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The Effect of Timing on Jump Bidding in Ascending Auctions

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We investigate the role of timing in ascending auctions under the premise that time is a valuable resource. Traditional models of the English auction ignore timing issues by assuming that the auction occurs instantaneously. However, when auctions are slow, as Internet auctions used for procurement often are, there are significant opportunity or monitoring costs to bidders, and the choice of the size of the jump bid becomes a strategic decision. We study the choice in the experimental laboratory by systematically varying the opportunity costs associated with fast bidding. When time is more valuable bidders respond by choosing larger jump bids. Surprisingly, the economic performance of the auction is not significantly affected. We develop a simple model of ascending auctions with impatient bidders that provides insights into the effect jump bids have on auction performance.

Key words: auctions; experimental economics; jump bidding; procurement; behavioral issues in operations management

1. Introduction

The advent of the Internet provided new opportunities for the use of auctions in general and for the use of procurement auctions in particular. The use of *e-sourcing*[1] for procurement has been increasing over the past decade, with total revenues projected to exceed $3 billion by 2005.[2] Auctions are typically used as part of e-sourcing technologies and attracted considerable attention when General Electric claimed savings of over $600 million and net savings of over 8% in 2001 using SourceBid, a reverse auction tool that is a part of GE's Global Exchange Network (Global Exchange Services

2003). Other examples of the use of electronic auctions for procurement include the U.S. General Services Administration (Sawhney 2003), which attributed savings of 12 to 48% to the use of reverse auctions, and FreeMarkets, now part of Ariba—the leading e-sourcing provider—that saved approximately 20% for their customers on over $30 billion in purchases between 1995 and 2001.

The Internet allows geographically dispersed bidders to compete on price, potentially leading to lower costs for the buyers. Inernet auctions also give the auction designer greater flexibility in deciding on the relative speed of the auction. Internet auctions typically last anywhere from a few hours (FreeMarkets) to over a week (eBay). There are a number of practical settings, such as complex combinatorial auctions used to procure transportation services (see, for example, Ledyard et al. 2002) and department store sales (see, for example, Carare and Rothkopf 2005), in which fast auctions are not feasible. Standard auction theory does not consider the role of time in auctions; it assumes all auctions occur instantaneously. Although the standard theory may be sufficient when auctions are fast, as applications for slower, complex auctions become

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[1] E-sourcing refers to the use of Internet-enabled applications and decision support tools that facilitate competitive and collaborative interactions among buyers and suppliers, through the use of online mechanisms including, specifically, reverse auctions. See Engelbrecht-Wiggans and Katok (2006) for a discussion of the use of e-sourcing mechanisms for procurement. See Kouvelis, Chambers, and Wang (2006) for a discussion of research questions related to the development of Internet technologies and supply chain management.

[2] According to a September 2002 report by the Aberdeen Group (Aberdeen Group 2002), e-sourcing revenues increased from $820 million in 2001 to $1.14 billion in 2002 and are projected to increase to $3.13 billion in 2005.

more prevalent, the issues of time, its associated costs, and the effect these costs have on bidding behavior become more relevant.

High-value procurement auctions have two key features that make studying bidder behavior when time is valuable particularly pertinent: (1) they often have activity-based ending rules, so bidder behavior can affect the auction duration, and (2) executives involved in these high-valued auctions often have high opportunity costs associated with their time (e.g., they are highly paid and have many other responsibilities). Many on-line auctions used for procurement utilize some sort of "soft close" rule instead of a fixed ending time that is familiar from eBay. For example, the Federal Communications Commission (FCC), in its description of the commonly used SMR auction, stated the following about how an auction is ended: "In an SMR auction, there is no preset number of rounds. Bidding continues, round after round, until a round occurs in which all bidder activity ceases. That round becomes the closing round of the auction."[3] As a result of the above activity-based ending rule, the length of the auctions varied dramatically (the PCS DEF Block auction lasted 142 days). The discussion of the choice of auction ending rules has been an important topic in designing the FCC spectrum auctions, as well as other auctions, such as those for transportation services (Ledyard et al. 2002). Even in simpler settings, many auctions use a soft close that allows bidder to respond if a bid is placed in the closing minutes.

Because the results of procurement auctions can significantly affect a supplier's profitability, the auctions also generally require the attention of executives within the company and, at times, the services of highly paid consultants. The consultants often charge on an hourly or daily basis, and executives have other important issues in the company to address. Therefore, if the supplier can end the auction sooner with similar results, the supplier is likely to experience lower costs. In addition, there may be added benefits to the early completion of an auction, such as allowing more time to prepare to provide the terms of the supply contract.

Therefore, we investigate the role of bidder impatience on behavior in English auctions. The English auction is an open outcry, ascending auction; at any time bidders can bid amounts greater than the current high bid and possibly some minimum increment, and the winner is the bidder who placed the last high bid. Bidders in the English auction can take actions that affect auction duration and reduce the costs associated with slow auctions. They can do this by placing *jump bids* that are greater than the minimum increase required by the auctioneer. The empirical relevance of jump bidding has been widely noted in a number of settings including some of the largest, highest revenue auctions. Isaac, Salmon, and Zillante (2007) examine 41 spectrum auctions conducted by the FCC and determined jump bidding is a persistent and common feature of these auctions (sometimes over 40% of the bids are jump bids). Easley and Tenorio (2004) used data from 236 internet auctions and reported that jump bidding was observed in over one third of their sample, providing additional evidence that an environment very similar to the one we analyze and implement in the laboratory is applicable to internet auctions.[4]

The jump bidding strategy, although beneficial in reducing the auction duration, may also negatively affect auction performance. The winning bidder may pass by the second highest willingness-to-pay, and this may result in foregone profits for the bidder, Alternately, because placing bids extends the auction and increases costs, bidders will never bid precisely up to their valuation (Proposition 2). Thus, bidders may stop bidding prior to reaching the second highest willingness-to-pay, and this may result in reduced revenue for the auctioneer. Although a number of experimental studies suggested jump bidding may be detrimental to auction performance (Banks et al. 2003; Porter et al. 2003), our study systematically varies the incentives for jump bidding to observe the extent to which jump bidding affects the overall performance of the institution. We find that although bidder behavior is affected by an increase in the opportunity cost of time, the aggregate performance of the auction (efficiency, bidder profits, and seller revenue) is robust to the costs. The results are particularly relevant for designers of high-valued procurement auctions.

