder chooses either to bid at the current clock price or to exit. Once a bidder exits she cannot bid again. If both bidders stay in, the auction proceeds to the next round. If one bidder exits, then the bidder who stayed in wins the good. The resolution of the other cases and the payments will depend on the auction format.

2.1 Highest-rejected-bid (HRB)

In the HRB format, the final price is determined by the highest-rejected bid. If a bidder exits in round t, the bidder submits an exit bid—a price between P_{t-1} and P_t at which she wants to exit. If more than one bidder remains, the auction continues to another round; if all but one bidder exits, the remaining bidder wins and pays the highest exit bid; if all bidders exit, the bidder with the highest exit bid wins and pays the second-highest exit bid.

Proposition 1. *In the HRB auction, truthful bidding (bidding up to one's value) is a weakly-dominant strategy. The HRB auction is efficient and maximizes seller revenue.*

The dominant strategy result is standard and holds regardless of the number of bidders, the number of goods, or how values are drawn. All that is required is that each bidder demands only a single good. Thus, highest-rejected bid is the Vickrey price, thereby inducing truthful bidding. Efficiency is an immediate implication of truthful bidding.

The HRB auction has extremely desirable properties in our setting. It is both efficient and maximizes seller revenues. Moreover, the bidding strategy is simple—just bid up to your true value—and is best regardless of what the other bidders are doing. Another important property of the HRB auction is that a bidder cannot lose at an affordable price as long as she bids her value. Hence, neither the winner nor the loser ever regrets having bid as they bid. The winner could not do better by exiting earlier; the loser could not do better by staying in longer.

2.2 Lowest-accepted-bid (LAB)

In the LAB format, the final price is determined by the lowest-accepted bid. If a bidder exits in round *t*, the bidder submits an exit bid—a price between P_{t-1} and P_t at which she wants to exit. If more than one bidder remains, the auction continues to another round; if all but one bidder exits, the remaining bidder wins and pays the current price; if all bidders exit, the bidder with the highest exit bid wins and pays her exit bid.

Proposition 2. *In the symmetric equilibrium of the LAB auction (see Table 1), a bidder, who exits bid at* P_t*, bids* $b(v_i, P_{t-1}) = E[Y|P_{t-1} < Y_k < v_i]$ *where* Y_k *is the highest of* $k-1$ *independently drawn values and k is the number of bidders present at* P_{t-1}*. The LAB auction is efficient and maximizes seller revenue.*

The LAB auction in our setting is efficient and maximizes seller revenues. Nonetheless, one might favor the HRB auction because of its simple bidding strategy without bid shading. In the LAB auction, bidders must do a difficult equilibrium calculation to determine the optimal level of bid shading.

2.3 Lowest-accepted-bid with provisional winners (LABpw)

Our third version of the discrete clock auction has provisional winners instead of exit bids. This approach is common in spectrum auctions, and was used in the 2010 India 3G spectrum auction. It is theoretically investigated in Cramton and Sujarittanonta (2010).

With two bidders, one of the bidders is selected at random as the provisional winner at the reservation price P_0. In each round, each bidder chooses either to bid at the current price or to exit. If both bidders stay in, one of the bidders is selected at random as the provisional winner and the auction proceeds to the next round. If one bidder exits, then the bidder who stayed in wins the good at the current price. If both bidders exit, then the provisional winner wins the good at the prior price.

An important difference between the auction described here and a standard ascending-bid auction is a provisional winner must keep topping her own bid in order to be eligible to bid in subsequent rounds. In contrast, in a standard ascending-bid auction, a provisional winner does not need to bid, since if her bid is topped, she can still bid in the next round.

Proposition 3. *In a perfect Bayesian equilibrium of the LABpw auction, the provisional loser stays in provided her value is not yet reached; the provisional winner exits at a level below her true value. The exit level depends on the provisional winning history. The outcome is inefficient and does not maximize seller revenue.*

The LABpw auction uses provisional winners, rather than exit bids, to determine who wins in the event both bidders exit in the same round. This creates two sources of inefficiency. First, without exit bids, there is no precise value information to determine who has the higher value. Second, the provisional winner designation creates differential bid shading (provisional winners shade bids, whereas provisional losers do not). Since in our setting there is no conflict between efficiency and revenue maximization, it is clear that the LABpw auction does not maximize seller revenue. The seller should favor HRB or LAB on both efficiency and revenue grounds. In addition, the equilibrium strategies in LABpw are greatly complicated by history dependence.

2.4 Theoretical predictions for the experiment

In our experiment, two bidders compete to buy a single good. Bidder *i*'s private value for the good is v_i where each v_i is independently drawn from the uniform distribution on $[50,100]$ and $\mathbf{P} = (50,60,70,80,90,100)$. By Proposition 1, in HRB the bidder submits her value as an exit bid. By Proposition 2, the equilibrium strategy is given in Table 1.

Table 1. Equilibrium Strategy for LAB auction

Value	Exit Round	Exit bid function
$[50,70)$	1	$25+\frac{1}{2}v_i$
$[70,90)$	3	$35+\frac{1}{2}v_i$
$[90,100]$	5	$45+\frac{1}{2}v_i$

Ex ante symmetry—the fact that the bidders' values are drawn from the same distribution—is critical for Proposition 2. This allows for a symmetric equilibrium. Since the exit bid functions are the same and strictly increasing, the bidder with the highest value wins and the outcome is efficient. Revenue maximization then follows from the revenue equivalence theorem. The assignment is the same as in the HRB auction, and both auctions give the bidder with a value of 50 a payoff of 0.

In LABpw, the provisional loser stays in provided her value is not yet reached; the exit strategy for the provisional winner is given in Table 2.

Table 2. Provisional Winner's Equilibrium Strategy for LABpw auction

Round	History†	Critical Value‡
1	(1)	74
2	(1,1)	84
	(0,1)	70
3	(1,1,1) and (1,0,1)	94
	(0,1,1)	90.8
	(0,0,1)	80
4	(1,0,0,1), (0,1,0,1) and (0,0,0,1)	90
	Otherwise	100
5	Any	100

†History vector denotes whether the bidder is a provisional winner (denoted by 1) or not (denoted by 0) in all the rounds up to the current round;

‡Critical Value denotes the threshold such that the bidder stays in if her value is above the corresponding threshold.

