Time is Money:

The effect of clock speed on seller's revenue in Dutch auctions

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Time is Money: The effect of clock speed on seller's revenue in Dutch auctions

This study examines the role of timing in auctions under the premise that time is a valuable resource. When one object is for sale, Dutch and first-price sealed bid auctions are strategically equivalent in standard models, and therefore, they should yield the same revenue for the auctioneer. We study Dutch and first-price sealed bid auctions in the laboratory, with a specific emphasis on the speed of the clock in the Dutch auction. At fast clock speeds revenue in the Dutch auction is significantly lower than it is in the sealed bid auction. When the clock is sufficiently slow, however, revenue in the Dutch auction is higher than the revenue in the sealed bid auction. We develop and test a simple model of auctions with impatient bidders that helps to reconcile prior findings in both the laboratory and the field.

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1. Introduction and related literature

The popularity of Internet auctions, such as eBay, has made timing issues in auctions particularly salient. Traditionally, auction houses, such as Christie's, required bidders or their representatives to assemble at a specific place and time, and therefore auctions had to be conducted fairly quickly (often lasting less than an hour). In contrast, Internet auctions allow geographically dispersed bidders to participate, making it possible to conduct auctions that last many days. One disadvantage of long Internet auctions is that they may impose high monitoring costs on the bidders, affecting the strategy of the bidders and the revenues of the auctioneer. There is some evidence that Internet auctioneers are aware of this disadvantage, since they make attempts to mitigate monitoring costs by offering email notifications and proxy bidding. Recently eBay introduced a "buy-it-now" feature, aimed at impatient bidders, that allows them to win an object immediately for a certain pre-specified price (ADD CITE). The "buy-it-now" price is typically higher than the expected price at the end of the auction. The popularity of this feature suggests that there is a substantial number of eBay bidders who place some value on being able to end the auction quickly. While timing issues such as the length and speed of the auction are clearly issues that must be confronted by the practical auction designer, most theory models of auctions do not consider such factors. In the standard auction model, all auction institutions are assumed to be completed instantaneously making the study of timing impossible.

We examine the role of timing in auctions under the premise that time is a valuable resource, so bidders may take monetarily costly actions in order to save time. We focus specifically on two common auction formats, strategically equivalent under standard theory, but quite different in terms of transaction timing:

- *Dutch* (Dutch) auction is also known as a reverse clock auction; price descends until a bidder decides to accept the current price stopping the auction and buying at that price.
- *First-price sealed bid* (sealed bid) auction, where bidders submit a single sealed bid. The highest of these bids is selected as the winner, and the winning bidder pays the amount that she bid.

In theory the Dutch and the sealed bid mechanisms are strategically equivalent, even under the assumptions of risk aversion and affiliated valuations, and therefore are supposed to yield the same revenue to the auctioneer. However, they vary considerably in their dynamic properties. Under the Dutch auction, if bidders care about time, they may decide to end the auction earlier; while they would pay a higher price, they may be willing to accept the tradeoff of a higher price for time saved. In the sealed bid auction, bidders typically have no discretion over the timing of the auction. In practice, almost all sealed bid auctions end after a specified period of time during which bids are accepted; while a bidder may want to end the auction sooner, there is no way to accomplish this through the bidding. The cost of time in a typical sealed bid auction is sunk.

There are two seemingly conflicting sets of studies that compare revenues in the Dutch and the sealed bid auctions. One set of studies is reported by Cox, et al. (1982), and Cox, et al. (1983) and finds that Dutch auctions yield lower revenues than sealed bid auctions when conducted in the laboratory using artificial commodities. Another study, reported by Lucking-Reiley (1999), finds that slow Dutch auctions for Magic™ Cards conducted over the Internet yield higher revenues than analogous sealed bid auctions.

While there are many possible explanations for these seemingly conflicting results, we focus on two of the most likely causes. One explanation is that the studies differed markedly in the speed of the Dutch clock used. While the Cox et al. laboratory studies used clocks that descended between .75% and 2% of their maximum value every *second*, the Lucking-Reiley field study used a clock that decreased approximately 5% per *day*.[1] Since slower auctions impose higher monitoring and opportunity costs on bidders and are generally less exciting, the slow clock may cause the bidders to end the auction early.

The second explanation is that laboratory and field studies can yield systematically different results because there is something special about the laboratory that induces bidders to take a 'gamblers' mentality - lowering the auction price - whereas in field experiments bidders are much more cautious and time sensitive. Lucking-Reiley (1999) argues that,

> "Laboratory experiments, which to date have provided the vast majority of data on bidders' behavior in auctions, can be criticized on the grounds that subjects' behavior in an artificial laboratory environment may not be exactly the same as their behavior would be in the "real world." The Magic card market provides an opportunity to run controlled experimental auctions in the field rather than in the laboratory."

[1] The actual decrement of the clock varied. Bidders were not informed of the exact clock speed. Therefore, an alternative explanation of higher bidding could be a rational response by risk averse bidders to a random clock.

Consistent and unexplained deviations in laboratory experiments from field observations would challenge the experimental precept of *parallelism* (Smith 1982).[2]

We study Dutch and sealed bid auctions in the laboratory, systematically varying the speed of the Dutch clock, in order to gain insights into the role of transaction timing in auction performance. We find strong evidence that the clock speed matters. Most significantly we find that, depending on the speed of the clock in the Dutch auction, the ordering of revenue generated by the two auction institutions flips. This result may have significant implications for practical auction design; it suggests that when a slow Dutch clock is necessary the seller might prefer a Dutch auction, but, when fast Dutch clocks are required, the sealed bid mechanism might be more profitable. This also demonstrates that the previous studies discussed are not necessarily in conflict. We then develop a simple model of auctions with impatient bidders. This theory helps to reconcile prior findings in both the laboratory and the field and is generally consistent with our experimental findings.