We begin by briefly reviewing some related literature (Section 2) We formulate some simple theory that helps us articulate research hypotheses and provide a baseline for laboratory tests (Section 3). We then implement impatience in the laboratory with a treatment in which bidders can complete as many auctions as they can during a fixed period of time. We compare bidding behavior in the treatment (hence referred to as the "timed" treatment) with the behavior in sessions in which bidders completed a fixed and pre-determined number of auctions in a session (hence referred to as the "untimed" treatment). The description of the

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[3] From http://wireless.fcc.gov/auctions/default.htm?job=about_auctions&page=2.

[4] Easley and Tenorio (2004) data came from auctions that were conducted on two Internet auction sites, Onsale.com and uBid.com. Auctions on both sites had activity-based closing rules: ". . . this rule specified that, after the posted closing of the auction, bidding would stop when no bid has been received in the last 5 (Onsale) or 10 (uBid) minutes." (p. 1412). The closing rule for our laboratory auctions was the same: it specified that the bidding stops if there were no new bids for 30 seconds.

experimental design and the protocol is given in Section 4, and the results are given in Section 5. In Section 6 we present conclusions and discuss practical implications of our work. Proofs are contained in the Appendix.

2. Related Literature

In the current paper we extend our previous findings (Katok and Kwasnica 2007), where we focused specifically on two common auction formats: the Dutch or reverse clock auction and the first-price sealed bid auction. Although these auctions are strategically equivalent under the traditional assumptions of auction theory, they vary markedly in terms of the role of timing. In the Dutch auction, a decision to stop the clock at a higher price is also a decision to end the auction earlier. In the first-price sealed bid auction, the bidders have no direct ability to control the time at which the object is sold. However, in both cases, the auction designer can make important design choices based upon the importance of timing; he can select different clock speeds (Dutch auction) or decide on different closing times for accepting bids (sealed bid auctions).

In our previous research (Katok and Kwasnica 2007) we developed a simple theory of Dutch auctions with impatient bidders and tested the theory in the laboratory by comparing four institutions: the sealed bid first-price auction and the Dutch auctions with three different clock speeds (slow, medium, and fast). We reported that, contrary to standard theory but in line with our theory of impatient bidders, the auctioneer's revenue increases as the clock slows. In addition to providing a valuable insight for auction designers, our work also provided an explanation to an often-cited anomaly in the experimental auction literature: Cox, Roberson, and Smith (1982) reported that fast Dutch auctions in the laboratory yield lower revenue than sealed bid first-price auctions, but Lucking-Reiley (1999) reported the opposite result for a slow Dutch auction conducted over the Internet. Our theory of impatient bidders organizes that data, as well as our own data, that compare the institutions in a more controlled way. Carare and Rothkopf (2005) described a decision theoretic model of a slow Dutch auction that can also explain some of the differences.

Most previous studies that model costly bidding in ascending-bid auctions focused on the value of jump bidding as a technique for bidders to signal their values. Avery (1998) developed a model for the affiliated value setting, and Daniel and Hirshleifer (1998) and Easley and Tenorio (2004) presented a model for the private value setting. Those models assume bidders incur a cost every time they *place a bid* and demonstrate that there exist equilibria in which bidders place large jump bids early to communicate information and end bidding early. Our focus is on bidding behavior when *time itself*, rather than the actual placement of bids, is valuable, so bidders incur cost that increases with auction duration. In that, we examine a setting similar to what we originally studied (Katok and Kwasnica 2007), in which bidders experience significant opportunity or monitoring costs associated with the auctions. Isaac, Salmon, and Zillante (2007) also examined a model with bidder impatience, but they imposed discounting and used a simulation-based approach to arrive at their theoretical results.

An early and influential work was that of Rothkopf and Harstad (1994). They examined the choice of bid increments in single-unit ascending auctions. They also presented a decision theoretic model where bid jumping is optimal late in the auction. Recently, Bapna, Goes, and Gupta (2003) examined the important issue of bid increment choice by the auctioneer in multi-unit auctions. To develop a tractable model, they make a number of modeling assumptions, including focusing on a pedestrian bidding by the bidders. Rather than assuming a particular behavior by the bidders, our objective is to understand the strategic choices made by impatient bidders. Hopefully, a better understanding of jump bidding strategies by bidders will result in even better bid increment choices by a revenue maximizing auctioneer.

3. A Simple Model of English Auctions with Impatient Bidders

We consider the English auction with two bidders. Both bidders are risk neutral and have independent privately known values v_i drawn with support on $[0, \bar{v}]$. We assume bidders are impatient. As time passes, bidders experience a cost $c(t)$ for participating in the auction. We assume that $c(t) \geq 0$ and increasing in t. A bidder's profit from participating in an auction that lasts for time t is given by

$$u_i(v_i, t) = \begin{cases} v_i - b - c(t) & \text{if win} \\ -c(t) & \text{otherwise} \end{cases},$$

where b is the price the winning bidder pays. The cost $c(t)$ can be thought of as the cost of monitoring the auction or the opportunity cost associated with the time spent bidding in the auction. A bidder must pay these costs win or lose, regardless of the actual number of bids placed.

In the laboratory, the costs are most likely the bidder's perceived value of ending the auction earlier to speed the completion of the experimental session or to complete more auction periods. In practice, they might be the salaries of designated bidders or the cost associated with delayed contract completion. Note that the costs also distinguish our model from that of

Daniel and Hirshleifer (1998) and Easley and Tenorio (2004); in both of those models bidders bear the costs only upon bidding. Although the models are most appropriate in settings where other costs, such as those associated with monitoring the auction or the opportunity costs associated with delayed completion of the transaction, are minimal, in the realm of on-line procurement there are numerous settings in which the auction will require considerable attention by highly paid executives *throughout* the auction and earlier consummation of the contract could result in substantial savings.