3 Experimental method

The experiments were run at the Experimental Economics Lab at the University of Maryland. All participants were undergraduate students at the University of Maryland. The experiment involved six sessions. In each session one of the three treatments was administered. The numbers of participants in each treatment were 30 (HRB), 32 (LAB), and 30 (LABpw). No subject participated in more than one session. Participants were seated in isolated booths. Each session lasted about 80 minutes. Bidder instructions for each treatment are in the Appendix. To test each subject's understanding of the instructions, the subject had to answer a sequence of multiple choice questions. The auctions did not begin until the subject answered all of the multiple choice questions correctly.

In each session, each subject participated in 21 auctions. The first auction was a practice auction. Each auction had two bidders, selected at random among the subjects. Bidders were randomly rematched after each auction. All bidding was anonymous. Bids were entered via computer. The experiment is programmed in z-Tree (Fishbacher 2007). At the conclusion of each auction, the bidder learned whether she won and the price paid by the winning bidder.

Bidders had independent private values for a fictitious good. All values were uniformly distributed between 50 and 100, rounded to the nearest cent. Both bidders were IN at the starting price of 50. The price increased by 10 if both bidders stayed IN the prior round. Thus, the possible price levels in each auction were 50, 60, 70, 80, 90, and 100. There were a maximum of five rounds in the discrete clock auction. The auction concluded as soon as a round was reached in which one or both bidders stayed OUT.

Treatment HRB. In each round, the computer asks the bidder if she is IN or OUT at the current price. If the bidder stays OUT, the bidder must specify an exit bid between the current price and the prior price. If the bidder stays IN and the opponent stays OUT, then the bidder wins and pays the opponent's exit bid. If the bidder stays OUT and the opponent stays IN, then the opponent wins at the bidder's exit bid. If both stay OUT, then the bidder with the higher exit bid wins and pays the smaller of the exit bids. If both stay IN, then the price increases by 10 and the auction continues to the next round.

Treatment LAB. In each round, the computer asks the bidder if she is IN or OUT at the current price. If the bidder stays OUT, the bidder must specify an exit bid between the current price and the prior price. If the bidder stays IN and the opponent stays OUT, then the bidder wins and pays her exit bid. If the bidder stays OUT and the opponent stays IN, then the opponent wins and pays her exit bid. If both stay OUT, then the bidder with the higher exit bid wins and pays her exit bid. If both stay IN, then the price increases by 10 and the auction continues to the next round.

Treatment LABpw. One of the bidders is selected at random as the provisional winner at the price of 50. In each round, the computer asks the bidder if she is IN or OUT at the current price. If the bidder stays IN and the opponent stays OUT, then the bidder wins and pays the current price. If the bidder stays OUT and the opponent stays IN, then the opponent wins at the current price. If both stay OUT, then the provisional winner of the prior round wins and pays the prior round price. If both stay IN, then one of the bidders is selected at random as the provisional winner at the current price, price increases by 10 and the auction continues to the next round.

The winner in each auction earned her value minus the price paid in Experimental Currency Units (ECU). At the end of the experiment, total earnings were converted to US Dollars, at the conversion rate of 10 ECU = 1 US Dollar. Subjects also received a $5 show-up fee. Cash payments were made at the conclusion of the experiment. The average subject payment was $19.77.

4 Experimental results

As in any dynamic auction, bidding strategies of all bidders are not observable. For example, in the Dutch auction only the bid of the winner, or in the English auction only the bids of the losers are observable. Nonetheless, it is still possible to make revenue and efficiency comparisons, which are important in auction design. Later, we will study the bidding strategies based on the observable bids.

Table 3 shows the outcomes of each treatment. Treatment HRB, LAB and LABpw consist of 300, 320 and 300 auctions, respectively. Treatments HRB and LAB, which are theoretically efficient, yield the efficient allocation with a frequency of 92% and 90.3%, respectively.

Treatment LABpw yields the efficient allocation 85.3% of the time. Using the Wilcoxon-Mann-Whitney test, LABpw is significantly less efficient than HRB (z=2.57, p=0.01), but there is no significant difference between LAB and HRB (z=0.74, p=0.46).

Table 3. Outcomes of treatment HRB, LAB and LABpw

	HRB	*LAB*	*LABpw*
Frequency of efficient allocation	92.0%	90.3%	85.3%
	(1.57)	(1.65)	(2.04)
Revenue per auction	67.35	69.85	69.33
	(0.70)	(0.60)	(0.65)
Seller's share of gains from trade	80.8%	84.8%	85.3%
	(0.86)	(0.71)	(0.77)
Theoretical revenue per auction	67.06	67.12	65.27
Number of auctions	300	320	300

Standard errors are shown in the parentheses.

On the other hand, treatment LAB and LABpw yield higher revenues than HRB (Table 3). The revenue results are robust even if we consider the seller's share of the gains from trade (the ratio of the price and winner's value) which can be thought of as the proxy for the revenues. Treatment HRB gives the seller a smaller share of the gains from trade than treatment LAB and LABpw. The Wilcoxon-Mann-Whitney test shows LAB and LABpw yield significantly higher seller's share than HRB (z = -3.28, p<0.01 and z = -3.25, p<0.01, respectively).

