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Demand Reduction and Preemptive Bidding in Multi-Unit License Auctions

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Abstract

Multi-unit ascending auctions allow for equilibria in which bidders strategically reduce their demand and split the market at low prices. At the same time, they allow for preemptive bidding by incumbent bidders in a coordinated attempt to exclude entrants from the market. We consider an environment where both demand reduction and preemptive bidding are supported as equilibrium phenomena of the ascending auction. In a series of experiments, we compare its performance to that of the discriminatory auction. Strategic demand reduction is quite prevalent in the ascending auction even when entry by the newcomer imposes a (large) negative externality on incumbents. As a result, the ascending auction performs worse than the discriminatory auction both in terms of revenue and efficiency, while the two auction formats offer similar chances for newcomers to enter the market.

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1 Introduction

Following the US spectrum auctions in 1994, governments around the world decided to employ auctions to assign scarce resources. For instance, the rights to use gas stations along highways, airport slots, phone numbers and telecommunication frequencies are now often sold via auctions. In many cases, some variant of the ascending auction is used, presumably because of its initial success in the spectrum auctions organized by the FCC. The initial enthusiasm was tempered somewhat when instances of successful collusion were identified in multi-unit ascending auctions (Cramton and Schwartz 2000). Concerns about collusion in ascending auctions were further underlined in recent theoretical papers. Noussair (1995), Engelbrecht-Wiggans and Kahn (1998) and Ausubel and Cramton (1998) all point at auctions where bidders with multi-unit demand have incentives to reduce their demand and split the available supply at low prices. It is now well-known that demand reduction can be supported as a non-cooperative equilibrium of both uniform-price sealed bid auctions and ascending auctions. Notice that demand reduction does not only have devastating consequences for revenue, but that it also harms efficiency. When firms reduce their demand all firms win licenses, regardless of their ability to operate at low costs in the subsequent market.

Apart from demand reduction there is also an equilibrium at the other end of the theoretical spectrum. In many license auctions both incumbents and newcomers fight for a limited number of licenses. Typically, entry by a newcomer imposes a negative externality on incumbents. In the gasoline market, for instance, incumbent firms often fear that supermarkets will enter and set very competitive gasoline prices in an attempt to attract customers to their core business. A series of theoretical papers by Jehiel et al. (1996, 1999), Jehiel and Moldovanu (2000) and Das Varma (2002, 2003) shows that in situations with identity-dependent externalities sellers may employ auctions to exploit the preemptive motive of incumbents. In an attempt to keep the entrant out of the market, incumbents may engage in predatory bidding and drive up the revenue to levels that exceed the economic value of the licenses. The ascending auction format may be particularly conducive to predatory bidding, because incumbents can verify during the auction that other incumbents contribute their share to keeping the entrant out of the market. Whether the preemptive equilibrium is regarded as a successful outcome or not depends on the goals pursued by the seller. A seller who is mainly interested in raising revenue fares well in the preemptive equilibrium of the ascending auction. A similar remark applies when the seller's goal is to promote an efficient allocation of licenses. Sellers who want to encourage entry by newcomers, however, will be less happy if bidders coordinate on the

preemptive equilibrium.

Given the opposing theoretical equilibria, the performance of the ascending auction will depend crucially on the equilibrium selection process. This renders establishing the appropriateness of using ascending auctions to allocate licenses an inherently empirical issue. In this paper, we provide a serious test of the ascending auction through a series of experiments where we vary the level of the negative external effect imposed by the entrant. We assess the empirical appeal of the demand reduction equilibrium and the preemptive equilibrium in a setting where both equilibria are given a good shot. We also evaluate the performance of the ascending auction in the light of the performance of the (sealed bid) discriminatory auction where the highest bidders pay their own bids. Discriminatory auctions do not support collusion in equilibrium. At the same time, there is a smaller role for preemptive bidding because in the symmetric equilibrium of the discriminatory auction newcomers face better perspectives to enter the market than in the preemptive equilibrium of the ascending auction. So a comparison of the performance of the two auction formats may very well depend on the type of equilibrium selected in the ascending auctions.¹

In the auction environment that we consider two incumbents compete with one entrant for six identical licenses. For experimental simplicity and to keep the formal model tractable, we assume that bidders have flat demand for the licenses offered. In particular, each bidder draws an independent private value that is valid for each license bought. Each single bidder is allowed to buy three licenses at most. If the entrant acquires one or more licenses, both incumbents experience a negative external effect. This holds even when an incumbent does not buy any license. The only way to prevent the negative external effect is to keep the entrant completely out of the market. We compare the two auction formats under three different regimes: one where the external effect is absent, another one where a mild negative effect exists and a final regime where there is a strong negative effect. In the ascending auction the demand reduction equilibrium coexists with the preemptive equilibrium in all three regimes. Notice that the setting is conducive for either equilibrium. Both are implemented via symmetric bidding of the relevant actors. In the demand reduction equilibrium, all three bidders have to reduce their demand to two licenses to divide total supply equally at zero prices. In the preemptive equilibrium, each incumbent has to acquire three licenses

¹We have chosen to limit our attention to the two auction formats that are most often observed in practice. It would also be interesting to compare the results of these auctions with the performance of the optimal auction but it is unknown for our setting. Jehiel and Moldovanu (2001) show that the optimal auction often does not exist in multi-unit auctions with allocative externalities.

to keep the entrant out. Intuitively, one would expect that demand reduction becomes less focal when the harm inflicted by the entrant increases. Our experiment allows us to investigate this issue of equilibrium selection empirically.