The English auction begins at time $t = 1$. Bidders can simultaneously enter bids or abstain from bidding. Whenever a new bid is placed, the high bid, b_t, is announced and the auction moves to the next round. There is a minimum bid increment m assumed to be constant for every round.[5] Therefore, a bid in round $t + 1$ must be greater than or equal to the previous high bid plus m, or $b_{t+1} \geq b_t + m$. The auction ends at round t if both bidders abstain.[6]

A bidder's strategy is a decision to abstain or bid a certain amount greater than or equal to the current high bid plus the increment, given the history of bids placed. An equilibrium is then a set of strategies and consistent beliefs for each bidder such that each bidder maximizes her expected utility given the strategies of the other bidders. In contrast to the Dutch and sealed bid auctions examined by Katok and Kwasnica (2007), where each player selects at most one action, the English auction is a dynamic game with many actions (bids) by each player. This complicates the analysis and makes complete characterization of the equilibrium set nearly impossible. Whereas Isaac, Salmon, and Zillante (2007) used simulation to deal with this problem, we investigate what sorts of actions we can rule out as potential equilibria and then we turn to the laboratory to provide more detailed insights.

We first ask whether costs, as we have implemented them, will cause jump bidding. If there is no jump bidding, then bidders must be bidding the minimum increment m at all times until they reach their value.

This behavior is known as *pedestrian* or straightforward bidding. The first proposition shows that for sufficiently high opportunity costs we can expect jump bidding in any equilibrium.

PROPOSITION 1. *For all m, there exists c(t) such that pedestrian bidding is not an equilibrium.*

Intuitively, when monitoring or opportunity costs accrue rapidly, a bidder would prefer to speed up the auction by increasing the bid by more than the minimum increment. For example, by increasing the bid by $2m$, a bidder knows that the auction will end at least one round sooner. The cost of the strategy is that she may pay a higher price in the event that she wins, but if the opportunity costs are high enough relative to the minimum bid increment she will prefer to offset the costs.

Unfortunately, it is difficult to say much more explicitly concerning what types of jump bidding equilibria we will see. There are certainly multiple equilibria and an exact characterization would involve complete description of a huge dynamic game. Because the game structure and costs are similar to that used by Daniel and Hirshleifer (1998), we know there are jump bidding equilibria that involve signaling. In a signaling equilibrium, the bidders learn about the private value of the other bidder via the bids placed. Although very complex signaling equilibria are possible, most reasonable strategies involve few bids in the early rounds of the auction. In fact, following from Daniel and Hirshleifer, there exists a signaling equilibrium where all bidders bid the risk neutral Nash equilibrium bid in the first-price sealed bid auction in round one and abstain in subsequent rounds. Although interesting, we do not expect such strategies to be the primary motivation for jump bidding. Therefore, we examine general characteristics of other types of equilibria of the English auction where time is valuable.

We begin by showing that performance of the auction can be affected by the presence of these costs. We show that bidders will never be willing to raise the bid level to their value. This may impact the performance of the auction by lowering revenue collected (because the bid fails to reach the second highest valuation) and reducing efficiency.

PROPOSITION 2. *In any equilibrium, for all v, m, and c(t), there exists some standing high bid $b < v$ such that bidders will prefer to stop bidding.*

Intuitively, the minimum increment immediately preceding each bidder's value $(v - m)$ is an upper bound on the bids they are willing to place in the auction; increasing the bid to one's value extends the auction by at least one round and results in no profit from the purchase of the object. However, the extent to which

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[5] In practice, the bid increment often changes during the course of the auction. The results presented here could be extended to such settings, but we maintain a fixed increment for simplicity. We discuss how our results might provide insights into the optimal design of increment levels in the Conclusions.

[6] We assume the auction has a soft close. Although many common consumer-to-consumer auction sites such as eBay use fixed closing time or hard close rules, almost all large business-to-business auctions utilize some sort of soft close that depends upon bidding activity. Although the way these rules are implemented may differ, the results of this research can provide insights into bidding behavior in many different auction implementations because bidders have the opportunity to speed up the auction by placing higher jump bids. Roth and Ockenfels (2002) discussed the different strategic incentives provided by hard and soft close rules.

the behavior actually affects final auction performance is indeterminate. Auction performance can be affected in a number of ways. First, as we know from Proposition 1, bidders will be placing jump bids in equilibrium. This might cause them to jump over the second highest value, leading to increased revenue for the seller and lower profits for the bidder. Second, as we know from Proposition 2, bidders will never get closer than one increment below their value. Thus, it is possible the auction could end before bidding reaches the second highest value, resulting in lower seller revenue and higher bidder profits. Finally, both these behaviors open the door for potential losses in economic efficiency (the highest valuing bidder does not win the object). Because these effects influence auction performance in opposite ways, we turn to the laboratory to understand jump bidding behavior when time is valuable.

4. Design of the Experiment

In all auctions two bidders compete for one unit of an artificial commodity, with the value of the commodity drawn from a discrete uniform distribution of 1 to 100. New values were drawn for each auction round. In every session there was a maximum of five independent markets (1–5), totaling 10 bidders participating at any given time. Each market had a different set of value draws, but the value draws were the same for all sessions.

The auction institution was the canonical English auction. Bidders were free at any time to place any bid they liked. The only requirement was that the bid must be strictly greater than the current high bid. There was no minimum bid increment. We chose to avoid specific mention of a bid increment in fear that it might act as a natural focal point for bidders. Given the discrete nature of valuations, it is reasonable to assume that unit bids might have been assumed to be the minimum bid by many bidders.[7] We used a simple soft close activity-based rule to end the auction; if no new bids were placed for 30 seconds, the auction ended and the object was awarded to the high bidder at the amount of her last bid. Thus, any new bid always extended the auction at least 30 seconds and other bidders always had the opportunity to respond to new bids. Bidders were then given 40 seconds to record their earnings before the start of a new auction round. They were informed of their new value draw and bidding began again against the same bidder.[8]

The objective of the study was to systematically vary the costs associated with auction duration to observe how bidder behavior and auction performance responded to the change. We implemented the following two treatments:

1. Untimed. Bidders are told they will complete exactly 20 auction periods.

2. Timed. Bidders are told they can complete as many auction periods as possible in 60 minutes. At the end of 60 minutes, the bidders were paid according to the number of auctions actually completed.

The expectation was that in the untimed treatment the costs associated with a longer auction are not significant because the bidders know they will complete 20 auctions no matter what, and completing auctions faster only results in ending the experimental session slightly sooner. In the timed treatment, the speed of the auction is more salient; by completing the auctions faster, bidders are able to complete more auctions and increase their earnings. In our view, the strength of the design is that it induces the higher cost of time in the timed treatment naturally, which makes the environment more realistic. An alternative could have been to charge bidders some explicit fee $c(t)$, increasing in t. The number of auctions was chosen in the untimed treatment to closely approximate the number of auctions completed in the timed treatment to control for possible learning or wealth differences across treatments.