Figure 1a. Actual and theoretical seller's share of gains from trade per auction

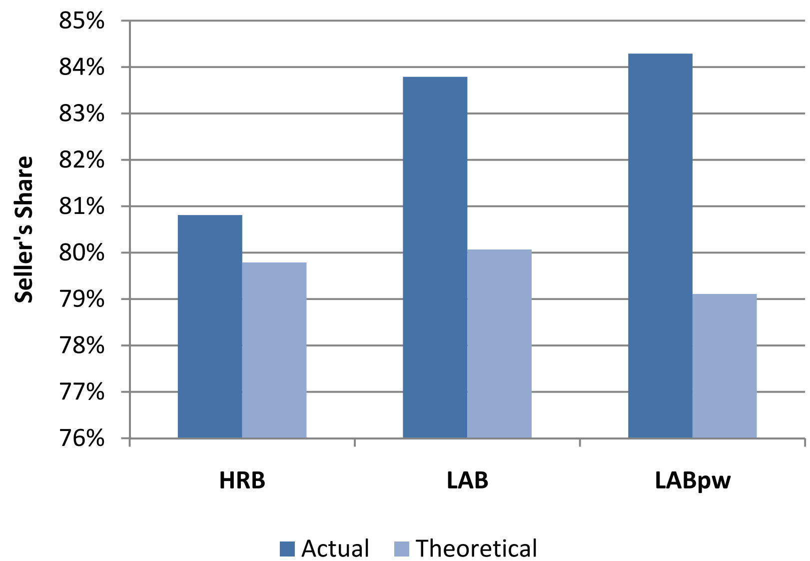


Figure 1a compares actual (what we observed in the experiment) and theoretical seller's share of the gains from trade per auction. Theoretical seller's share is the equilibrium seller's share given the realization of values. The actual seller's share of HRB is not significantly different from the theoretical prediction ($t=0.41$, $p=0.68$), but actual seller's share of LAB and LABpw are significantly higher than the theoretical share ($t=4.51$, $p<0.01$ and $t=6.27$, $p<0.01$). This evidence implies that subjects bid more aggressively than the equilibrium prediction and as a result the seller receives higher revenue. These aggressive bidding behaviors are investigated in the next subsections.

Figure 1b. Average differences between actual and theoretical revenues per period

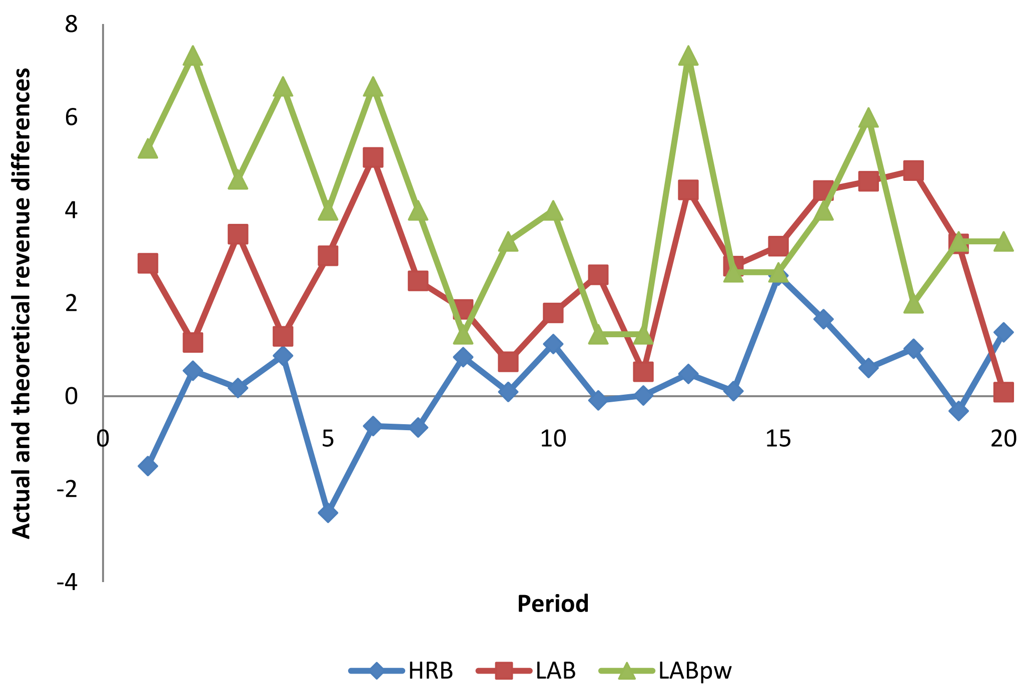
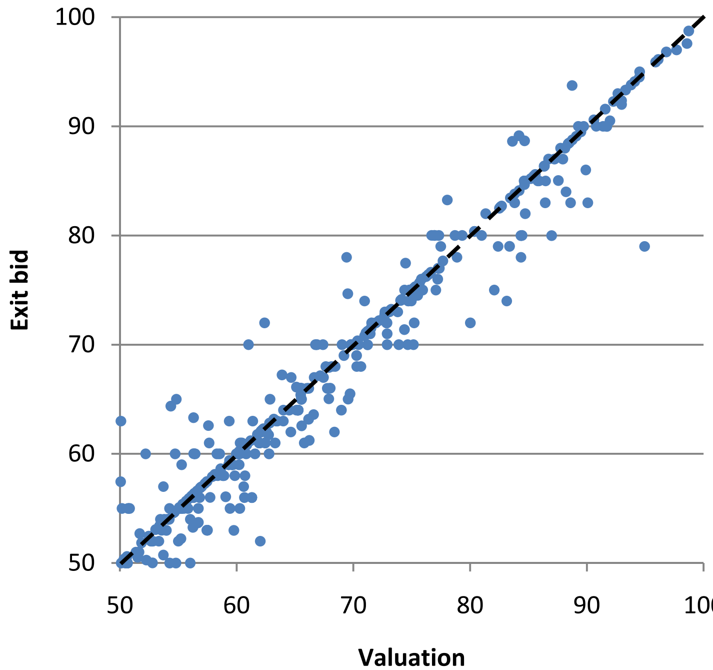


Figure 1b plots the average differences between the actual and theoretical revenues period by period. The revenues we observed in the HRB are close to the prediction of the theory, however the actual revenues are higher than the theoretical ones both in LAB and in LABpw. These results suggest that the subjects follow a truthtelling strategy in HRB, but they overbid in LAB and LABpw. Next, we will study the bidding strategies in detail.

4.1 Bidding behavior in treatment HRB

Figure 2 plots exit bids and corresponding values in HRB. The dashed line is a truthful bid function. To further examine bidding behavior, we estimate regressions of exit bids on values with bidder fixed effects, clustered by bidder. Subjects submitted a total of 342 exit bids. The deviation from truthful bidding is on average close to zero but there are instances of bid shading and bidding above one's value. 83 percent of exit bids were submitted in the round that theory predicts. The vast majority of subjects were successful in waiting until the right round to exit. Since the binary decision of staying in or out is similar to the strategic thinking of the English auction, this finding is in line with the success of value bidding in English auction experiments. Harstad (2000) finds that subjects who gain experience in auctions with this kind of binary decision making perform better in discovering the value bidding strategy in second-price sealed-bid auctions. Staying in the HRB auction until the price reaches the correct level provides a similar experience as participating in an English auction. Hence, once a subject reaches that round her exit bid is close to the true value. In line with this argument, the deviations from truthful bidding diminish for higher valuations. The reason might be that a bidder with high value makes more binary decisions before the price reaches her value and this helps her discover equilibrium exit bids.