Comparisons of the expected performance of the Dutch and sealed bid auctions were first presented by Vickrey (1961) who showed that the descending price Dutch auction is strategically equivalent to the sealed bid auction. Cox, et al. (1983) propose explanations of lower prices in Dutch auctions in the laboratory that conjectures that participants make systematic errors in the Bayesian updating in Dutch auctions or that they receive some non-monetary enjoyment from participating in the auction. There have been only a few studies of slow Dutch auctions that all focus on different factors than the direct value of time. Carare and Rothkopf (2005) describe a model of a slow Dutch auction and provide a simple game theoretic model allowing bidders to return to a slow Dutch auction at a later date. The Carare and Rothkopf (2005) models provide a

[2] Smith defines parallelism as follows; "Propositions about the behavior of individuals and the performance of institutions that have been tested in laboratory microeconomies apply also to nonlaboratory microeconomies

theoretical explanation of Lucking-Reiley's results, but not of the Cox et al. results. Adams et al. (1995) combine a Dutch auction with a search model and random arrivals of bidders. They show that under certain conditions a fixed price – clock speed of zero – is optimal.

The paper proceeds as follows. Section 2 contains the experimental design. In Section 3, we present the experimental results. In Section 4, we present a simple model of Dutch auctions where bidders care about timing. Section 5 concludes.

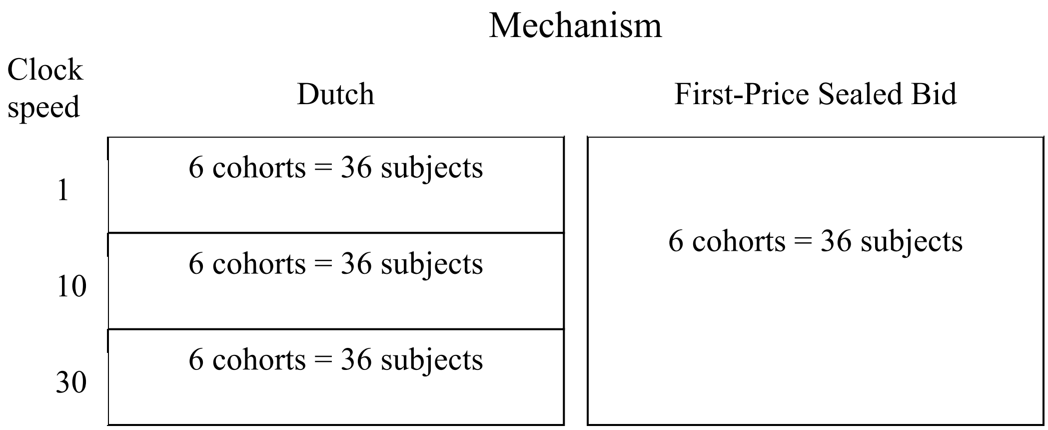
2. Design of the Experiment

Our design manipulates two factors: the auction mechanism, which is either the first-price sealed bid, or the reverse-clock Dutch, and the speed of the Dutch clock. In all auctions three bidders compete for one unit of an artificial commodity, with the value of the commodity drawn from the uniform (integer) distribution on 1 to 100. The sealed bid mechanism was a standard first-price sealed bid auction with a zero reserve price. Bidders were required to place integer bids between 0 and 100 tokens.[3] In all Dutch treatments, the price starts at 100 tokens, and goes down by 5 tokens every *d* seconds, where *d* (= 1, 10, and 30 seconds) is the clock speed. Therefore, *d*=1 represents the fastest rate (per second) and *d*=10 and 30 are slower rates. In the Cox et al. studies, the Dutch clock speed varied along with the number of bidders, and all speed levels were fairly fast: the clock decreased by between 1.5% and 4% every 2 seconds. In our study we held the number of bidders at 3 and the clock increment at 5, which is 5% of the maximum artificial commodity value of 100. So all Cox et al. clocks are between our 1 and 10 second treatments, and our 30 second treatment has a significantly slower clock. While it was

where similar *ceteris paribus* conditions hold."

[3] The bid increments were different in sealed bid treatments (1) than in Dutch treatments (5). Restricting the bidding to integers was a natural choice in the sealed bid treatment. The different bid increments cannot explain the treatment effect.

unrealistic to run controlled laboratory experiments with a clock speed comparable to the Lucking-Reiley study, it was our hope that a 30 second clock would be sufficient to make monitoring costs salient. In order to give bidders time to reflect on their values, a 5 second value observation period was added to the *d*=1 treatment.[4] Figure 1 summarizes our experimental design.



Each treatment consisted of 21 auctions. In each auction three bidders competed for one unit of an artificial commodity. Values were drawn from a uniform distribution between 0 and 100. Participants were matched in six-person cohorts, and randomly re-matched within the cohort each round. Each treatment consisted of six cohorts (36 participants).

Figure 1: Experimental design.

During each session participants are matched in groups of 6 (we call each group of 6 a *cohort*). Each cohort participates in a sequence of 21 auctions, with two separate groups of three bidders bidding in each round. After each round the participants are randomly re-matched within the cohort, in a way that no participant is matched with the same two participants for two consecutive auctions. The participants are told this. New values were drawn for each of the 21

[4] We were concerned that bidders might not have sufficient time to determine a strategy before the clock started its speedy descent. In the other treatments, bidders had at least 10 seconds before the first decrements.

auction rounds. The value draws were the same for all of the treatments. Within a treatment, 3 cohorts shared the same value draws.

All sessions were conducted at the Harvard Business School's Computer Laboratory for Experimental Research (CLER) between February 2001 and October 2001. Participants were recruited through flyers posted on billboards. Cash was the only incentive offered. Participants were paid their total individual earnings from the 21 auctions plus a $10 show-up fee at the end of the session. The software was built using the zTree system (Fischbacher 1999). Sessions lasted between 60 and 100 minutes (the d=30 sessions were the longest and the sealed bid sessions were the shortest) and average earnings were $25. All subjects participated only once.

3. Results

Sealed Bid

Under the assumption of risk neutrality, the expected value of the high bid is 50.[5] Average revenue (high bid) under the sealed bid treatment was 64.9 tokens, which is consistent with previous experimental findings that bidders bid above the risk neutral Nash equilibrium (Kagel 1995). Further, a simple linear regression of bid on value and a constant term yields coefficients of 1.81 (constant) and 0.807 (value). Table 1 reports the observed average revenue for each independent cohort. Pooled across all cohorts, the efficient allocation, the highest bidder wins the objects, was obtained 89% of the time. Table 2 reports the observed proportion of efficient allocations for each independent cohort. On average, it took bidders 19 seconds to complete bidding in a sealed bid auction period.