Previous experimental work addressed the question whether bidders reduce their demand in the absence of negative external effects. They indeed appear to do so in both uniform-price auctions and ascending auctions. Alsemgeest et al. (1998), for instance, study the ascending auction and a sealed-bid auction where the price for each unit equals the lowest accepted bid. They consider two environments: one with single-unit demand and another one with two-unit demand. Some demand reduction is observed in the ascending auction with two-unit demand. The sealed bid auction generates more revenue in both environments. List and Lucking-Reiley (2000) report the results of a field experiment in which they sell sports cards. They find some evidence for demand reduction in uniform-price auctions, although revenues do not differ from those in a Vickrey auction because bidders bid too high on their first units. Kagel and Levin (2001) let a single two-unit human bidder bid against a computer in a uniform-price auction, an ascending auction and the Vickrey/Ausubel auction. Both the uniform-price and the ascending auction produce substantial demand reduction, but the level of demand reduction is more pronounced in the latter. Lastly, in an environment where two bidders with flat demand compete for two units, Engelmann and Grimm (2003) compare the performance of five auction formats: the uniform-price, the ascending, the discriminatory, the Vickrey and the Ausubel auction. They observe more pronounced demand reduction in the ascending auction than in the uniform-price auction. They even observe low bids in the Ausubel auction, where demand reduction is not supported in equilibrium. Overall, pooling the results across studies, the conclusion is justified that demand reduction is more pronounced in ascending auctions than in uniform-price auctions.

As far as we know, our experiments are the first to investigate the impact of negative external effects on auction outcomes. The experiments reveal that demand reduction remains to have a strong empirical bite when incumbents have incentives to keep the entrant out of the market. In particular, we find that although the presence of a negative external effect makes strategic demand reduction less focal in the ascending auctions, it is always observed more often than preemptive bidding. Because demand reduction is so widespread, the ascending auction is outperformed by the discriminatory auction in terms of revenue and efficiency. Entry levels under the two auction formats are about the same. Taken together, our results suggest that the ascending auction is prone to collusion even when there are strong preemptive motives

to defect.

The remainder of the paper is organized as follows. Section 2 provides the details of the auctions, the experimental design and procedures. Section 3 presents the theoretical analysis for our setup. In Section 4 we discuss the experimental results and Section 5 concludes.

2 Experimental design

The experiment was computerized. Subjects started with on-screen instructions. They also received a summary of the instructions on paper (see Appendix A). The actual experiment consisted of two parts. Part 1 started with a practice period followed by 15 periods. Part 2 consisted of 1 period only. Subjects received instructions for the second part only after the first part was completed. They earned points in each (real) period of the experiment, which were exchanged at the end of the experiment at a rate of 1 euro for 80 points. Table 1 summarizes the details of the 6 treatments. Each subject participated in one treatment only.

Subjects were assigned to the same group of 3 bidders throughout the whole first part. In each period, 6 identical goods were sold to the 3 subjects of a group. Each subject received one integer private value from the $U[0, 100]$ distribution, which was valid for each of the 6 goods being offered for sale. Subjects derived a constant marginal payoff equal to their private value for each good bought. Each subject could buy at most 3 goods in a period. Subjects were only informed about their own private value and private value draws were independent across subjects and periods. All these rules were common knowledge. We kept the private value draws constant across treatments. Thus, differences between treatments cannot be attributed to differences in draws.

We used three levels of the negative external effect: $x = 0$, $x = 50$ and $x = 100$. The external effect was kept constant within a treatment. Each subject was assigned a fixed role that she kept during the whole experiment. For the treatments with $x = 0$ subjects were assigned to ‘symmetric’ roles of Types A, B and C. In the treatments with $x > 0$, Types A and B personified the incumbents and Type X represented the entrant. Each bidder received a profit on purchases equal to the number of goods bought times the bidder’s private value minus the sum of the prices paid for the goods. Type X’s profits were entirely determined by the profit margins on the goods bought. Types A and B knew that if Type X would buy 1, 2 or 3 goods, an amount of 50 (100) points would be subtracted from their profits on purchases when $x = 50$ ($x = 100$). The negative external effect was also inflicted upon an

Table 1: Experimental design

treatment	auction	external					private		
		effect	# groups	size	composition	# licenses	restriction	values	
asc0	ascending	$x = 0$	8	3	3 sym	6	3	$U[0, 100]$	
asc50	ascending	$x = 50$	8	3	2 inc, 1 entr	6	3	$U[0, 100]$	
asc100	ascending	$x = 100$	8	3	2 inc, 1 entr	6	3	$U[0, 100]$	
disc0	discriminatory	$x = 0$	8	3	3 sym	6	3	$U[0, 100]$	
disc50	discriminatory	$x = 50$	8	3	2 inc, 1 entr	6	3	$U[0, 100]$	
disc100	discriminatory	$x = 100$	8	3	2 inc, 1 entr	6	3	$U[0, 100]$	

incumbent when she did not buy any good herself. So there was no escape from an external effect once it occurred. The only possibility to prevent the negative external effect was to keep the entrant completely out of the market.