Figure 2. Plot between values and exit bids in HRB auction



We regress exit bid on value with subject fixed effects, clustered by subject. The regression results are shown in Table . We cannot reject the null hypothesis that the coefficient of value is equal to one.

Table 4. Regression of exit bids on values in HRB auction

Independent variables	(1)
Constant	1.93 (1.20)
Value	0.97* (0.02)
R-squared	0.949

* Significant at 95% confidence interval. Standard errors are shown in the parentheses. Sample size is 342.

Table shows the averages of the ratios of exit bids to values for each period. We observed 15 to 20 exit bids in each period. As the ratios in all periods are close to one, subjects on average bid truthfully throughout the experiment.

Table 5. Average ratio of exit bid to value by period in HRB auction

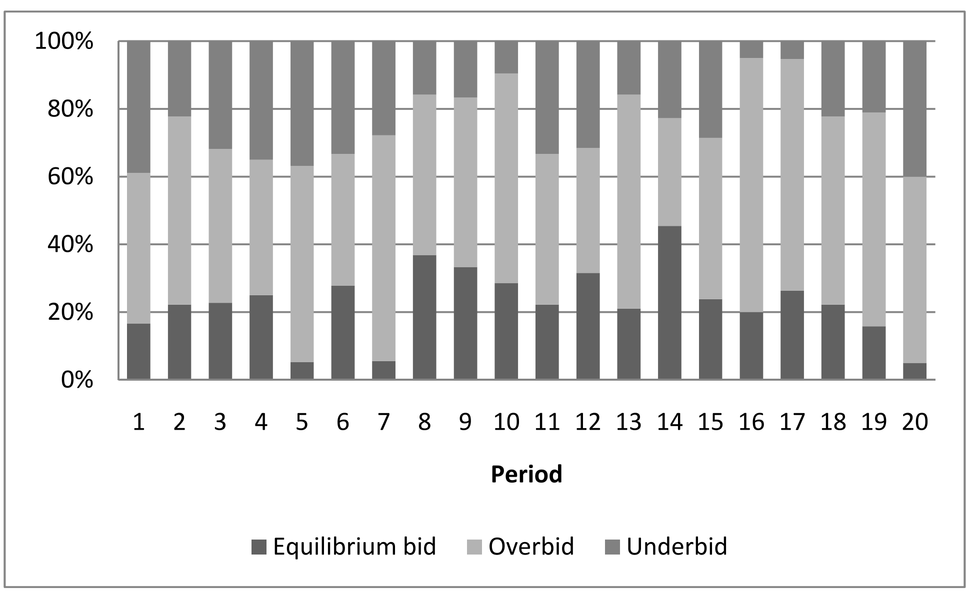
Period	*Exit bid / value*	*Period*	*Exit bid / value*
1	0.98 (0.04)	11	1.00 (0.04)
2	0.98 (0.04)	12	1.00 (0.04)
3	0.99 (0.07)	13	1.00 (0.05)
4	1.00 (0.08)	14	1.00 (0.04)
5	0.97 (0.05)	15	1.01 (0.05)
6	0.98 (0.02)	16	1.00 (0.05)
7	0.99 (0.03)	17	1.01 (0.03)
8	0.99 (0.03)	18	1.01 (0.04)
9	1.00 (0.04)	19	1.00 (0.04)
10	1.00 (0.05)	20	0.99 (0.02)

Standard deviations are shown in the parentheses.

4.2 Bidding behavior in treatment LAB

A total of 386 exit bids were submitted in LAB. The actual seller's share of gains from trade per auction is significantly higher than the theoretical prediction. This is the case because subjects bid more aggressively than the theory predicted as shown in Figure 3. We consider an exit bid as equilibrium bidding if it is within 1 percent of the theoretical prediction, otherwise as overbidding or underbidding.Starting from the first period, overbidding is observed and it is persistent throughout the experiment. 66 percent of exit bids lie above the theoretical exit bid.

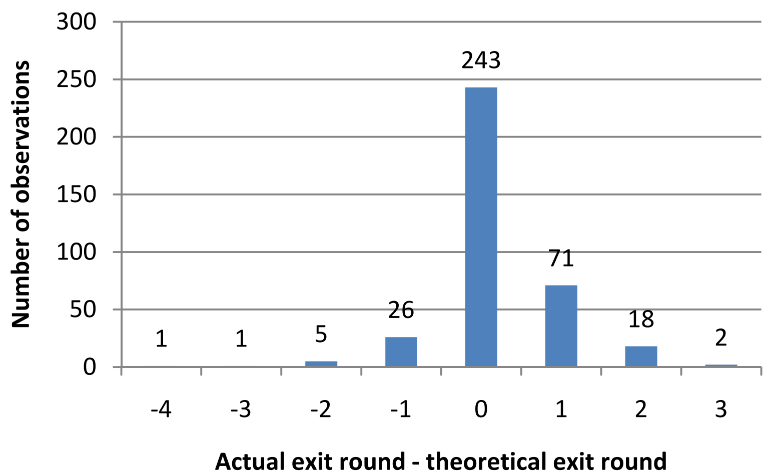
Figure 3. Percentage of over-, under-, equilibrium-bidding per period in LAB auction



4.3 *Bidding behavior in treatment LABpw*

A total of 367 exit decisions are observed. As predicted by the theory (Propositions 3), provisional losers tended to stay in until value was reached (only 11 violations out of 600 auctions). Additionally, similar to treatment LAB, aggressive bidding behavior in treatment LABpw is observed, as indicated by the higher revenue than the theoretical prediction and a mean exit price that is higher than the theoretical exit price. Figure 4 shows a histogram of differences between the actual and theoretical exit round. There are 91 instances of bidders staying in extra rounds versus 33 instances of bidders exiting early compared with the theory. In addition, among 233 active bidders at the end of the auction, 18 bidders bid more than value. It was mostly the provisional winners who failed to follow the equilibrium.