A total of 23 independent markets (46 subjects) were observed under the timed treatment, and 21 (42 subjects) independent markets were observed under the untimed treatment. In total, 942 (533 timed, 409 untimed) separate auction rounds were observed.[9]

All sessions were conducted at Penn State's Laboratory for Economic Management & Auctions between March 2001 and October 2001. The software was developed using the zTree system (Fischbacher 1999). Participants were recruited through e-mail announcements. Cash was the only incentive offered. Participants were paid their total individual earnings from the auctions plus a $7 show-up fee at the end of the session. Sessions lasted between 80 and 120 minutes and average earnings were $21.84 and $18.34 in the timed and untimed treatments, respectively. All subjects participated only once.

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[7] However, there are bidders who bid well below one unit at times.

[8] Although the repeated interaction between the same bidders might invite repeated game strategizing, it was necessary to capture the benefits of faster bidding. If fast bidders had to wait for slower bidding groups to end their auction to be rematched, the incentive for fast bidding would have been mitigated. There is also little

reason to believe that bidders could coordinate on a collusive strategy with one object for sale and no communication (Isaac and Walker 1985).

[9] The number of untimed auction rounds was less than 420 as a result of a computer malfunction in one session. The data are included in the analysis, with the exception of the reported average number of periods completed. The computer error was unexpected so it should not have affected behavior.

Table 1   Summary of Auction Performance

Average (standard deviation)	Treatment		
	Untimed	Timed	t statistic (p value)
Efficiency	0.89	0.90	0.79
	(0.13)	(0.18)	(0.4364)
Bidder profit per auction	21.66	24.48	1.46
	(8.50)	(9.65)	(0.1569)
Buyer revenue per auction	48.55	47.83	0.89
	(7.72)	(7.98)	(0.3832)
Seconds per auction	187.50	147.87	4.61
	(32.05)	(32.36)	(0.0001)
Number of auctions	20.00	23.13	2.64
	(0.00)	(6.43)	(0.0146)
Seconds per bid	9.31	12.13	3.23
	(2.77)	(3.77)	(0.0037)
Size of the jump bid	3.23	5.58	4.28
	(1.40)	(2.55)	(0.0003)
Percentage of auctions ended early	0.28	0.40	1.95
	(0.23)	(0.27)	(0.0635)
Distance between high bid and second valuation	5.42	5.85	0.85
	(5.26)	(6.28)	(0.4044)
Bids per auction	10.93	6.83	4.73
	(3.48)	(2.91)	(0.0001)
Correlation between the first bid and value	0.28	0.43	2.37
	(0.27)	(0.21)	(0.0263)
Number of observations	20	23	

5. Results

In this section we discuss the results and how they compare to the model of bidding in Section 2. We report the summary of the performance of auctions and the comparisons between the untimed and the timed treatments in Table 1. All comparisons are done using a *t* test for samples with unequal variances and using averages for each independent market as the unit of observation. The *p* values reported are one-sided.

Result 1: The Performance of the Auction Is Not Affected

One of the primary concerns associated with jump bidding is that it allows for significant changes in the economic performance of the auction. For example, because bidders will always stop before their actual value, it is possible the auction will not achieve allocative efficiency and seller revenue may decline. Therefore, perhaps the most intriguing result is that along a number of dimensions the performance of the auction does not suffer in the timed treatment.

First, consider allocative efficiency. An auction is said to be allocatively efficient if the bidder with the highest value was the winning bidder. In the untimed condition 89% of all auction periods are efficient, and in the timed condition the proportion of efficient periods is 90%. The difference is not statistically signifi-

cant. Bidder profits and seller revenue are also similar under the two treatments. Per-auction bidder profits average 21.66 per period under the untimed treatment as opposed to 24.48 under the timed condition. The difference is not statistically significant. Average seller revenue is 48.55 when the auction is untimed and 47.43 when it is timed (also not significantly different).

When combined with the findings of Katok and Kwasnica (2007), the first result demonstrates that the effect of timing is not independent of the institution. In English auctions bidder impatience does not affect the seller's revenues, but in Dutch auctions, as we reported previously (Katok and Kwasnica 2007), bidder impatience increases the seller's revenue in a slow Dutch auction. Interestingly, bidder impatience does not affect efficiency in either mechanism.

Result 2: Auctions Are Completed Faster in the Timed Treatment

The time between the first and last bids placed in each auction period averaged 187.50 seconds in the untimed treatment, but is significantly smaller at 147.87 seconds in the timed treatment.[10] This allows bidders in the timed treatment to complete significantly more auction periods than in the untimed treatment (23.13 vs. 20 in the timed condition).

Given the auction institution investigated, bidders actually had two methods they could use to speed up bidding. They could place bigger jump bids or respond more quickly to bids placed by the other bidders. For example, consider bidders who are placing jump bids of 10 every 10 seconds. They could accomplish the same task by placing bids of 1 greater than the high bid every 1 second. The faster strategy would have the advantage of avoiding jumping over the second highest value. However, there is probably a maximum rate at which bidders can reasonably respond to bids, and fast bidding might accentuate the bid preparation costs as reported by Daniel and Hirshleifer (1998). We expected we might see both types of increases in the timed treatment. The opposite is the case; bidders tend to take somewhat longer between bids in the timed treatment. The number of seconds per bid is 9.31 in the untimed treatment and slightly larger, at 12.13, in the timed treatment. The difference is statistically significant. It may be that the added salience of the jump bid choice might have induced bidders to consider their bid somewhat longer. Despite the slower rate of bid placement, the bid level increases faster under the timed treatment.

[10] This is not the actual length of the auction. Due to the 30-second closing rule, all auctions lasted at least 30 seconds more. In addition, the data do not record the time elapsed between the opening of the auction period and the first bid placed. The first bid was generally placed shortly after the opening of the auction, and there is little reason to expect significant variation due to the treatments.