[5] See Section 4 for a review of the risk neutral Nash equilibrium prediction when timing is not considered.

Cohort	Dutch *d* =1	*d* =10	*d* =30	Sealed
1	57.74	63.21	66.31	64.24
2	60.00	62.14	64.52	64.26
3	59.05	60.36	65.95	65.50
4	61.31	64.52	67.38	64.00
5	58.81	63.93	67.38	67.69
6	56.43	63.33	68.10	63.60
Average	58.89	62.92	66.61	64.88

Table 1. Average revenue (high bids) in six independent cohorts.

Cohort	Dutch d = 1	d = 10	d = 30	Sealed Bid
1	0.810	0.854	1.000	0.952
2	0.810	0.905	0.905	0.810
3	0.810	0.810	0.886	0.905
4	0.881	0.929	0.881	0.860
5	0.905	0.929	0.881	0.976
6	0.905	0.833	0.857	0.833
Average	**0.853**	**0.876**	**0.902**	**0.889**

Table 2. Proportion of efficient allocations.

Dutch

Under the Dutch treatments the average revenue was 58.89 (*d*=1), 62.92 (*d*=10), and 66.61 (*d*=30). As in the sealed bid treatment, all averages are above the risk neutral prediction. The percentage of efficient allocations was 85% (*d*=1), 88% (*d*=10), and 90% (*d*=30). We report revenue and efficiency for each independent cohort in Tables 1 and 2. Average auction length varied, as expected, with the speed of the clock: 53 seconds for *d*=1, 94 seconds for *d*=10, and 264 seconds for *d*=30.

Comparing Institutions

We summarize our results in Figure 2.

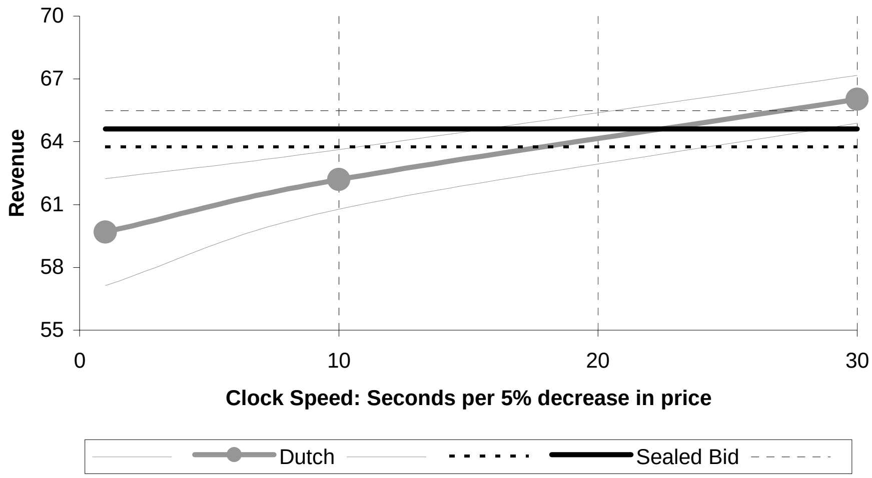


Figure 2. The summary of experimental results. The graph plots average revenue per unit in the 21 auctions, as a function of the speed of the clock. The solid lines represent averages, and the dotted and light gray lines represent ± 2 standard errors.

The average revenue in the 1-second Dutch treatment is 9% below the sealed bid revenue. The differences Cox et al. report are in the 3%-5% range, so since our 1-second clock is faster than the Cox et al. clocks, the differences we find are in line with Cox et al. The average revenue in the 30-second Dutch treatment is only 2% above the sealed bid revenue, in contrast to the 23% difference Lucking-Reiley reports. This, however, is not surprising, since the Lucking-Reiley price decreased by 5% per day, and the price in our 30-second treatment decreased by 5% every 30 seconds. We compare the average revenue in the Dutch and the sealed bid auctions using a Wilcoxon-Mann-Whitney Rank Sum test, and find that the differences are statistically significant in all treatments (the *p*-value for the 1-second Dutch vs. sealed bid is 0.0011, the *p*-value for the 10-second Dutch vs. sealed bid is 0.0206, and the *p*-value for the 30-second Dutch vs. sealed bid is 0.0043).[6] The proportions of the auctions that are efficient are not significantly different.

[6] Similar *p*-values were also obtained using a *t*-test for samples with unequal variance.

Alternative Explanations

While we focus on timing issues and the value of time, there are other potential explanations for the observed data. The Cox et al. explanation of lower revenues in fast Dutch auctions is that bidders derive some pleasure or thrill from the "waiting game." An alternative explanation for the significantly lower prices in our 1-second Dutch clock treatment is that the combination of speed of the clock and slow bidder reaction might consistently bias the bid level downward (bidders are not stopping the clock as fast as they would like to). The data suggest that for this explanation to be salient bidder reactions would have to be quite slow—on average more than 1 second elapsed between where the bidders should have stopped the clock if they were bidding consistent with the sealed bid auction and where they actually did stop the clock. Since our 1-second Dutch clock is slightly faster than the fastest Cox. et al. clock, we test the hypothesis that the particularly low revenues in the 1-second auction are due to bidder errors. If it were the case that bidders react too slowly given the clock speed, and the resulting bids are lower than what the bidders intended, we would expect to see some upwards adjustment of bids over time (to correct for these slow reactions). Therefore, we compare the average differences between the 1-second Dutch and sealed bid revenues, over the first 10 vs. the last 10 rounds. The difference is not statistically significant (the one-sided *p*-value is 0.2200).[7] In addition, bidding in the 10-second Dutch treatment, where bidder reaction time was clearly not an issue, was also significantly below the sealed bid treatment.

A final explanation of the Dutch-sealed bid non-isomorphism is that bidders might be failing to Bayesian update properly (Cox et al. 1983). Although Bayesian updating errors might be higher for faster clocks (because there is less time to think), there is no evidence that people

[7] We are not claiming that this is conclusive evidence that there is no bidder error in our 1 second treatment, but we suggest that bidder error, if it is there, is unlikely to be sufficient to explain our data.

do Bayesian updating properly in general (Camerer 1995), and there is no reason to believe that a few extra seconds would make a difference. Therefore, we would expect errors in Bayesian updating to have a similar effect in all three Dutch treatments.