Our modeling of the external effect was based on the idea that in most license auctions winners engage in a form of Bertrand competition in the aftermarket. With Bertrand competition, a newcomer will drive down consumer prices to the competitive level independent of the number of licenses it acquires. In our reduced form model, we therefore chose the external effect to be independent of the number of licenses acquired by the entrant.

Notice that subjects in the treatments with $x > 0$ could easily lose money in some periods because of the external effect. Therefore, we provided subjects with a starting capital that they did not have to pay back after the experiment. The starting capital in treatments $x = 0$, $x = 50$ and $x = 100$ equalled 200, 750 and 1500 points, respectively. Subjects knew that if they finished the experiment with a negative balance they would go home without any money. It never happened that a subject's balance actually became negative.

Part 2 lasted for just a single period. To cover potential losses in this part, at the beginning of part 2 subjects received an additional bonus of 500 (1000) points in the treatments with $x = 50$ ($x = 100$). The only difference between a period of part 1 and the period of part 2 was that the payoff in part 2 was automatically multiplied by 10. Subjects thus played for much more money in the period of part 2. For statistical reasons we kept the group compositions the same as in part 1. We did not inform subjects about this aspect and none of them asked about it. The auction format and the level of the external effect were kept constant across parts.

In the ascending auctions, bidders first simultaneously submitted their 'initially demanded quantity'. This initial demand represented the number of goods on which they wanted to start bidding. It had to be an integer number from the set $\{0, 1, 2, 3\}$. When the sum of initial demands within a group was less than or equal to 6, the period ended immediately and all bidders received their requested goods at a price of zero.² In case the sum of initial demands was greater than 6, a thermometer (or clock) started rising point-by-point from 0 points onwards. The thermometer's 'temperature' showed the price

²In accordance with the usual practice of license auctions, we did not use reserve prices in either auction format. In the recent 3G auctions, most countries refrained from setting a reserve price (Netherlands) or they set very low reserve prices (e.g., Germany, Austria, Switzerland, Italy). As Klemperer (2003) notes, "[But] serious reserve prices are often unpopular with politicians and bureaucrat who –even if they have the information to set them sensibly– are often reluctant to run even a tiny risk of not selling the objects, which outcome they fear would be seen as a 'failure'."

level that all active bidders were prepared to pay for the number of goods that they still demanded. At every price each bidder had the possibility to decrease her demand. The thermometer continued to rise until the price where the sum of the demanded quantities equalled 6. This was the price that each bidder had to pay for all the goods that were assigned to her in accordance with her demanded quantity.

When the thermometer started rising, each bidder was and remained completely informed about each of the demanded quantities of the other two bidders. In case one of the bidders decreased her demand, the thermometer halted for four seconds to give the bidders the possibility to process the information. Bidders were not able to increase their demand within a period. They only had the possibility to decrease their demanded quantity as long as the total demanded quantity in the group exceeded 6. The computer kept track of how much a bidder could reduce her demanded quantity.³ At the end of a period bidders were informed about their own earnings but not about the earnings of others.

In the discriminatory auctions, bidders simultaneously submitted three (integer) bids. They also had the possibility to bid on fewer than 3 goods.⁴ All the bids in a group were ordered and the 6 goods were assigned to the 6 highest bids.⁵ The bidder who submitted a highest bid bought the good at a price equal to the amount bid. In case of tied bids the bids were ordered on the basis of a lottery. At the end of a period bidders were informed about the facts that were relevant to their own earnings but they were not informed about the earnings of others.

In total we recruited 144 subjects from the student population of the University of Amsterdam. The subjects were equally divided over the 6 treatments, so we obtained per treatment data on 8 independent groups of 3 subjects each. The experiment lasted for about one and a half hours. Subjects earned on average 30.80 euros with a minimum of 5.10 euros and a maximum of 80.30 euros.

³In the exceptional case where two (or even three) bidders simultaneously decreased their demanded quantity such that the total demanded quantity would become smaller than 6, a lottery would determine whose demanded quantity would be decreased and whose demanded quantity would remain constant.

⁴In all treatments, we had a lower bound of 0 on subjects' bids. In the treatments with $x = 0$, $x = 50$ and $x = 100$ the upper limit of subjects' bids was equal to respectively 100, 125 and 150. The upper limit was never reached in the experiments.

⁵Notice that in both auctions there was a possibility that some goods remained unsold in a period. In the ascending auctions this happened when the sum of the initially demanded quantities was less than 6. In the discriminatory auctions this would occur when in total fewer than 6 bids were submitted.

3 Equilibrium predictions

In section 3.1 we discuss, for the environment described above, the demand-reduction and preemptive equilibrium outcomes for the ascending auction. In section 3.2 we discuss the preemptive equilibrium for the discriminatory auction. For ease of exposition we consider bidder values that are uniformly distributed on $[0,1]$ rather than on $[0,100]$, i.e. we choose dollar units rather than pennies so that values and bids are scaled by $1/100$. Consequently, the external effect used in the experiment is $x = 0$, $x = \frac{1}{2}$, and $x = 1$.