Figure 1   The size of the jump bid over time and the number of auctions with various numbers of bids placed. (a) Average size of the jump bid over time. (b) Percentage of auctions with various numbers of bids placed.
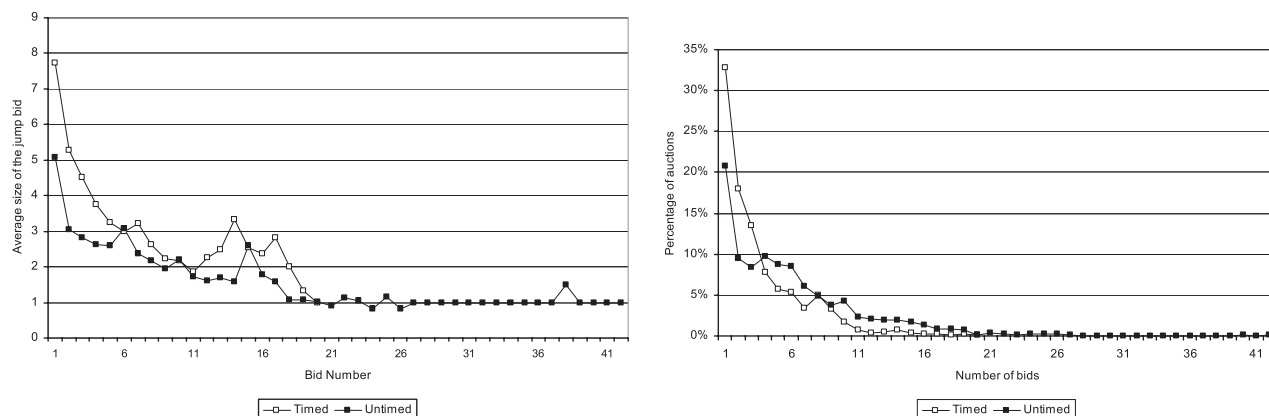
Result 3: Bidders Place Larger Jump Bids in the Timed Treatment

The average size of the jump bid in the timed treatment is 5.58 compared with 3.23 in the untimed condition, and the difference is highly significant.

For the remainder of the paper, we focus on the size of the jump bid as the strategic choice variable. The next step is to investigate how the size of the jump bid is affected by other variables in the auction such as bidder values and the current high bid. Figure 1 illustrates how the size of the jump bid changes over time (Figure 1a) and the percentage of auctions that had various numbers of bids placed (Figure 1b). The "bid number" in Figure 1a refers to the order in which the bid was placed in the auction by a particular bidder. In other words, bid number 1 is the first bid placed by a bidder, bid number 2 the second, and so on.

The average first bid placed is higher in the timed treatment than in the untimed treatment, and the average size of the jump bid decreases with each subsequent bid. The decrease appears to be somewhat faster in the timed treatment than in the untimed treatment. More bids are placed in the timed treatment than in the untimed treatment. The percentage of auctions that have one, two, and three bids placed is higher in the timed treatment, but the number of auctions with four or more bids placed is higher in the untimed treatment.

Figure 2 shows the size of the first (Figure 2a) and the average (Figure 2b) jump bid as a function of the bidder's value.

Bidders with higher values start out bidding higher in both treatments, and they also appear to sustain the higher bidding level in both treatments, but the average size of the jump bids appears to be uniformly higher at medium and high values in the timed treatment.

Figure 3 shows the size of the average jump bid by period (Figure 3a) and the total number of auctions that took place in a given period (Figure 3b).

The average jump bid stays constant in the timed treatment, but appears to increase in later periods of the timed treatment. Figure 3b illustrates that the number of auctions starts decreasing after period 20 and decreases quite sharply, so the larger average jump bids in later periods are due to a small number of groups that were actually able to conduct this many auctions. There is also endogeniety in the sense that

Figure 2   The size of the first and the average jump bid as a function of the bidder's value. (a) The average size of the first jump bid. (b) The size of the average jump bid.
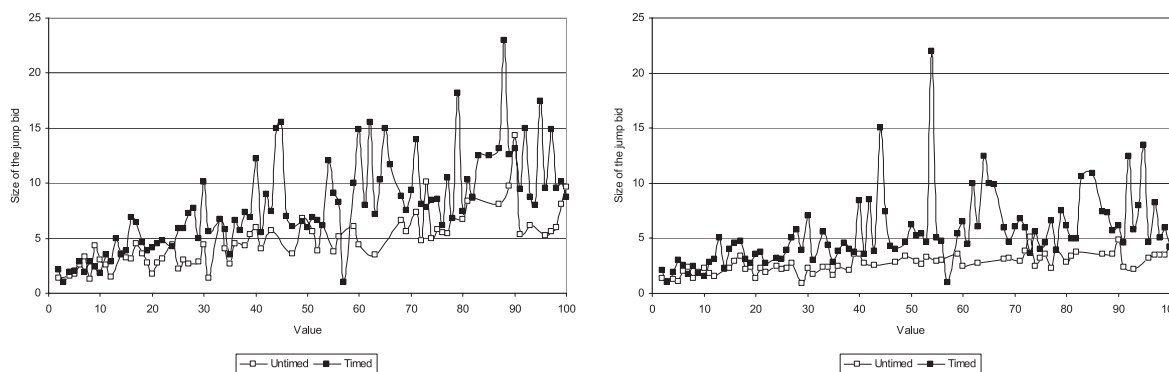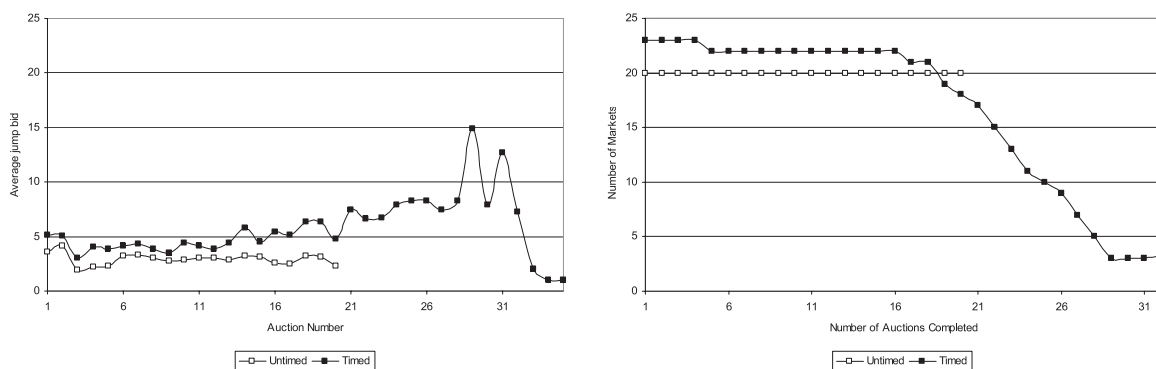
Figure 3   Activity per period. (a) Average jump bid per period. (b) The number of auctions in a session.

groups who use bigger jump bids will be able to complete more auctions in the timed treatment.