4. A simple theory of bidder behavior in Dutch auctions

Having shown that bidder do indeed respond to changes in the Dutch clock and that those changes can actually result in a reordering of the revenue comparisons of the two institutions, we now look for a theory model that allows one to incorporate the value of time into bidding decisions in auctions. Our goal is to develop a simple and tractable model that is at least qualitatively consistent with the experimental results presented. In such, the theory model must predict both higher bidding relative to the sealed bid auction for the Dutch auction with slow clock speeds but lower bidding with sufficiently fast clock speeds. We begin by presenting a fairly general model of the value of time in auctions, and then present a particular parameterization that is consistent with our data.

Let there be $N \geq 2$ bidders labeled $i = 1, \ldots, N$. Bidders are risk neutral and have independent private values v_i which are random variables V_i drawn from the common cumulative distribution function F with support on $[0, \overline{v}]$ and probability density function $f(v) > 0$ for all v.[8] Cox et al. (1983) examine a similar auction model except that they assume bidders receive only positive non-monetary payoffs from longer auctions associated with the thrill of the 'waiting game.' They allow bidders to derive some non-monetary enjoyment from participation in the auction. Let $a(t)$ be the level of this added utility at time t. We assume that $a(t) \geq 0$, and $a(t)$ is differentiable and increasing for all t. The Cox et al. model can only

[8] The results here can be easily extended to allow for risk aversion. While Proposition 1 holds for risk averse bidders, the inclusion of even CRRA risk averse bidders is such that the equilibrium bid does not readily admit a closed-form solution.

lead to lower revenue in the Dutch auction, and does not account for the fact that time is also valuable. We generalize their model by assuming that bidders may also be impatient. As time passes bidders bare a cost $c(t)$ for participating in the auction. A bidder's profit from participating in an auction that lasts for time t is given by:

$$u_i(v_i,t)=\begin{cases} v_i-b+a(t)-c(t) & \text{if win} \\ a(t)-c(t) & \text{otherwise} \end{cases} \tag{1}$$

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. In the laboratory, these costs are most likely the bidder's perceived value of ending the auction earlier in order to speed the completion of the experimental session. In practice, they might be the salaries of designated bidders, or the effort of repeatedly returning to the auction website to see if the object is still available. We assume that $c(t)\geq 0$, and $c(t)$ is differentiable and increasing for all t. Combining the cost and enjoyment terms, let $e(t)=a(t)-c(t)$. For simplicity, we assume that $e(t)$ is common to all bidders.

The Dutch auction is characterized in the following manner. The auction begins at a high value, $v^S\geq\overline{v}$ and price decreases at a constant rate $1/d$ per unit time.[9] Therefore, at time t the price at which bidders can end the auction is given by $b(t)=v^S-(1/d)t$. Alternatively, the amount of time it takes for the auction to reach the bid b is given by $t(b)=d(v^S-b)$. If there are no bids then the auction ends when price equals zero, which happens at time $T=dv^S$. Note that $t'(b)=-d$.

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[9] In the laboratory experiments presented here $v^S=\overline{v}$, but, depending on the sign of $e'(t)$, the auctioneer may want to select the clock starting point so as to maximize revenue. However, if $v^S<\overline{v}$, it is possible that some measurable subset of bidders would want to stop the auction at $t=0$. This would potentially create tie bids and the equilibrium

Let us suppose that bidder i waits until the clock reaches a bid of b and all other bidders are waiting to stop the auction using the equilibrium bidding strategy $b^*(v)$.[10] We assume that $b^*(v)$ is strictly monotone increasing.[11] Therefore, the probability of the bidder winning when she waits until b and is playing against $N-1$ others who are playing the equilibrium strategy is given by:

$$\begin{aligned} H(b) &= \Pr\{b^*(V_j) < b, \forall j \neq i\} \\ &= \Pr\{V_j < \sigma(b), \forall j \neq i\} \\ &= F(\sigma(b))^{N-1} \end{aligned} \tag{2}$$

where $\sigma(b)$ is the inverse of the equilibrium bid function. In equilibrium, waiting until b must be a best response to her opponents' strategies, or b must maximize the bidder's expected utility:

$$U(b,v) = (v - b + e(t(b)))H(b) + \int_{x \geq b} e(t(x))dH(x). \tag{3}$$

The expected utility function is similar to the standard function for a risk neutral bidder without waiting costs except that the non-monetary cost/enjoyment function $e(t(b))$ is added. The far right-hand side term is the expected monitoring costs incurred when the auction ends before b. This leads to the following first-order condition:

$$\frac{\partial U(b,v)}{\partial b} = (v - b + e(t(b)))H'(b) - (1 + de'(t(b)))H(b) + e(t(b))H'(b) = 0, \tag{4}$$

which can be simplified to yield

$$(v-b)\frac{H'(b)}{H(b)} - 1 = de'(t(b)). \tag{5}$$

Notice that when $d = 0$ or $e'(t(b)) = 0$ then we have the standard first-order condition for the first-price sealed bid auction or the Dutch auction without waiting costs. Using the fact that

bid functions described might change. We do not expect that a low starting point would change many of the qualitative features of the slow Dutch auction bidding strategies.

[10] One could look for an equilibrium stopping function $t^*(v)$ that represents the time a bidder will stop the clock. Using $b(t)$, this could then be converted to the bid at which the clock is stopped. We opted for expressing the equilibrium in terms of the standing bid in order to preserve continuity with standard equilibrium bid functions in sealed bid auctions.

b must be prescribed by the equilibrium strategy, or $v = \sigma(b)$ and the boundary condition that $\sigma(0) = 0$, we can rewrite (5) as follows

$$(\sigma(b) - b)\frac{(N-1) f(\sigma(b))\sigma'(b)}{F(\sigma(b))} - 1 = de'(t(b)). \quad (6)$$

In the appendix, we verify that a sufficient second-order condition holds.