3.1 Ascending auction

We start with the symmetric case without externalities ($x = 0$). There is an obvious candidate for the demand-reduction equilibrium, in which all three bidders request only two licenses and the market clears at zero prices. To verify that this is indeed an equilibrium, suppose, without loss of generality, that bidders 2 and 3 demand only two licenses at zero prices. Bidder 1's profit when she follows the demand reduction equilibrium and only demands two licenses is equal to $2v_1$, with v_1 bidder 1's value for a single license. Her expected profits of demanding more, i.e. three licenses, depends on her beliefs about the way bidders 2 and 3 will react to her deviation. We assume that bidder 1 believes that her rivals will bid competitively in this case, i.e. they will each keep bidding on two licenses up to their valuations. Bidder 1's expected payoff of deviating is therefore given by $\max_b(\pi_1^e(b|v_1))$, where $\pi_1^e(b|v_1)$ denotes bidder 1's expected payoff when she is willing to keep bidding on three licenses until the price level reaches b after which she "stops," i.e. reduces her demand to two licenses, and the auction ends.⁶

$$\begin{aligned} \pi_1^e(b|v_1) &= 3 \int_0^b \int_0^b (v_1 - \min(v_2, v_3)) dv_2 dv_3 \\ &\quad + 3 \int_0^b \int_b^1 (v_1 - v_2) dv_2 dv_3 + 3 \int_b^1 \int_0^b (v_1 - v_3) dv_2 dv_3 \\ &\quad + 2 \int_b^1 \int_b^1 (v_1 - b) dv_2 dv_3. \end{aligned} \tag{1}$$

Here the top line corresponds to the case where bidder 1 has the highest-value, in the middle line bidder 1 has the middle value, and in the bottom

⁶Recall that if the other bidders each demand two licenses and bidder 1 initially demands three licenses, she cannot lower her demand below two licenses since total demand cannot fall below the total supply of six licenses.

line bidder 1 has the lowest value. Bidder 1's expected payoff in (1) is readily computed as

$$\pi_1^e(b|v_1) = b^2(1 - v_1) - 2b(1 - v_1) + 2v_1. \quad (2)$$

Note that $\pi_1^e(b|v_1)$ is *convex* in b with $\pi_1^e(0|v_1) = 2v_1$ and $\pi_1^e(1|v_1) = 3v_1 - 1$. Hence, bidder 1's payoff is maximized by choosing $b = 0$, i.e. reducing demand to two licenses at zero prices.

Next, consider what happens if the entrant imposes a negative externality, $x > 0$, on the incumbents when she wins a license. The demand reduction outcome just described can again be sustained in equilibrium since no incumbent bidder can avoid the negative externality when the other two bidders demand only two licenses from the start. In other words, when others follow the demand equilibrium described above, an incumbent bidder will incur the negative externality no matter what she does, and the presence of the negative externality therefore will not alter her optimization problem.

Proposition 1. *The demand reduction equilibrium outcome, in which all three bidders demand only two licenses at zero prices, is an equilibrium outcome for all levels of the negative externality x .*

Not surprisingly, the demand reduction outcome is not the unique equilibrium outcome for the ascending auction. For the case of no negative externality, i.e. $x = 0$, another usual suspect is the competitive equilibrium outcome where all bidders bid up to their values on all three licenses. Indeed, the standard logic underlying truthful bidding in the single-license case carries over to our environment and bidding up to one's value on all three licenses is indeed an equilibrium. When $x > 0$, however, this is no longer true as incumbent bidders profit from excluding the entrant from the market. We next derive the *preemptive* equilibrium, in which incumbents bid on all three licenses to price levels that possibly exceed their values in an attempt to keep the entrant out of the market.

First, given that both incumbents bid on three licenses, it is optimal for the entrant to bid up to her value on all three licenses, $B_E(v) = v$. Let $B_I(v)$ denote the drop-out level for an incumbent bidder with value v , i.e. the price level at which she reduces demand from three to zero licenses. The differential equation that determines $B_I(v)$ can be derived from a simple marginal argument. Suppose an incumbent who has value v bids instead as if her value were $v + \epsilon$. Such a deviation alters the outcome of the auction only if the bidder turns from a loser into one of the winners. This requires that either (i) the other incumbent has a value between v and $v + \epsilon$ and the

entrant has a value higher than $B_I(v)$, or (ii) the entrant has a value between $B_I(v)$ and $B_I(v + \epsilon)$ and the other incumbent has a value higher than v . The former case happens with probability $\epsilon(1 - B_I(v))$ and the bidder's net gain of deviating from v to $v + \epsilon$ in this case would be $3v - 3B_I(v)$. The latter case happens with probability $\epsilon B_I'(v)(1 - v)$ and the net gain would be $3v - 3B_I(v) + x$. In equilibrium, bidding truthful should be optimal, so:

$$(1 - B_I(v))(3v - 3B_I(v)) + B_I'(v)(1 - v)(3v - 3B_I(v) + x) = 0. \quad (3)$$

For $x = 0$ we simply have $B_I(v) = v$, but for $x > 0$ no analytic solution exists. We can, however, give a partial characterization of $B_I(v)$. Under the assumption that $B_I(v)$ is non-decreasing, (3) implies that $v < B_I(v) < v + x/3$, i.e. incumbent bidders bid above their true valuations. Furthermore, $B_I(v) = 1$ implies that $v = 1 - x/3$, so incumbents with higher values all bid 1.⁷

Proposition 2. *In the preemptive equilibrium outcome, incumbents bid above their true values on all three licenses. Their optimal bid function, $B_I(v)$, satisfies (3) for $0 \leq v \leq 1 - x/3$ and $B_I(v) = 1$ for $v \geq 1 - x/3$.*

The incumbents' bid functions for the three values of x employed in the experiment are given in Figure 1.