In summary, average jump bids are higher in the timed treatment than in the untimed treatment, and the difference is due to several factors: (1) Bidders in timed treatment start out bidding higher, and although bidders in both treatments decrease the sizes of their jump bids over time and bidders in the timed treatment decrease them faster (Figure 1a), nevertheless, because auctions end quicker in the timed treatment (Figure 1b) the average jump bids remains higher in that treatment. (2) Both initial and average jump bids increase with value, but the jump bids for the same value are generally higher in the timed treatment (Figure 2). (3) The sizes of the jump bids do not change in later periods in untimed treatments but do increase in timed treatment (Figure 3a).[11]

Result 4: There Is Significant Heterogeneity in Bidder Behavior

Figure 4 illustrates the distributions of average jump bids by individuals in the timed and the untimed treatments. Although smaller jump bids are more common under the untimed treatment, there are still differences across bidders.

The heterogeneity can be observed in two more ways. First, in the OLS estimate, the R^2 increases from 0.16 to 0.34 when we add the fixed effects. Additionally, in individual regressions, the percentage of bidders for whom any given parameter is significant ranges from about 30% to about 76%. The R^2's in individual regressions range from 0 to 0.74, with me-

dian at 0.25, so how the size of the jump bid relates to other variables for any given individual varies greatly. Interestingly, for individuals for whom the estimates are significant, virtually all of them have the same sign as the OLS estimates with fixed effects (except for the *PERIOD* estimates, which are not significant in the OLS with fixed effects), so although not all bidders respond to all the parameters in the same way, when they do respond their response is consistent with our model.

## Result 5: Bidders Stop Bidding before Reaching Their Value

Another prediction of the theory is that when bidders are impatient they will stop bidding below their value. In fact, as the cost of time increases we expect bidders will stop short of their value sooner. There is some evidence of this behavior in the data. We first examine the proportion of experimental auctions that ended before the second highest valuation. When this happens, both bidders could have increased the level of bidding but decided not to. Under both treatments, a surprisingly large proportion of the auction periods end early. In the untimed treatment, 28% of all auction periods ended early. In the timed treatment, the percentage rises to 40%. The difference is weakly significant.

The proportions also suggest there is still a sizable portion of the auctions that meet or exceed the second highest valuation. This is not surprising because the eventual winner, in making strategic jump bid choices, can easily bid past the second highest value. The treatment condition does not seem to affect the average distance between the highest bid and the second highest valuation, which is 5.42 (untimed) and 5.85 (timed).

In Figure 5 we plot the distribution of the difference between the highest bid and the second highest valuation for the two treatments. The differences in the timed treatment are a bit more spread out than in the timed treatment.

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[11] We can obtain results 1–3 more formally by using a regression model in which we regress the size of the jump bid on the treatment type (timed or untimed, the order of the bid, period, value, and the interaction effects between the treatment and the other variables). The size of the jump bid is higher in the timed treatment and decreases significantly as the auction continues. The size of the jump bid also appears to increase with bidder value. The effect of period and value is more pronounced in the timed treatment. We estimated the model using OLS with fixed effects for bidders; details are available from the authors.

Figure 4   Distributions of average jump bids by bidder.
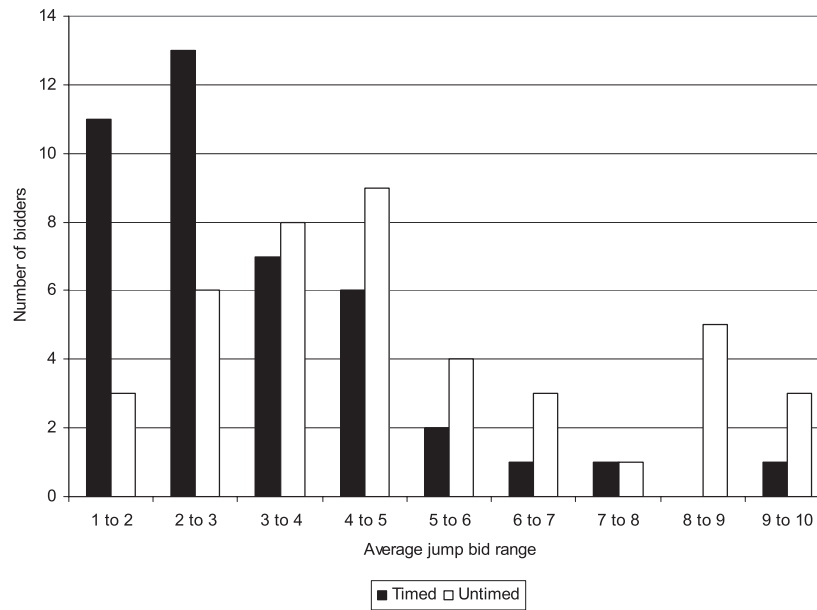
Result 6: There Is Some Evidence of Signaling
The only equilibrium we can easily identify is a signaling equilibrium similar to that already discussed by Daniel and Hirshleifer (1998) and Avery (1998). Signaling equilibria entail bidders placing value revealing high bids very early on in the auction process. As the discussion following Result 3 indicates, bid choices do appear related to a bidder's private value. Therefore, it is possible that the other bidder might update her information based upon the observed jump bid choice. There is little evidence that this is actually happening. If signaling is occurring, auctions should end after a few bids. However, under both treatment conditions the average number of bids is relatively high: 10.93 (untimed) and 6.83 (timed). Although these averages are significantly different, the difference is not surprising because the size of the jump bid also increased in the timed treatment. Figure 6 shows the distribution of the number of bids placed by each market. Most groups average five or more bids per auction; in the timed treatment 74% of markets average at least five bids per auction and in the untimed treatment the proportion is 95%.