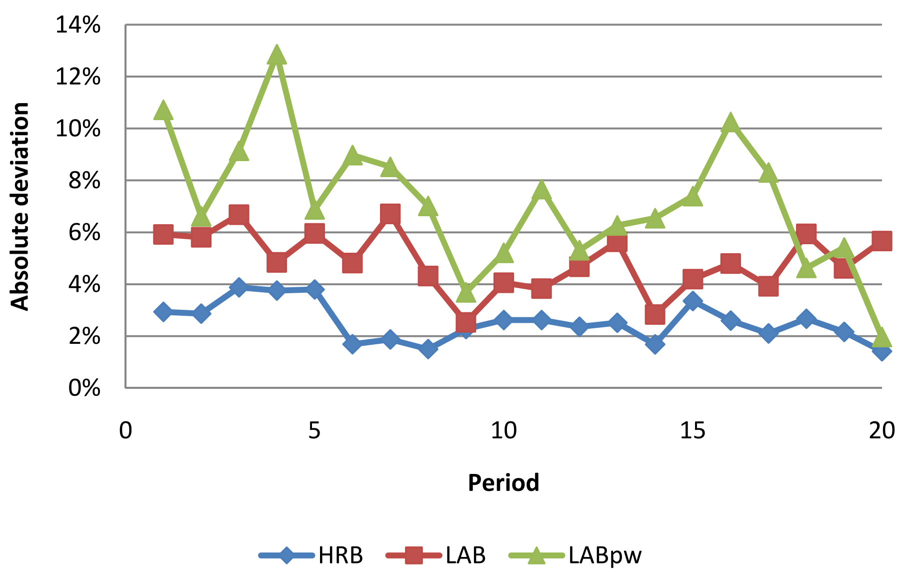
Figure 4. Histogram of differences between actual and theoretical exit rounds in LABpw



4.4 *Learning*

All auction formats are played 20 periods. In order to see if there is any difference between bidders' early and late plays, and whether learning is taking place, we compare the actual and theoretical exit bids throughout the experiment. We measure the deviations from equilibrium by the absolute percentage deviation: the absolute value of the difference between actual and theoretical exit bid divided by the theoretical exit bid for each auction. Figure 5 shows average absolute percentage deviations by period. Figure 5 suggests that bids in HRB and LAB auctions do not change much as bidders gain experience. HRB deviations are within 4 percent of the theoretical exit bids from the beginning of the session. LAB deviations do not vary much over time either. However, the deviations in LAB are consistently higher than in HRB. Absolute percentage deviations in LABpw are the highest, and show some tendency to decline over time, especially in the final five periods. Since provisional losers are successful in discovering equilibrium strategy, the variation in Figure 5 in LABpw is due to deviations of the provisional winners.

Figure 5. Average absolute deviation by period



5 Conclusion

The pricing rule is of fundamental importance in practical auction design. Pricing impacts both the efficiency and the revenues of the auction. Although there is an immense literature on the pricing rule in static (sealed-bid) auctions—first-price vs. second-price in single unit auctions and pay-as-bid vs. uniform-price in multi-unit auctions—little is known about alternative pricing rules in dynamic auctions commonly used in practice. We show how different pricing rules influence bidding behavior in discrete clock auctions in a simple setting.

Based on the standard theory in which bidders seek to maximize profits, the highest-rejected-bid (HRB) and the lowest accepted-bid (LAB) auctions seem equally good. They maximize revenues and are fully efficient in our unit-demand setting. Despite this theoretical result, LAB pricing is often used in practice. In our experiments, the LAB auction, both with and without exit bids, yielded higher revenues than the HRB auction. The HRB auction did better on efficiency grounds than LAB with provisional winner, but not significantly so when compared to LAB. Although there is a significant overbidding in LAB, this overbidding is not as severe as LAB's limit case, first-price sealed-bid auction. Perhaps, the dynamic nature of LAB enables bidders to handle the complex bidding strategies. It may be interesting to study the discrete clock auctions by varying the number of rounds and price increments. This may enable us to understand better the overbidding puzzle in sealed-bid auctions.

Developing strategies in HRB requires two things: when to exit as in an English auction, and what exit bid to submit as in a second-price sealed bid auction. Bidders submit exit bids close to their valuations. The tendency of bidding above value found in second-price auctions is not observed here. We conjecture that this is due to the experience bidders gain in deciding whether to exit each round. That thinking process is similar to decision making in an English auction. Harstad (2000) finds that practicing English auctions improves performance in second-price sealed-bid auctions. Similarly, our experiment shows that the multiple-round implementation of the second-price auction eliminates the tendency to overbid when faced with second-price incentives. The dynamic implementation also limits the spread between the highest bid and the price to at most one bid increment.

In situations like spectrum auctions where efficiency is the most important objective rather than revenue, we recommend the HRB auction since it achieves the efficient outcome with a simple value-bidding strategy. On the other hand, bidding strategy in the LAB auction is complex even in the simplest cases.

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Appendix: Bidder Instructions

Treatment HRB

Experiment Instructions

Welcome to the auction experiment. In this experiment, you will participate in auctions as a bidder. The precise rules and procedures that govern the operation of these auctions will be explained to you below.

Various research foundations have provided funds for this research. The instructions are simple, and if you follow them carefully and make good decisions you can finish the experiment with a considerable amount of money, which will be paid to you in cash at the end. The experiment will last about 80 minutes.

The type of currency used in this experiment is Experimental Currency Units (ECU). Participants completing the session do not risk losing any money. At the end of the experiment all your earnings will be converted to US Dollars. The conversion rate is 10 ECU = 1 US Dollar. You will be paid in cash when you finish the experiment. The more ECU you earn, the more US Dollars you earn. If you participate in this experiment until the session is over, then you will be paid an additional 5 US Dollars.

Auction Rules and Calculation of Earnings

You will be participating in 20 auctions. At the beginning of the first auction, you will be randomly matched with another participant in this room; every auction, you will be randomly re-matched with a different participant. In each auction you will be bidding against the participant with whom you are matched.

In a given auction, there is a fictitious good that is sold and your aim is to bid in order to win this good. When the first auction starts, you will observe your valuation of the fictitious good. Your valuation is a number between 50 and 100 and it is randomly selected from the [50,100] interval with equal probability and rounded to the nearest cent. The other bidder participating in this auction also receives his or her independent valuation for the fictitious good and his or her valuation is also randomly selected from [50,100] interval. Each bidder will know only his or her own valuation.