[Figure 1 about here]

3.2 Discriminatory auction

The demand reduction equilibrium cannot be sustained in the discriminatory auction since bidders cannot alter the prices they pay for the licenses they win by bidding low on other licenses. In fact, in the discriminatory auction it is optimal to bid the *same* for all three licenses, see Lebrun and Tremblay (2003).⁸ Consider therefore the preemptive equilibrium where all three

⁷Note that bidding higher makes no sense since a bid of 1 already beats the entrant's bid.

⁸Lebrun and Tremblay prove this for more general demand configurations than the flat demand employed in our experiment. The basic intuition for our setup is as follows: suppose, in contradiction, that a bidder with value v places three different bids $b_1 < b_2 < b_3$. The optimal b_3 is determined by trading off the profit conditional on winning, $v - b_3$, against the probability of winning as determined by the distribution of the sixth-highest of the others' bids. Likewise, the optimal b_2 (b_1) is determined by trading off $v - b_2$ ($v - b_1$) against the winning probability as determined by the distribution of the fifth-highest (fourth-highest) of others' bids, since one (two) of the own bids are higher. But this implies $b_1 > b_2 > b_3$, the desired contradiction.

bidders bid on all three items, and incumbents take into account their true values and the externality $x > 0$. It will prove useful to introduce the inverses $\Phi_E(b)$ and $\Phi_I(b)$ of the bidding functions $B_E(v)$ and $B_I(v)$ respectively. The differential equations the inverse bid functions have to satisfy can be derived from a marginal analysis similar to the one in the previous subsection. For the entrant we have

$$-3(1 - (1 - \Phi_I(b))^2) + 3(\Phi_E(b) - b)(1 - (1 - \Phi_I(b))^2)' = 0. \quad (4)$$

To understand this equation recall that, in equilibrium, the gain for an entrant of type $\Phi_E(b)$ of bidding $b + \epsilon$ instead of b should balance the cost. The cost of such a deviation is 3ϵ when the entrant is *not* the lowest bidder, which happens with probability $(1 - (1 - \Phi_I(b))^2)$. The potential gain $3(\Phi_E(b) - b)$ occurs when the deviation changes her from a loser to a winner, which happens when the lowest of the two incumbent values was somewhere between $\Phi_I(b)$ and $\Phi_I(b + \epsilon)$: the probability of this event is $\epsilon(1 - (1 - \Phi_I(b))^2)'$. Similarly, for the incumbent bidders we have

$$\begin{aligned} -3(1 - (1 - \Phi_I(b))(1 - \Phi_E(b))) + 3(\Phi_I(b) - b)(1 - (1 - \Phi_I(b))(1 - \Phi_E(b)))' \\ + x\Phi_E'(b)(1 - \Phi_I(b)) = 0. \end{aligned} \quad (5)$$

The two terms in the top line have the same interpretation as in equation (4). The extra term in the bottom line occurs when a losing incumbent, by raising her bid slightly, beats the entrant's bid, which has the extra benefit that the negative externality is avoided. This happens when the entrant's value was between $\Phi_E(b)$ and $\Phi_E(b + \epsilon)$ and the other incumbent's value was above $\Phi_I(b)$: the probability of this event is $\epsilon\Phi_E'(b)(1 - \Phi_I(b))$.

For the case with no externality, $x = 0$, the first-order differential equations (4) and (5) can be solved to yield $\Phi_I(b) = \Phi_E(b) = \Phi(b)$ where

$$\Phi(b) = \frac{1}{4} \left(3 + 3b - \sqrt{9 - 30b + 9b^2} \right), \quad (6)$$

defined for $0 \leq b \leq \frac{1}{3}$ with $\Phi(0) = 0$ and $\Phi(\frac{1}{3}) = 1$. Since the differential equations (4) and (5) are necessary conditions and their solutions are unique, the inverse bid functions constitute the unique equilibrium. It is straightforward to invert (6) to yield the symmetric bidding function as shown by the thick solid line in Figure 4.⁹

⁹The equilibrium bid functions of Proposition 3 can also be derived more directly. Note that the payoff of a bidder who has value v but bids as if her value is w is given by $\pi^e(w|v) = (v - B(w))(1 - (1 - w)^2)$. Optimizing with respect to w and equating the result to zero at $w = v$ yields a first-order differential equation that is solved by (7).