There are some groups, however, that do place very few bids. Six groups in the timed treatment and one group in the untimed treatments averaged fewer than five bids per round. The small number of bids may be suggestive of signaling or even tacit collusion. For

Figure 5   The distribution of the difference between the highest bid and the second highest valuation.
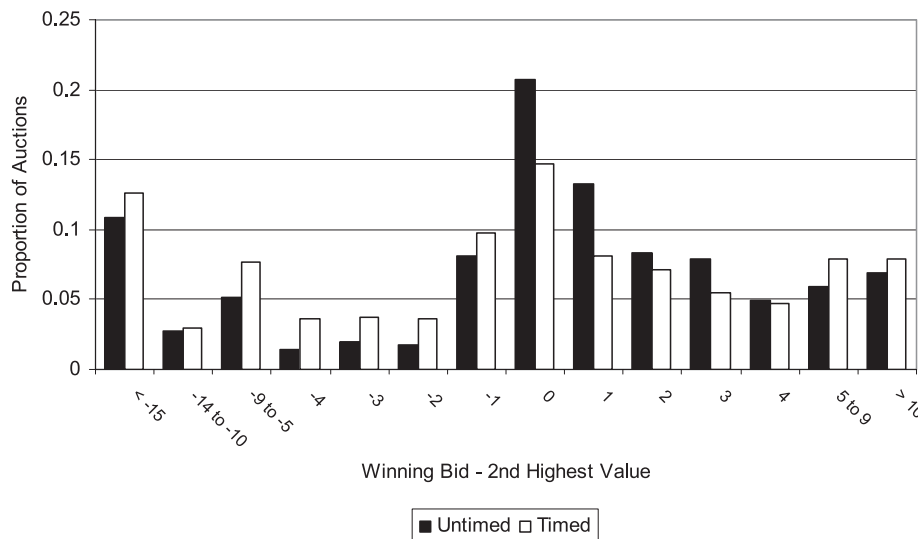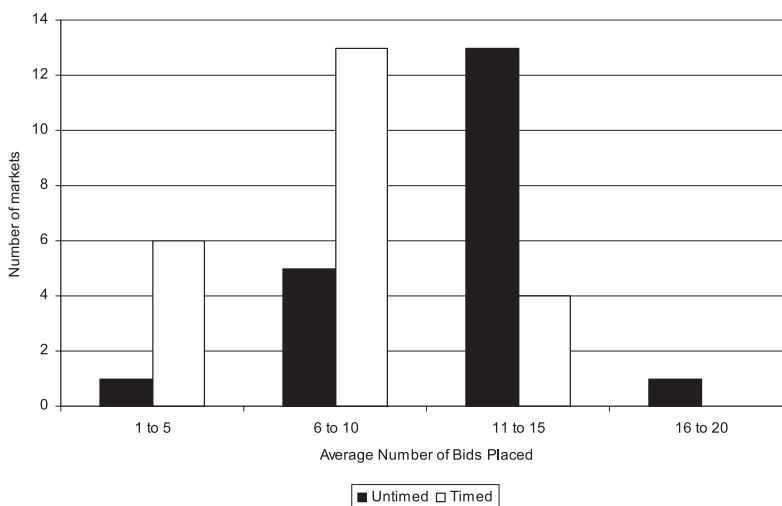
Figure 6   Distribution of average number of bids placed by market.

example, one group (Market 5 on 4/12/01) consistently placed one or two bids per auction (average 1.85). Because Kwasnica and Sherstyuk (2007) showed that bidders in ascending auctions for multiple objects can form tacit collusive agreements given enough time, it is worth investigating whether the behavior is more like collusion or signaling.[12]

To provide a sense of the amount of signaling that might be happening, we compute the correlation between the first bid and the bidder's value in each market and summarize the data in Figure 7.

The average correlation is 0.28 in the untimed treatment and 0.43 in the timed treatments. The difference is significant, suggesting that there may be more signaling in the timed treatment than in the untimed treatment. The average correlation in the seven (one untimed and six timed) markets that averaged five or fewer bids per auction is 0.52, which is significantly higher than the correlation of 0.33 in the other markets ($t = 2.10$, p value (one-sided) $= 0.0416$). This is additional evidence that bidders in markets with fewer bids may be signaling, because in the simplest models of tacit collusion there is no correlation between bids and values.

6.   Conclusion and Discussion
We present an experiment and a simple model of English auctions with impatient bidders. The results of the laboratory experiment are largely consistent with the predictions of the model. Bidders tend to increase the size of their jump bids as time becomes more costly and the size of the jump bid is a decreas-

ing function the bid order (as well as the current high bid) and an increasing function of the bidder's valuation.

The data also reveal some more surprising results. Most importantly, making time more costly does not appear to directly impact the performance of the English auction. The auctions under the timed condition are just as efficient, yield the same revenue, and generate the same bidder profits as the untimed auctions. One of the primary motivations for the study of costly bidding is that it might impact the performance of the auction so we find the result intriguing. It is in contrast, for example, to the results we reported previously (Katok and Kwasnica 2007), where we reported that slow Dutch auctions can yield higher revenues than faster Dutch auctions and first-price sealed bid auctions.

Why might this be happening? We think there are at least two potential explanations. It may be that the experimental treatment may not have made time sufficiently costly. Although it is clear that bidders did react to the treatment condition, perhaps the cost was not enough to create inefficient outcomes or differences in the division of surplus. Alternately, given that bidders are following strategies in which the size of the jump bid decreases at high bid levels and close to their value, bidders are less likely to cross over the second highest value by much. For all cases in which they do jump beyond the second highest value, there are instances in which the bidding ends early (before the second highest value). It stands to reason that auctions with a greater number of bidders pose greater problems for efficiency because the expected distance between the first and second highest values will be smaller. Bidders might also have a greater incentive to signal high valuations by placing large jump bids early.

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[12] The distinction between signaling and collusion is small in this setting. One might address this as whether the bids are consistent with a one-shot non-cooperative signaling equilibrium or must be supported by a repeated game influenced collusive arrangement.