The price for the fictitious good will start at 50 and will gradually increase to 60, 70, 80, 90, and 100. At price level 50, both you and your opponent are in the auction. The computer will ask you if you would like to stay in the auction when the price increases to 60. You either stay IN which indicates that you are willing to pay 60 for the good or you stay OUT. If you stay out for at a price of 60, you need to enter an exit bid which must be an amount between 50 and 60. The exit bid is the maximum amount that you are willing to pay for the good. For example, if you stay out and indicate that your exit bid is 54, then it means you would be willing to pay at most 54 for the good. The exit bid has to be an amount between the previous price level and the current price at which you are staying out. There are four possible things that can happen:

- You stay IN, and your opponent stays OUT with an exit bid of, say, 55: Then you win the fictitious good and pay 55, your opponent's exit bid.
- You stay OUT with exit bid of, say 57, and your opponent stays IN: Then your opponent wins the fictitious good and pays 57, your exit bid.
- You stay OUT, your opponent stays OUT: Then the bidder who submitted the highest exit bid wins the fictitious good and pays the smaller of the exit bids.
- You stay IN, your opponent stays IN: Then the price moves to the next level which is 70.

If both you and your opponent stay in the auction for price level 60, then the computer will ask if you would like to stay in the auction when the price increases to 70. Again there are four possible things that can happen:

- You stay IN, and your opponent stays OUT with exit bid of, say, 65: Then you win the fictitious good and pay 65, your opponent's exit bid.
- You stay OUT with exit bid of, say 67, and your opponent stays IN: Then your opponent wins the fictitious good and pays 67, your exit bid.
- You stay OUT, your opponent stays OUT: Then the bidder who submitted the highest exit bid wins the fictitious good and pays the smaller of the exit bids.
- You stay IN, your opponent stays IN: Then the price moves to the next level which is 80.

If both you and your opponent stay in the auction for price level 70, then the computer will ask if you would like to stay in the auction at a price of 80.

The same procedure will repeat for price levels of 90 and 100. If both of you are still in the auction when the price level is 100, then the computer will randomly assign the fictitious good to one of the bidders with equal chance and that bidder will pay 100.

Please note that the price level increases only if both bidders stay in the auction. If only one bidder stays in and the other one stays out with an exit bid, the bidder who is in wins the good and pays the exit bid of the other bidder. Otherwise, if both bidders stay out then the one with the higher exit bid wins the good and pays the exit bid of the other bidder. For example, when the price level is 70, if you indicate to stay OUT with exit bid of 63, and your opponent indicates to stay OUT with exit bid of 67, then your opponent wins the good (he or she has the higher exit bid) and pays 63 (which is the smaller exit bid). If you both submit the same exit bid while staying out then, the computer randomly assigns the good to one of the bidders, and the winner pays the exit bid of the other.

When one bidder wins the good, the auction is over. If you are the winner at a certain price, then you earn the difference between your valuation and the price. For example, let us say you have a valuation of 82.55 for the fictitious good in the current auction and you win the good at a price of 61. Then your earning from this round is

Earning = 82.55 – 61 = 21.55 ECU

When the first auction is completed, the second auction will start. At the beginning of the second auction, you will be randomly matched with another participant in this room and play with that person in this round. First, the computer will show you your new valuation for the good for this auction. It is again a randomly selected number from [50,100] interval. Your opponent will also observe his or her own valuation for the good for this auction privately. The same auction rules as in the first auction will apply.

There are 20 auctions in total. The computer will sum up your earnings in ECU in all auctions and convert this amount to the US Dollars by dividing by 10. We will pay you this amount in cash at the end of the experiment in person.

In order to make sure that you understand the rules of the auction, we have a test period before the real session starts. In this test period, you will see some multiple choice questions about the auction rules. Please answer those questions to the best of your knowledge. You may look at the hard copy of the instructions while answering them. Once you answer all the questions correctly, one practice auction will be conducted for which no payment will be made. Then the experiment will start with 20 real auctions.

Please ask if you have any questions.

Questions for the test period *(asked to the subjects during the test period by the computer)*

1) The price level just moved from 60 to 70 and the computer asks you if you would like to stay in at a price of 70. You said that you are IN and your opponent said that he or she is OUT with an exit bid of 65. Then what would be the outcome of the auction?
    a) You would win the good and pay 60.
    b) Your opponent would win the good and pay 70.
    c) You would win the good and pay 65.
    d) Nobody would win the good and the price would move to 80.

Answer: (c)

2) The price level just moved from 70 to 80 and the computer asks you if you would like to stay in for price level 80. You decided to stay OUT for price level of 80. What are the possible exit bids you may enter?
    a) Any amount between 65 and 70.
    b) Any amount between 70 and 80.
    c) Any amount between 60 and 70.
    d) Any amount between 80 and 90.

Answer: (b)

3) Let us say, your valuation of the good is 91 for the current round. The price level just moved from 70 to 80 and the computer asks you if you would like to stay in for price level 80. You said that you are OUT with an exit bid of 77 and your opponent said that he or she is OUT with an exit bid of 74. Then what would be your and your opponent's earnings for this round?
    a) You would win the good and pay 77. You would earn 14 and your opponent would earn 0.
    b) Your opponent would win the good and pay 74. You would earn 0 and you cannot know your opponent's earning without knowing his or her valuation.
    c) You would win the good and pay 80. You would earn 11 and your opponent would earn 0.
    d) You would win the good and pay 74. You would earn 17 and your opponent would earn 0.

Answer: (d)

Treatment LAB

<u>Experiment Instructions</u>

Welcome to the auction experiment. In this experiment, you will participate in auctions as a bidder. The precise rules and procedures that govern the operation of these auctions will be explained to you below.

Various research foundations have provided funds for this research. The instructions are simple, and if you follow them carefully and make good decisions you can finish the experiment with a considerable amount of money, which will be paid to you in cash at the end. The experiment will last about 80 minutes.