Proposition 3. *With no externality, the unique symmetric equilibrium of the discriminatory auction is given by*

$$B_I(v) = B_E(v) = \frac{v}{3} \left(\frac{3 - 2v}{2 - v} \right). \quad (7)$$

In the presence of an externality, $x > 0$, no analytic solutions to the above differential equations (4) and (5) exist. They can, however, be solved using numerical techniques. For the two values of x used in the experiment, $x = \frac{1}{2}$ and $x = 1$, the bid functions for the entrant and the incumbents are shown as gray lines in Figures 6 and 7. Notice that incumbents' bids exceed those of an entrant with the same value. Also, low-value incumbents bid above their true values even though in a discriminatory auction they will have to pay their own bid when they win.

We are interested to what extent the ascending format of the previous subsection is more (or less) prone to preemptive bidding than the discriminatory auction studied here. One natural measure is the probability that the entrant wins a license in either format. In a preemptive equilibrium where bidders place the same bids on all three licenses, this occurs when the entrants' bid is not the lowest:

$$P_{entry} = \int_{\Phi_E(B_I(0))}^1 (1 - (1 - \Phi_I(B_E(v_E)))^2) dv_E, \quad (8)$$

where $B_I(\cdot)$ and $B_E(\cdot)$ are the optimal bidding functions in the respective auction formats, and $\Phi_I(\cdot)$ and $\Phi_E(\cdot)$ are their inverses. Using the numerical solutions in Figures 1 and 5-7 it is straightforward to determine the entrant's entry probability for the different scenarios. In the ascending auction they are 66.7%, 57.3%, and 45.4% when $x = 0$, $x = 50$, and $x = 100$ respectively. In the discriminatory auction they are 66.7%, 61.0%, and 55.3% when $x = 0$, $x = 50$, and $x = 100$ respectively. In this sense, the ascending auction is more prone to preemptive behavior by the incumbents.¹⁰

¹⁰Part of the intuition behind this result is that in the discriminatory auction incumbents face a strategic risk if they try to keep out newcomers, which they do not have in the ascending auction. In the discriminatory auction it may namely happen that an incumbent attaches high values to the licenses and bids high, while the fellow incumbent attaches low values to the licenses and bids low. As a consequence, the newcomer enters the market and a negative external effect materializes while at the same time the competitive incumbent pays a lot for the licenses that it obtains. Clearly, the incumbents' equilibrium bids take this risk into account (and incumbents bid less than in the absence of this risk). In the ascending auction, an incumbent bidder only bids above the licenses' values if the fellow incumbent is still active in the auction. So this strategic risk does not exist in the ascending auction.

4 Results

We present our findings in two parts. We start with an overview of the aggregate results and compare the performance of the two auctions in terms of revenue, efficiency and opportunities for entry. Then we discuss the main patterns in the individual bidding data and we address the matter of equilibrium selection in ascending auctions.

Most of our results are roughly the same for the 15 periods of part 1 where we used low stakes and the single period of part 2 where we used high stakes. To present our findings in a compact manner, we have chosen to pool the results of parts 1 and 2 and to report separate results only in those cases where they differ significantly.

4.1 Revenue, efficiency and entry

Table 2 shows that, for all levels of the externality x , the discriminatory auction raises more revenue than the ascending auction. The table lists the observed average revenues together with the predicted revenues.¹¹ For the ascending auctions we have separated the predicted revenues based on the preemptive equilibrium and those based on the demand reduction equilibrium.¹² As explained in the previous section, the latter equilibrium does not exist in the discriminatory auction. With negative external effects the ascending auctions raise about 50% of the revenue collected in the discriminatory auctions. Without external effects the ascending auction performs

¹¹Parts 1 and 2 of the experiment resulted in statistically similar revenues for 5 out of 6 treatments; when we consider the realized revenues as fraction of the available Nash revenues at the preemptive equilibrium, the only significant difference is obtained for the treatment disc100. Here the relative revenue provides the appropriate measure for comparison between parts 1 and 2, because we kept values constant across treatments but not across parts. As it appears the randomly drawn values of part 2 are accidentally more favorable for raising revenue. In treatment disc100, average observed revenue equals 190.5 in part 1 and 284.8 in part 2, while the predicted Nash preemptive revenues equal 217.6 and 242.4, respectively. The ratios of these observed and predicted revenues differ significantly (Mann-Whitney rank test ($m = n = 8$, $p = 0.02$)). The test results of the other 5 treatments are far from significant, however (all $p > 0.28$).

¹²In all cases the predictions listed in Table 2 are based on the *actual* private value draws used in the experiments. These predictions may slightly differ from the ones based on the $U[0, 100]$ distribution (cf. Section 3). E.g., when $x = 0$ the preemptive equilibria of the two auction formats are revenue equivalent in the general model and are predicted to yield the seller 150. Yet for the particular private values that we use the preemptive equilibrium in the ascending auction yields a slightly higher revenue than the equilibrium in the discriminatory auction.