Figure 7 **Average correlation between the first bid and the bidder's value.**
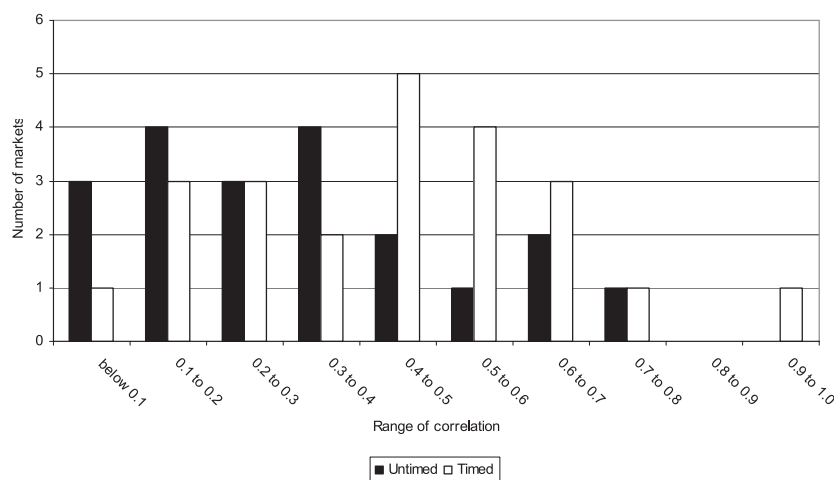
But the fact that in the laboratory bidders decrease their jump bids as the bid level increases, and that this prevents efficiency losses, offers a valuable insight to auction designers. A critical yet little studied element of auction design is that the auctioneer usually selects a minimum bid increment level. A better understanding of bidder behavior in these environments would provide insights that we would like to feed back into the revenue (or efficiency) maximizing decisions of the mechanism designer.

What increment should the auctioneer set given that he knows time is costly and bidding takes time? For example, eBay's rules about minimum bid increments prescribe that bid increments *increase* in proportion with the bid level, not decrease. Given that many people treat eBay as if it were an English auction (see, for example, Roth and Ockenfels (2002) and Ockenfels and Roth (2002, 2006)), impatience may actually cause a decrease in efficiency on eBay (in contrast to our experiment), because at high bid levels the institution would prevent people from increasing their bids in smaller increments. The practical question of how to set the minimum bid increment most effectively in an eBay-like setting may well be an empirical one. Given that bidders are impatient (many do not understand proxy bidding and bid on eBay as if it were an English auction, whereas others use the hard closing rule strategically and snipe) a controlled laboratory setting may be appropriate to gain further insight into this question.

The FCC spectrum auctions also use an increasing minimum increment schedule. Although the justification for the FCC design is to speed up the auction, it seems that bigger increments early on and small increments in the end might be more beneficial. In fact, as our experiments demonstrate, that is what occurs naturally when bidders are given the choice of increment level; these sorts of decreasing increment levels

are what one often observes when watching a skilled oral auctioneer at work.

Finally, the distinction between collusion and signaling should be examined more closely. Although some of the literature on jump bidding has identified signaling equilibria, recent work by Brusco and Lopomo (2002) and Kwasnica and Sherstyuk (2007) reported that signaling can be used for tacit collusion (e.g., coordinating on a strategy that is Pareto improving for the bidders). When bidding is costly, can collusive signaling equilibria be found?

Acknowledgments

Appendix

Proof of Proposition 1. Suppose not. Then for all $c(t)$ and m bidding $b_{t+1} = b_t = m$ up to v_i is an equilibrium for both bidders. Consider a bidder with a value v_i and suppose the current high bid is held by the other bidder (j) at $b_t = v_i - 3m$. Then pedestrian bidding would prescribe that bidder i bid $b_{t+1} = v_i - 2m$ in the next round. Then, given that the other bidder is also bidding in such a manner, a number of things can happen. If $v_i - 3m \leq v_j < v_i - m$, bidder i will win with a bid of b_{t+1} since j will be unwilling to raise the bid. If, however, $v_j \geq v_i - m$, the other bidder will outbid bidder i in the next round with a bid of $b_{t+2} = v_i - m$. If so, then i will bid $b_{t+3} = v_i$ in the next round. In which case, bidder i will

be outbid only if $v_j \geq v_i + m$.[13] The expected value from pedestrian bidding at this stage is thus given by:

$$E^P = (2m - c(t + 1))p_1 + (-c(t + 3))[p_2 + p_3]$$
$$+ (-c(t + 4))p_4 \quad (1)$$

where

$$p_1 = F(v_j < v_i - m | v_j \geq v_i - 3m)$$
$$p_2 = F(v_i - m \leq v_j < v_i | v_j \geq v_i - 3m)$$
$$p_3 = F(v_i \leq v_j < v_i + m | v_j \geq v_i - 3m)$$
$$p_4 = F(v_j \geq v_i + m | v_j \geq v_i - 3m).$$

Note that $p_1 + p_2 + p_3 + p_4 = 1$. Now consider a jump bidding strategy of bidding $b_{t+1} = v_i - m$. If this strategy is used, then bidder i will win in this round if $v_j \leq v_i$, and bidder i will be outbid (and not bid again) if $v_j > v_i$. This strategy yields the following expected payoff:

$$E^J = (m - c(t + 1))[p_1 + p_2] + (-c(t + 2))[p_3 + p_4]. \quad (2)$$

By supposition that pedestrian bidding is an equilibrium, it must be that $E^P \geq E^J$, or

$$mp_1 + (-m + (c(t + 1) - c(t + 3)))p_2 + (c(t + 2)$$
$$- c(t + 3))p_3 + (c(t + 2) - c(t + 4))p_4 \geq 0. \quad (3)$$

Note that since $c(t)$ is increasing mp_1 is the only positive term. Thus, it is easy to see how one could construct cost functions to yield a contradiction. Specifically, let cost be linear in t, or $c(t) = ct$. Then we have the following inequality from (3):

$$mp_1 + (-m - 2c)p_2 + (-c)p_3 + (-2c)p_4 \geq 0$$
$$m(p_1 - p_2) - c(2p_2 + p_3 + 2p_4) \geq 0$$
$$c \leq \frac{m(p_1 - p_2)}{2p_2 + p_3 + 2p_4}.$$

Thus, as long as $c > m(p_1 - p_2)/2p_2 + p_3 + 2p_4$, the jump bidding strategy will be preferred yielding a contradiction with pedestrian bidding being an equilibrium.

Proof of Proposition 2. Consider $b_t = v_i - m$. In this case, not bidding (abstaining) yields the guaranteed payoff (loss) of $-c(t)$ whereas bidding $b_{t+1} = v_i$ (the minimum acceptable bid) yields a payoff of either $-c(t + 1)$ if bidder i wins the auction, or $-c(t + 2)$ if bidder i is subsequently outbid. Clearly, $-c(t) > -c(t + 1)p + -c(t + 2)(1 - p)$ for all p and t, where $p > 0$ is the probability of the auction ending at $b_{t+1} = v_i$. This shows that bidders will always stop bidding *at least* one increment before reaching their value.

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[13] This result holds even if we allow for pedestrian bidding where bidders stop short of their value as we show to be the case in all equilibria where time is valuable (Proposition 2).