We begin by examining the conditions under which bid shading is still equilibrium behavior. It is possible that if costs accrue too quickly relative to the clock speed bidders would prefer to end the auction before the clock reaches their value.

Lemma 1: If $e'(t) \geq -d$ for all t, then $b^*(v) \leq v$ for all v.

Proof:

Note that $\frac{(N-1) f(\sigma(b))\sigma'(b)}{F(\sigma(b))} > 0$. If $e'(t) \geq -d$, then $de'(t(b)) + 1 \geq 0$ and $(\sigma(b) - b)$ must be greater than or equal to zero, or $\sigma(b) \geq b$. Since $\sigma(b)$ is the inverse bid function, this obviously implies that $b^*(v) \leq v$.■

A corollary of this lemma is that the assumed boundary condition of $\sigma(0) = 0$ is also satisfied. Since it is unrealistic to expect that monitoring costs will accumulate faster than the speed of the clock, we assume throughout that $e'(t) \geq -d$ for all t. If this was not satisfied, all bidders would prefer not to participate in the auction.

We next show how the equilibrium bid function, which is a solution to the differential equation (6), is related to changes in d and $e'(t)$.

Proposition 1: The equilibrium bid function is decreasing in $de'(t)$, or if $d_1 e_1'(t) > d_2 e_2'(t)$ for all t, then $b_1^*(v) < b_2^*(v)$ for all v.

Proof:

[11] See the appendix for verification of strict monotonicity of the equilibrium bid function.

Note that if $\sigma_1(b) > \sigma_2(b)$ for all b then it must be that $b_1^*(v) < b_2^*(v)$ for all v. Since b^* is strictly increasing and $\sigma_1(0) = \sigma_2(0) = 0$, it is sufficient to show that $\sigma_1{}'(b) > \sigma_2{}'(b)$ for all b. From the necessary first-order condition given by equation (6) we have that

$$\begin{aligned} \sigma_1{}'(b) &= (1 + d_1 e_1{}'(t(b))) \frac{F(v)}{(N-1) f(v)(v-b)}, \\ \sigma_2{}'(b) &= (1 + d_2 e_2{}'(t(b))) \frac{F(v)}{(N-1) f(v)(v-b)}. \end{aligned} \tag{7}$$

Then, it follows easily that

$$\begin{aligned} \sigma_1{}'(b) - \sigma_2{}'(b) &= (d_1 e_1{}'(t(b)) - d_2 e_2{}'(t(b))) \frac{F(v)}{(N-1) f(v)(v-b)} \\ &> 0, \end{aligned} \tag{8}$$

or $\sigma_1{}'(b) > \sigma_2{}'(b)$ for all $b > 0$.■

The proposition shows that the equilibrium bid function reacts as expected to changes in the clock speed or the non-monetary costs. For example, Dutch auctions with slower clock speeds (bigger d) will, ceteris paribus, lead to higher bidding when non-monetary costs outweigh non-monetary enjoyment or $e'(t) < 0$ and lower bidding when the auction is itself enjoyable ($e'(t) > 0$). When there are no non-monetary costs, the clock speed is irrelevant. The first-price sealed bid auction is the special case where $d = 0$. In this case, when waiting costs are significant or $e'(t) < 0$, the Dutch auction will yield higher bids than in the first price sealed bid auction. When $e'(t) > 0$, we obtain the Cox et al. result that the Dutch auction yields lower bids than the first-price sealed bid auction. Higher (lower) bidding leads to higher (lower) expected revenue for the auctioneer so that equivalent statements about auction revenue can be formulated.

While this result provides a potential explanation for differences in revenue from the Dutch and sealed bid auctions, it is not sufficient to explain the observed switch in ordering of revenue outcomes with different clock speeds. Since $d > 0$ in the Dutch auction, it must be that for some (fast) clock speeds $e'(t) > 0$, but for slow clocks $e'(t) < 0$. In other words, the non-monetary cost and benefits must be affected by the speed of the clock itself, so the cost/benefit function is really a function of the clock speed *d*. While the rate at which monitoring costs accumulate is unlikely to change in response to the clock speed, a slower clock might lower bidders' sense of enjoyment from the auction. For example, slow auctions in the experimental lab could be perceived as boring by subjects. Formally, this is equivalent to assuming that $\partial a'(t,d)/\partial d < 0$ for all t. Therefore, even if the bids from the Dutch auction start off below those of the sealed bid auction for fast clock speeds, there will be a sufficiently slow clock speed such that $e'(t) < 0$.

An example with uniform value draws

Let v_i be drawn from the uniform distribution on $[0,1]$ for each of the bidders. In this case the risk neutral bidder's equilibrium bid strategy in the sealed bid auction is the following:

$$b(v) = \frac{N-1}{N}v. \tag{9}$$

In order to provide some intuitive results, we assume a fairly simple model of non-monetary compensation. We assume that $a()$ and $c()$ are both linear in t. The bidder's non-monetary enjoyment declines with slower clocks yielding $a(t,d) = (a/d)t$, and monitoring costs are unaffected by the clock speed and accrue linearly, or $c(t) = ct$. Under this specification, it is as if the same amount of enjoyment is garnered from the auction for each 'tick' of the clock regardless of how slow the clock is, but costs per tick of the clock increase as the clock slows down. Thus, we have that $e(t) = et$ where $e = (a/d) - c$. Using the first-order condition from (6) and the fact that $F(\sigma(b)) = \sigma(b)$ and $f(\sigma(b)) = 1$, the equilibrium stopping strategy in the Dutch auction can easily be calculated to translate to stopping the clock at the bid:

$$b(v) = \frac{N-1}{N+ed}v \qquad (10)$$

or,

$$b(v) = \frac{N-1}{N+a-cd}v. \qquad (11)$$

When $e < 0$, the Dutch auction will cause bidders to increase their bids whereas when $e > 0$ bids will decrease. Note that the equilibrium bid function is very similar to the CRRA model of Cox et al. (1982).