Table 2: Revenues

		Ascending	Discriminatory	Mann-Whitney		
$x = 0$	Actual	39.6	<i>71.4</i>	151.9	<i>54.3</i>	$p = 0.00$
	Nash preempt	162.8	<i>117.4</i>	148.9	<i>36.1</i>	
	Nash dem red	0.0	<i>0.0</i>			
$x = 50$	Actual	93.0	<i>116.0</i>	182.3	<i>63.5</i>	$p = 0.00$
	Nash preempt	197.1	<i>119.4</i>	183.3	<i>35.7</i>	
	Nash dem red	0.0	<i>0.0</i>			
$x = 100$	Actual	102.0	<i>140.9</i>	196.4	<i>89.3</i>	$p = 0.00$
	Nash preempt	234.0	<i>128.3</i>	219.2	<i>34.8</i>	
	Nash dem red	0.0	<i>0.0</i>			

Notes: Standard deviations in italics. The Mann-Whitney rank tests compare the realized revenues for the ascending and discriminatory auctions using the 8 average observations per independent group as data.

even worse. The differences between the two auctions are highly significant.¹³ In the discriminatory auctions, the actual revenues trace the predicted revenues very closely for disc0 and disc50 and reasonably well for disc100. In the ascending auctions, the average revenues fall short of the revenues predicted on the basis of the preemptive equilibrium. In these auctions, the demand reduction equilibrium with zero revenue turns out to be a strong force pulling the revenues downward.¹⁴

Figures 2 through 4 show histograms of the revenues for the cases $x = 0$, $x = 50$ and $x = 100$, respectively. Without external effects the frequency distribution of the ascending auction has a pronounced mode at zero revenue. Even when negative external effects are introduced the mode of the distribution stays at zero, although somewhat less pronounced. So demand reduction seems to be the strongest force in the ascending auctions, even

¹³We employ a prudent testing procedure. All tests reported are two-sided tests with independent averages per group as data points.

¹⁴The levels of demand reduction in parts 1 and 2 are of the same magnitude. For instance, 6 of the 8 groups in asc0 successfully reduced demand in part 2. This suggests that bidders reduce their demand for the ‘right’ non-cooperative reasons, and that it is not due to a repeated game effect or low stakes.

when one of the bidders produces a substantial negative externality for the others.

[Figures 2 through 4 about here]

Sellers will typically be interested in the robustness of an auction and dislike formats that produce highly fluctuating outcomes. Note that the discriminatory auctions also beat the ascending auctions in this respect. Table 2 shows that, although the discriminatory auctions result in a higher variance of revenues than theory predicts, they do better than the ascending auctions. This result is confirmed graphically in Figures 2 through 4.

In both types of auctions the presence of a bidder who imposes negative externalities on others is good news for the seller. In the ascending auctions, the seller collects significantly more revenue when there is a moderate external effect of $x = 50$ than when there is no external effect. An increase of the negative external effect to $x = 100$ further enhances the revenue for the seller but not significantly so.¹⁵ The introduction of a bidder with negative effects for the others has quantitatively smaller effects in the discriminatory auctions. The test results are similar though: the difference in revenue between disc50 and disc0 is significant, while the difference between disc100 and disc50 is not.¹⁶ We summarize the above findings on revenue in the following result:

Result 1. (i) For every level of the external effect, x , the discriminatory auction raises significantly more revenue than the ascending auction. (ii) In both auction formats the presence of negative externalities increases the seller's revenue.

Ascending auctions are often promoted on efficiency grounds, i.e. they “put the licenses in the hands of the firms that value them the most.” Although the argument is basically sound, there are two countervailing forces. Consider the case where government sells licenses to use gas stations along highways. Here, colluding incumbents may coordinate to keep a price-fighting entrant out. Although the ascending auction may put the licenses in the hands of the incumbents who value them the most, this may very well harm consumer surplus and social efficiency (for this argument, see also Ewerhart and

¹⁵For asc0 versus asc50 we find $p = 0.04$, for asc50 versus asc100 we obtain $p = 0.83$ (Mann-Whitney rank tests with $m = n = 8$).

¹⁶For disc50 versus disc0 we find $p = 0.02$, for disc100 versus disc50 we obtain $p = 0.21$ (Mann-Whitney rank tests with $m = n = 8$).

Moldovanu 2001). The other possibility why an ascending auction may harm efficiency occurs when firms decide to split the market as predicted by the demand reduction equilibrium. This equilibrium puts some licenses in the hands of firms with inferior private value components. So in the end it is an empirical question which of the auction formats should be chosen to pursue efficiency. Result 2 provides an answer to this question for the setting considered in our experiment.

Result 2. (i) The discriminatory auction yields higher efficiency levels than the ascending auction for every level of the external effect, x . (ii) In both auction formats, the presence of negative externalities decreases efficiency (only) when the externality represents a social harm.

We first report the results for an efficiency measure that is valid for industries where the negative externality imposed on incumbents does not represent a social harm. Consider the example where a price-fighting entrant tries to penetrate a market of colluding incumbents. Here the price-fighter will produce a negative externality for the incumbents, but not for society.¹⁷ For this type of example the ‘traditional efficiency measure’ seems most appropriate. This measure is calculated as the ratio of the sum of the realized private (or use) values and the maximally available sum of private values. Table 3 presents the results for this efficiency measure. Notice that the discriminatory auctions produce higher efficiency levels than the ascending auctions. The differences in efficiency levels are noteworthy and significant for the treatments without externalities ($x = 0$) and the ones with mild externalities ($x = 50$). For the auctions with strong externalities ($x = 100$) the effect is small and insignificant at the conventional level.