The type of currency used in this experiment is Experimental Currency Units (ECU). Participants completing the session do not risk losing any money. At the end of the experiment all your earnings will be converted to US Dollars. The conversion rate is 10 ECU = 1 US Dollar. You will be paid in cash when you finish the experiment. The more ECU you earn, the more US Dollars you earn. If you participate in this experiment until the session is over, then you will be paid an additional 5 US Dollars.

Auction Rules and Calculation of Earnings

You will be participating in 20 auctions. At the beginning of the first auction, you will be randomly matched with another participant in this room; every auction, you will be randomly re-matched with a different participant. In each auction you will be bidding against the participant with whom you are matched.

In a given auction, there is a fictitious good that is sold and your aim is to bid in order to win this good. When the first auction starts, you will observe your valuation of the fictitious good. Your valuation is a number between 50 and 100 and it is randomly selected from the [50,100] interval with equal probability and rounded to the nearest cent. The other bidder participating in this auction also receives his or her independent valuation for the fictitious good and his or her valuation is also randomly selected from [50,100] interval. Each bidder will know only his or her own valuation.

The price for the fictitious good will start at 50 and will gradually increase to 60, 70, 80, 90, and 100. At price level 50, both you and your opponent are in the auction. The computer will ask you if you would like to stay in the auction when the price increases to 60. You either stay IN which indicates that you are willing to pay 60 for the good or you stay OUT. If you stay out at a price of 60, you need to enter an exit bid which must be an amount between 50 and 60. The exit bid is the maximum amount that you are willing to pay for the good. For example, if you stay out and indicate that your exit bid is 54, then it means you would be willing to pay at most 54 for the good. The exit bid has to be an amount between the previous price level and the current price at which you are staying out. There are four possible things that can happen:

- You stay IN, and your opponent stays OUT: Then you win the fictitious good and pay 60.
- You stay OUT, and your opponent stays IN: Then your opponent wins the fictitious good and pays 60.
- You stay OUT, your opponent stays OUT: Then the bidder who submitted the highest exit bid wins the fictitious good and pays his or her exit bid.
- You stay IN, your opponent stays IN: Then the price moves to the next level which is 70.

If both you and your opponent stay in the auction for price level 60, then the computer will ask if you would like to stay in the auction when the price increases to 70. Again there are four possible things that can happen:

- You stay IN, and your opponent stays OUT: Then you win the fictitious good and pay 70.
- You stay OUT, and your opponent stays IN: Then your opponent wins the fictitious good and pays 70.
- You stay OUT, your opponent stays OUT: Then the bidder who submitted the highest exit bid wins the fictitious good and pays his or her exit bid.
- You stay IN, your opponent stays IN: Then the price moves to the next level which is 80.

If both you and your opponent stay in the auction for price level 70, then the computer will ask if you would like to stay in the auction at a price of 80.

The same procedure will repeat for price levels of 90 and 100. If both of you are still in the auction when the price level is 100, then the computer will randomly assign the fictitious good to one of the bidders with equal chance and that bidder will pay 100.

Please note that the price level increases only if both bidders stay in the auction. If only one bidder stays in and the other one stays out, the bidder who is in wins the good and pays the price for which he or she indicated to stay in. Otherwise, if both bidders stay out then the one with the higher exit bid wins the good and pays his or her exit bid. For example, when the price level is 70, if you indicate to stay OUT with exit bid of 63, and your opponent indicates to stay OUT with exit bid of 67, then your opponent wins the good (he or she has the higher exit bid) and pays 67 (his or her exit bid). If you both submit the same exit bid while staying out then, the computer randomly assigns the good to one of the bidders, and the winner pays his or her exit bid.

When one bidder wins the good, the auction is over. If you are the winner at a certain price, then you earn the difference between your valuation and the price. For example, let us say you have a valuation of 82.55 for the fictitious good in the current auction and you win the good at a price of 61. Then your earning from this round is

Earning = 82.55 – 61 = 21.55 ECU

When the first auction is completed, the second auction will start. At the beginning of the second auction, you will be randomly matched with another participant in this room and play with that person in this round. First, the computer will show you your new valuation for the good for this auction. It is again a randomly selected number from [50,100] interval. Your opponent will also observe his or her own valuation for the good for this auction privately. The same auction rules as in the first auction will apply.

There are 20 auctions in total. The computer will sum up your earnings in ECU in all auctions and convert this amount to the US Dollars by dividing by 10. We will pay you this amount in cash at the end of the experiment in person.

In order to make sure that you understand the rules of the auction, we have a test period before the real session starts. In this test period, you will see some multiple choice questions about the auction rules. Please answer those questions to the best of your knowledge. You may look at the hard copy of the instructions while answering them. Once you answer all the questions correctly, one practice auction will be conducted for which no payment will be made. Then the experiment will start with 20 real auctions.

Please ask if you have any questions.

Questions for the test period *(asked to the subjects during the test period by the computer)*

1) The price level just moved from 60 to 70 and the computer asks you if you would like to stay in at a price of 70. You said that you are IN and your opponent said that he or she is OUT with an exit bid of 65. Then what would be the outcome of the auction?
    a) You would win the good and pay 70.
    b) Your opponent would win the good and pay 70.
    c) You would win the good and pay 65.
    d) Nobody would win the good and the price would move to 80.

Answer: (a)

2) The price level just moved from 70 to 80 and the computer asks you if you would like to stay in for price level 80. You decided to stay OUT for price level of 80. What are the possible exit bids you may enter?
    a) Any amount between 65 and 70.
    b) Any amount between 70 and 80.
    c) Any amount between 60 and 70.
    d) Any amount between 80 and 90.

Answer: (b)

3) Let us say, your valuation of the good is 91 for the current round. The price level just moved from 70 to 80 and the computer asks you if you would like to stay in for price level 80. You said that you are OUT with an exit bid of 77 and your opponent said that he or she is OUT with an exit bid of 74. Then what would be your and your opponent's earnings for this round?
    a) You would win the good and pay 77. You would earn 14 and your opponent would earn 0.
    b) Your opponent would win the good and pay 74. You would earn 0 and you cannot know your opponent's earning without knowing his or her valuation.
    c) You would win the good and pay 80. You would earn 11 and your opponent would earn 0.
    d) You would win the good and pay 74. You would earn 17 and your opponent would earn 0.