The expected value of the highest valuation - the winner in both auction formats - is $N / N + 1$. Therefore, the expected revenue for the seller in the sealed bid auction is $ER_{Sealed} = N - 1 / N + 1$. The expected revenue from the Dutch auction is given by

$$ER_{Dutch} = \frac{(N-1)N}{(N+ed)(N+1)}, \qquad (12)$$

yielding an expected difference in revenue of

$$ER_{Dutch} - ER_{Sealed} = \frac{N-1}{N+1}\left(\frac{N}{N+ed} - 1\right), \qquad (13)$$

or

$$ER_{Dutch} - ER_{Sealed} = \frac{N-1}{N+1}\left(\frac{N}{N+a-cd} - 1\right). \qquad (14)$$

The expected revenue differences depend on the clock speed d. If $d = a / c$, we can expect the sealed bid and the Dutch mechanisms to yield the same revenue. Any slower clock speed -

$d > a/c$ - will result in greater revenue from the Dutch auction and any faster clock speed - $d < a/c$ - will result in lower revenue from the Dutch auction.

A final observation about the difference in behavior in the Dutch and sealed bid auctions is that as the number of bidders grows, $N \to \infty$, the difference in revenue declines regardless of the level of e. While we did not vary the number of bidders in our experiments, one would expect that large auctions would lead to little difference in expected revenue.[12]

Model Estimation

We now turn back to our experimental data in order to see how well the data fits our particular (and admittedly stylized) parameterization. Before proceeding it is necessary to discuss a complication related to the experimental data. It is well-known that in the laboratory participants generally bid above the risk neutral Nash equilibrium prediction, and we observe this in our data for all experiment treatments. Some of the results can be explained by risk aversion (see Kagel, 1995 for a literature review). Unfortunately, incorporating risk aversion directly into the model with impatient bidders is mathematically intractable.[13] The general theory results presented here can easily be extended to allow for risk aversion. While Proposition 1 holds for risk averse bidders, the inclusion of even CRRA risk averse bidders is such that the equilibrium bid does not readily admit a closed-form solution. If we do not account for this overbidding in the data, we know that our parameter estimates will be misleading.[14] We account for overbidding relative to the risk neutral Nash equilibrium directly, by introducing an overbidding factor k and estimating it from the data. While this solution is admittedly somewhat ad hoc, it

[12] This might explain why Aalsmeer runs fast Dutch auctions for flowers since the potential losses in revenue due to the fast speed might be mitigated by the large number of bidders.

[13] There are other explanations that can account for overbidding relative to the risk neutral Nash equilibrium in sealed bid first price auctions with privately-known values, for example aversion to regret (see Engelbrecht-Wiggans 1989).

proved the best solution given our inability to get bid functions for the risk averse bidders who care about timing. We estimate and compare four models:

- Model 1: The model without the cost of time that accounts for overbidding. $bid = value\left(\frac{n-1}{n}\right)k$. Here k is the constant to account for average overbidding relative to the RNNE.
- Model 2: The model without the cost of time that accounts for overbidding in each treatment separately. $bid^{treatment} = value^{treatment}\left(\frac{n-1}{n}\right)k^{treatment}$.
- Model 3: Impatient bidder model under the risk neutrality assumption: $bid = \left(\frac{n-1}{n+sa-dc}\right)value$. Here s = 0 for the sealed bid treatment and 1 otherwise, and d is the speed of the Dutch clock (1, 10 or 30), and is 0 for the sealed bid treatment.
- Model 4: Impatient bidder model that also accounts for overbidding in sealed bid auctions: $bid = value\left(\frac{n-1}{n+sa-dc}\right)k$. This is the same as Model 2, except k is a parameter to account for overbidding in the sealed bid treatment.

We present the four models in Table 3. Estimates in Table 3 are obtained using non-linear generalized least squares model weighted using the period variable because variability of the bids as a function of value goes down slightly over time (there is, however, no significant trend that we could detect with a linear model). We get virtually identical estimates and p-values without weighting by period, and slightly lower R^2 (0.90 for models 2 and 4, vs. 0.94).

[14] For completeness, we've included Model 3, which does not account for overbidding. As one can easily see from the results, the estimated parameters are inconsistent.

	Parameters						
			k				
Model	***a***	***c***	***d* = 1**	***d* = 10**	***d* = 30**	**Sealed Bid**	R^2
1	—	—	1.23 (0.0041)				0.939
2	—	—	1.14 (0.0084)	1.22 (0.0083)	1.32 (0.0083)	1.25 (0.0063)	0.947
3	-0.39 (0.0229)	0.0114 (0.0011)	—	—	—	—	0.890
4	0.27 (0.0259)	0.0143 (0.0010)	1.25 (0.0063)				0.947

Table 3. Parameter estimates.

Model 1 is the baseline model that accounts for overbidding but not for impatience. Model 2 demonstrates that, consistent with the revenue results, overbidding relative to RNNE is different in the four treatments.[15] Model 3 is the risk neutral model that accounts for impatience in the Dutch treatments, but not for the overbidding in the sealed bid treatment. For this reason we can see that the model does not fit as well, and the real clue that the model is lacking is the fact that the estimate for *a*, the enjoyment coefficient, is actually negative. Model 4 corrects this problem by including an overbidding coefficient. Note that Model 4 fits as well as Model 2, but with three parameters instead of four. The interpretation of Model 4 is the following: for every tick of the Dutch clock, subjects experience 0.27 tokens worth of enjoyment, and for every second of time they have to monitor the auction they also experience 0.0143 token's worth of opportunity cost of time (which translates into a perceived opportunity cost of 51.48 tokens, or about $5.14 per hour). For a fast treatment (d = 1), where the clock ticks every second, enjoyment outweighs cost, and subjects on average get 0.26 token's worth of net enjoyment. But for the slow treatment (d = 30), where the clock only ticks every 30 seconds, opportunity cost

[15] We also ran a regression to test for the treatment effects directly, and the differences are all statistically significant at the 0.01 level. The difference between sealed bid and Dutch 1 revenue is -0.1095 (SE = 0.0105, p < 0.0000), for Dutch 10 the difference is -0.0381 (SE = 0.0104, p = 0.0003, for Dutch 30 the difference is 0.0662 (SE = 0.0104, p < 0.0000).

outweighs the enjoyment so subjects experience 0.16 token's worth of monitoring cost. Since enjoyment slightly outweighs cost in the fast treatment, participants wait a little longer to stop the clock than they would have to bid at the Sealed Bid Auction level, and since cost outweighs enjoyment in the slow treatment, participants stop the clock a little earlier than they would have to bid at the Sealed Bid Auction level. While there are many possible parameterizations that might incorporate the cost of time and general overbidding, the empirical results presented here in Model 4 at least seem reasonable and provide some justification of the theory model presented.