Answer: (a)

Treatment LABpw

Experiment Instructions

Welcome to the auction experiment. In this experiment, you will participate in auctions as a bidder. The precise rules and procedures that govern the operation of these auctions will be explained to you below.

Various research foundations have provided funds for this research. The instructions are simple, and if you follow them carefully and make good decisions you can finish the experiment with a considerable amount of money, which will be paid to you in cash at the end. The experiment will last about 80 minutes.

The type of currency used in this experiment is Experimental Currency Units (ECU). Participants completing the session do not risk losing any money. At the end of the experiment all your earnings will be converted to US Dollars. The conversion rate is 10 ECU = 1 US Dollar. You will be paid in cash when you finish the experiment. The more ECU you earn, the more US Dollars you earn. If you participate in this experiment until the session is over, then you will be paid an additional 5 US Dollars.

Auction Rules and Calculation of Earnings

You will be participating in 20 auctions. At the beginning of the first auction, you will be randomly matched with another participant in this room; every auction, you will be randomly re-matched with a different participant. In each auction you will be bidding against the participant with whom you are matched.

In a given auction, there is a fictitious good that is sold and your aim is to bid in order to win this good. When the first auction starts, you will observe your valuation of the fictitious good. Your valuation is a number between 50 and 100 and it is randomly selected from the [50,100] interval with equal probability and rounded to the nearest cent. The other bidder participating in this auction also receives his or her independent valuation for the fictitious good and his or her valuation is also randomly selected from [50,100] interval. Each bidder will know only his or her own valuation.

The price for the fictitious good will start at 50 and will gradually increase to 60, 70, 80, 90, and 100. At price level 50, both you and your opponent are in the auction. Then the computer will randomly determine one of you as a **provisional winner**. Each bidder has 50% chance of being a provisional winner. Next, the computer will ask you if you would like to stay in the auction when the price increases to 60. There are four possible things that can happen:

- You stay IN, your opponent stays OUT: Then you win the fictitious good and pay 60.
- You stay OUT, your opponent stays IN: Then your opponent wins the fictitious good and pays 60.
- You stay OUT, your opponent stays OUT: Then the provisional winner wins the fictitious good and pays 50.
- You stay IN, your opponent stays IN: Then the price moves to the next level which is 70.

If both you and your opponent stay in the auction for price level 60, then the computer will randomly determine a new provisional winner and ask if you would like to stay in the auction when the price increases to 70. Again there are four possible things that can happen:

- You stay IN, your opponent stays OUT: Then you win the fictitious good and pay 70.
- You stay OUT, your opponent stays IN: Then your opponent wins the fictitious good and pays 70.
- You stay OUT, your opponent stays OUT: Then the provisional winner wins the fictitious good and pays 60.
- You stay IN, your opponent stays IN: Then the price moves to the next level which is 80.

If both you and your opponent stay in the auction for price level 70, then the computer will randomly determine a new provisional winner and ask if you would like to stay in the auction when price increases to 80.

The same procedure will repeat for price levels 90 and 100. If both of you are still in the auction when the price level is 100, then the computer will randomly assign the fictitious good to one of the bidders with equal chance, and the winner will pay 100.

Please note that the price level only increases if both bidders stay in the auction. Each time the price level increases a new provisional winner is randomly determined by the computer and each bidder has equal chance of being the provisional winner at that price level. The provisional winner wins the fictitious good at the previous price level if both bidders stay OUT at the current price level. Otherwise, if one bidder stays in and the other bidder stays out in the current round, then the bidder who is IN wins the good at the current price, regardless of the provisional winner designation.

When one bidder wins the good, the auction is over. If you are the winner at a given price, then you earn the difference between your valuation and the price. For example, let us say you have a valuation of 82.55 for the fictitious good in the current auction and you win the good at a price of 60. Then your earning from this round is

Earning = 82.55 – 60 = 22.55 ECU

When the first auction is completed, the second auction will start. At the beginning of the second auction, you will be randomly matched with another participant in this room and play with that person in this auction. First, the computer will show you your new valuation for the good for this auction. It is again a randomly selected number from [50,100] interval. Your opponent will also observe his or her own valuation of the good for this auction privately. The same auction rules as in the first auction will apply.

There are 20 auctions in total. The computer will sum up your earnings in ECU in all auctions and convert this amount to US Dollars by dividing by 10. We will pay you this amount in cash at the end of the experiment in person.

In order to make sure that you understand the rules of the auction, we have a test period before the real session starts. In this test period, you will see some multiple choice questions about the auction rules. Please answer those questions to the best of your knowledge. You may look at the hard copy of the instructions while answering them. Once you answer all the questions correctly, one practice auction will be conducted for which no payment will be made. Then the experiment will start with 20 real auctions.

Please ask if you have any questions.

Questions for the test period *(asked to the subjects during the test period by the computer)*

1) The price level just moved from 60 to 70 and the computer determined **you** as the provisional winner for the current price. The computer asks you if you would like to stay in for price level 70. You said that you are IN and your opponent said that he or she is OUT. Then what would be the outcome of the auction?

   a) Your opponent would win the good and pay 70.
   b) You would win the good and pay 70.
   c) You would win the good and pay 60.
   d) Nobody would win the good and the price would move to 80.

Answer: (b)

2) The price level just moved from 60 to 70 and the computer determined **your opponent** as the provisional winner for the current price. The computer asks you if you would like to stay in for price level 70. You said that you are OUT and your opponent said that he or she is OUT. Then what would be the outcome of the auction?

a) You would win the good and pay 70.
b) Your opponent would win the good and pay 70.
c) You would win the good and pay 60.
d) Your opponent would win the good and pay 60.

Answer: (d)

3) Your valuation of the good is 91 for the current auction. The price level just moved from 70 to 80 and the computer determined **you** as the provisional winner for the current price. The computer asks you if you would like to stay in for price level 80. You said that you are OUT and your opponent said that he or she is OUT. Then what would be your and your opponent's earnings for this auction?

a) You would win the good and pay 70. You would earn 21 and your opponent would earn 0.
b) Your opponent would win the good and pay 70. You would earn 0 and you cannot know your opponent's earning without knowing his or her valuation.
c) You would win the good and pay 80. You would earn 11 and your opponent would earn 0.
d) Your opponent would win the good and pay 80. You would earn 0 and your opponent would earn 15.

Answer: (a)