5. Conclusions

We present an experiment and a simple theory of Dutch auctions with impatient bidders that reconcile the two seemingly inconsistent results about revenue equivalence in first-price sealed bid, and Dutch auctions. We find that the speed of the Dutch clock does have a significant impact on auctioneer's revenue in laboratory experiments: fast clock speeds yield revenues that are significantly below the revenues in the sealed bid auction (consistent with Cox et al. 1982), while the revenue in auctions with a slow clock is higher than that in the sealed bid auction (consistent with Lucking-Reiley 1999). These results cannot be explained by bidder errors.

Why are there fast Dutch auctions if they yield lower revenue? Our theory and experimental results suggest that a patient auctioneer should be willing to commit to a slow Dutch clock in order to force acceptance of a higher standing price. In fact, in the limit, why not commit to offering a fixed price? The auctioneer might have a number of reasons to use a faster clock. First, the auctioneer is likely to pay some cost associated with longer auctions. The Dutch auction received its name from the flower auction in Aalsmeer, Holland that is used to trade flowers and plants with the annual worth of over 2 billion Dutch Guilders (Van den Berg 2001) Aalsmeer must sell thousands of lots of a highly perishable commodity. If they were to use a slow clock, far fewer lots could be sold. In other settings, such as Filene's, a department store well known for running a slow Dutch auction in the basement, or auctions of surplus items, time may be less critical. Second, the laboratory experiments we discussed did not allow the bidders to avoid participating in the auction. Endogenous entry is an important feature of real-world auctions (see for example Engelbrecht-Wiggans 1987, Engelbrecht-Wiggans 1993), and allowing endogenous entry is likely to have a substantial impact on the auction's outcome. If we were to allow for endogenous entry of bidders, we may find that some bidders with low values prefer to avoid the auction altogether rather than pay the exorbitant monitoring costs associated with a slow clock. Just as in sealed bid auctions, bidders with values below a certain cutoff level would choose not to bid. In fact, if $c - a > d$ none of the bidders would participate. Incorporating endogenous entry could lower allocative efficiency and auctioneer revenue.

Finally, time may affect bidder preferences in different ways. For example, a longer auction might lower a bidder's use value (v_i) for the object. Examples of objects that are likely to exhibit these sorts of preferences are durable goods that might promise a stream of income to the owner (rental apartments or spectrum rights) or items whose usefulness is restricted to a limited time (in style or winter clothing). When use values are declining one can show that the auction will end at a lower prices than a sealed bid auction (assuming the sealed bid auction itself is not too slow). These are probably not the correct sorts of preferences for laboratory experiments discussed here or even Lucking-Reiley's field experiments but might be common in many potential Dutch auction applications. For example, a florist's willingness to pay for a particular lot of flowers is almost definitely related to its freshness. If the auction had lasted a very long time, the flowers would be noticeably less fresh!

The results presented here allow us to make two conclusions. First, the choice of clock speed in a Dutch auction is an important design variable that must be considered carefully by the auctioneer. While it would be foolish to draw too many actual design lessons from the experimental results presented here, we believe that these results indicate the need for more formal theoretical analysis of specific design parameters in the Dutch auction. These results highlight the need to add factors, such as timing, into formal models of bidder behavior in order to obtain a theory that is applicable to real world auction design. The second conclusion is of a methodological nature. The results in Lucking-Reiley are not necessarily due to fundamental differences in field experiments from laboratory experiments. There are simple design changes – a slower clock – that allow one to replicate the qualitative features of this particular field experiment in a laboratory setting.

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Appendix

Lemma 2: $b^*(v)$ is strictly monotone increasing.

Proof: The indirect utility function from the equilibrium bid is

$$U^*(v) \equiv U(b^*(v), v) = (v - b^*(v) + e(t(b^*(v))))H(b^*(v)) + \int_{x \geq b^*(v)} e(t(x))dH(x). \quad (15)$$

Since $U^*(v)$ is a value function, we can apply the envelope theorem to obtain

$$U^{*\prime}(v) = \frac{\partial U(b^*(v), v)}{\partial v} = H(b^*(v)). \quad (16)$$

Since $U^*(v)$ is obviously convex, it follows that $U^{*\prime}(v) = H(b^*(v))$ is increasing in v. Since $H(b)$ is increasing in b it must be that $b^*(v)$ is increasing in v.

In order to demonstrate strict monotonicity, suppose that $b^*(v)$ is not strictly monotonic. Then there exists some interval (v_1, v_2) of values such that $b^*(v_1) = b^*(v_2)$. Consider a bidder with the value v_2. She could increase her expected profits by bidding slightly above $b^*(v_2)$ since when the second highest value is in (v_1, v_2) she now wins for certain. Since this is a measurable event, she can select a higher bid such that the loss in profit (and possibly enjoyment if $e'(t) > 0$) from a higher bid is more than offset by the increased probability of winning in this event.■

Lemma 3: $b^*(v)$ is a global maximizer.

Proof:

We show that $U(b, v)$ is increasing in b for $b < b^*(v)$ and decreasing in b for $b > b^*(v)$. Recall from (4) that

$$\frac{\partial U(b, v)}{\partial b} = (v - b + e(t(b)))H'(b) - (1 + de'(t(b)))H(b) + e(t(b))H'(b). \quad (17)$$

Therefore, we have that

$$\frac{\partial U(b,v)}{\partial b \partial v} = H'(b) > 0. \quad (18)$$

Let $b < b^*(v)$ and let $\hat{v}$ be such that $b^*(\hat{v}) = b$. By strict monotonicity of the bid function it follows that $v > \hat{v}$. By (18), we know that for all $b < b^*(v)$

$$\frac{\partial U(b,v)}{\partial b} \geq \frac{\partial U(b,\hat{v})}{\partial b} \equiv \frac{\partial U(b^*(\hat{v}),\hat{v})}{\partial b} \equiv 0. \quad (19)$$

Or, $U(b,v)$ is increasing in b for $b < b^*(v)$.

Now, let $b > b^*(v)$ and let $\hat{v}$ be such that $b^*(\hat{v}) = b$. By strict monotonicity of the bid function it follows that $v < \hat{v}$. By (18), we know that for all $b > b^*(v)$

$$\frac{\partial U(b,v)}{\partial b} \leq \frac{\partial U(b,\hat{v})}{\partial b} \equiv \frac{\partial U(b^*(\hat{v}),\hat{v})}{\partial b} \equiv 0. \quad (20)$$

Or, $U(b,v)$ is decreasing in b for $b > b^*(v)$. ■

The base text is for the Dutch mechanism with the 10 second clock. Whenever the numbers are different for the 1 and 30 second treatments, we include them in parenthesis. The parts that are different in the Sealed bid treatment are in *italics*.

Instructions

Introduction

This is an experiment in market decision-making. If you follow the instructions carefully and make good decisions, you can earn a considerable amount of CASH.

The experiment consists of a sequence of 21 auctions. At the end of the session you will receive ten dollars ($10) PLUS your total earnings from all 21 auctions.

It is important that you do not talk or in any way try to communicate with other people during the experiment. If you disobey the rules, we will have to ask you to leave.

Auction Description

In each auction you and two other participants will compete to purchase a fictitious asset. The price of the asset will start at 100 tokens and decrease every 10 seconds (1 second, 30 seconds) by 5 tokens. Any of the bidders can stop the auction and purchase the asset at the price displayed on the screen by clicking the “Submit Bid” button. The first person to click the button wins the asset and pays the price displayed on the screen, and the other two people earn 0 for that auction.

For sealed bid: you submit a bid by entering your bid amount into the text box on the screen, and clicking the "Submit Bid" button. The bidder who submits the highest bid, wins the asset and pays the amount of the bid., and the other two people earn 0 for that auction.

Resale Values and Earnings

If you purchase an asset, your earnings are equal to the difference between your resale value for that asset and the price you paid for the asset. Your resale value will be displayed on your screen at the beginning of each auction.

That is: YOUR EARNINGS = RESALE VALUE - PURCHASE PRICE.

For example if you pay 30 for the asset and your resale value is 64, your earnings are

EARNINGS FROM THE ASSET = 64 - 30 = 34 tokens.

Resale values will differ among individuals and auctions. For each bidder the resale value for the asset will be between 1 and 100. Each number from 1 to 100 has an equal chance of being chosen. It is as if the numbers from were stamped on 100 balls, one number on each ball, and placed in an urn. A random draw from the urn determines the resale value of an asset for an individual. Your chance of drawing a resale value between 1 and 10 is 10%, between 11 and 20 is 10%, between 21 and 30 is 10%, and so on. You are not to reveal your resale values to anyone. It is your own private information

At the end of each auction, all bidders will see the auction's outcome on their screens. If you won the auction, you will be informed of your earnings. If you did not win, you will be told that you did not trade, and your earnings for that auction are 0.

Your earnings from all previous auctions, along with your values, the winning prices, and the amounts you paid, will be displayed on your screen during each auction.

Example 1 Suppose that, in a given period the bidders have these resale values:

Bidder 1 has the resale value of 85
Bidder 2 has the resale value of 80
Bidder 3 has the resale value of 63

Suppose the market price changes as follows:

Beginning of the round: price = 100
After 10 (1, 30) seconds: price = 95
After 20 (2, 60) seconds: price = 90
After 30 (3, 90) seconds: price = 85
After 40 (4, 120) seconds: price = 80
After 50 (5, 150) seconds: price = 75

After 50 seconds Bidder 1 stops the auction.

For sealed bid: suppose Bidder 1 bids 75, bidder 2 bids 60, and bidder 3 bids 55.

Bidder 1 earns 85 – 75 = 10 tokens for this period, and bidders 2 and 3 earn 0 tokens for this trading period.

Matching

You will not be matched with the same two participants for two consecutive auctions. You will not be told which of the other participants in the room you are matched with, and they will not be told that you matched with them. What happens in any auction has no effect on what happens in any other auction.

Ending the experiment

At the end of the experiment, your earnings from all 21 auctions will be totaled and converted to dollars at the rate of ten (10) cents for each token. You will be paid this amount plus an additional $10, in private and in cash. The total payment will be displayed on your computer screen at the end of the session.

Now, please complete the quiz on the next page. If you have any questions raise your hand and I will come to where you are sitting and answer them. When everyone has completed the quiz I will go over the answers, show you a brief demo of the computer interface you will be using, and we will begin the decision making part of the experiment.

QUIZ

Question 1 Suppose the bidders' resale values are: 70 experimental dollars (bidder 1), 40 experimental dollars (bidder 2), 45 experimental dollars (bidder 3). The price changes as follows:

Beginning of the round:	price = 100
After 10 (1, 30) seconds:	price = 95
After 20 (2, 60) seconds:	price = 90
After 30 (3, 90) seconds:	price = 85
After 40 (4, 120) seconds:	price = 80
After 50 (5, 150) seconds:	price = 75

And after 50 seconds Bidder 1 stops the auction.

For sealed bid: suppose Bidder 1 bids 75, bidder 2 bids 30, and bidder 3 bids 25.

1. Who wins the auction? ___________________

2. What are the earnings of

bidder 1__________,

bidder 2__________ and

bidder 3__________?

Question 2 Suppose the bidders' resale values are the same as in Exercise 1: 70 experimental dollars (bidder 1), 40 experimental dollars (bidder 2), 95 experimental dollars (bidder 3). The price changes as follows:

Beginning of the round:	price = 100
After 10 (1, 30) seconds:	price = 95
After 20 (2, 60) seconds:	price = 90
After 30 (3, 90) seconds:	price = 85
After 40 (4, 120) seconds:	price = 80

And after 40 seconds Bidder 3 stops the auction.

For sealed bid: suppose Bidder 1 bids 60, bidder 2 bids 30, and bidder 3 bids 80.

1. Who wins the auction? ___________________

2. What are the earnings of

bidder 1__________,

bidder 2__________ and

bidder 3__________?