Without externalities the efficiency level in the ascending auctions is closer to the level predicted by the demand reduction equilibrium than the level predicted by the preemptive equilibrium. When externalities are introduced, actual efficiency moves slowly into the direction of the level predicted in the preemptive equilibrium. The realized efficiency level is about halfway between the two predicted levels when the negative externality is strong ($x = 100$). However, the increases in efficiency levels as the level of the external effect rises are not significant.¹⁸ A similar result applies for the discriminatory auctions; observed efficiency levels are independent of the level

¹⁷To the contrary, society as a whole may actually become strictly better off when competition is intensified.

¹⁸For asc0 versus asc100 we find $p = 0.09$, the other two p -values are above 0.21 (Mann-Whitney rank tests with $m = n = 8$).

Table 3: Efficiency in % based on use values only

		Ascending		Discriminatory		Mann-Whitney
$x = 0$	Actual	85.6	<i>10.4</i>	95.5	<i>6.7</i>	$p = 0.00$
	Nash preempt	100.0	<i>0.0</i>	100.0	<i>0.0</i>	
	Nash dem red	81.0	<i>8.9</i>			
$x = 50$	Actual	88.6	<i>11.6</i>	95.9	<i>6.2</i>	$p = 0.00$
	Nash preempt	99.7	<i>1.4</i>	99.8	<i>1.2</i>	
	Nash dem red	81.0	<i>8.9</i>			
$x = 100$	Actual	89.6	<i>10.2</i>	93.1	<i>10.2</i>	$p = 0.09$
	Nash preempt	97.5	<i>5.8</i>	99.2	<i>3.5</i>	
	Nash dem red	81.0	<i>8.9</i>			

Notes: Standard deviations in italics. The Mann-Whitney rank tests compare the realized efficiencies for the ascending and discriminatory auctions using the 8 average observations per independent group as data.

Table 4: Efficiency in % including external effects

		Ascending		Discriminatory		Mann-Whitney
$x = 0$	Actual	85.6	<i>10.4</i>	95.5	<i>6.7</i>	$p = 0.00$
	Nash preempt	100.0	<i>0.0</i>	100.0	<i>0.0</i>	
	Nash dem red	81.0	<i>8.9</i>			
$x = 50$	Actual	73.5	<i>24.1</i>	82.8	<i>22.6</i>	$p = 0.03$
	Nash preempt	94.7	<i>14.3</i>	94.4	<i>14.4</i>	
	Nash dem red	58.1	<i>24.5</i>			
$x = 100$	Actual	45.5	<i>68.5</i>	50.5	<i>59.9</i>	$p = 0.67$
	Nash preempt	83.3	<i>52.6</i>	77.4	<i>53.8</i>	
	Nash dem red	20.6	<i>62.5</i>			

Notes: Standard deviations in italics. The Mann-Whitney rank tests compare the realized efficiencies for the ascending and discriminatory auctions using the 8 average observations per independent group as data.

of the external effect.¹⁹

There may also be situations where the negative externality represents a social harm, e.g. when a polluting firm acquires a license. In such cases it makes sense to incorporate the externality in the efficiency measure. A straightforward way to do this is to calculate the realized efficiency level as the ratio of the realized surplus and the theoretically available surplus. Here the realized surplus equals the sum of the realized private values minus the sum of the realized negative externalities. The theoretically available surplus is determined by the allocation that maximizes the sum of the private values diminished by the corresponding negative external effects. Table 4 shows the results for this efficiency measure. Again the discriminatory auction significantly outperforms the ascending auctions for the case of mild externalities, but not for the case of strong externalities.

In the ascending auctions, the efficiency levels are roughly halfway the level predicted by the demand reduction equilibrium and the preemptive equilibrium. Because these predicted levels decrease with the level of the ex-

¹⁹For all three comparisons we find $p > 0.21$ (Mann-Whitney rank tests with $m = n = 8$).

ternal effect, so do the actual efficiency levels. In the discriminatory auctions the efficiency levels decrease significantly with the level of the external effect as well.²⁰ This gives the second part of Result 2.

Policy makers often want to know how particular auction formats affect the chances for possible entrants. It has been argued that auctions with a discriminatory element offer better chances to entrants than ascending auctions since the latter offer incumbents the possibility to trail entrants and outbid them with the smallest possible margin. Discriminatory auctions contain an element of surprise, as incumbents face a difficult task when they trade off the probability of winning against the profit margin in case they win. There is, however, another argument in the opposite direction. In ascending auctions there exists a demand reducing equilibrium even when the entrant imposes negative external effects on the incumbents. In such an equilibrium, the newcomer enters independent of her private value for the licenses. Thus, ascending auctions may stimulate entry, although perhaps for the wrong reasons. In our experimental auctions the two opposing arguments appear to balance out.

Result 3. Both the relative frequency of entry and the number of licenses the entrant buys conditional on entry are independent of the auction format and the level of the negative externality.

Table 5 reports the frequencies of market entry together with the number of goods the entrant obtains conditional on entry. This table does not include the treatments where external effects are absent, because when $x = 0$ bidders have symmetric roles. Comparing the two auction formats, there is no difference in the relative frequency with which entry occurs. This holds both with a mild and a strong externality. Notice that in the ascending auctions, entry levels are between the level predicted by the preemptive equilibrium and that predicted by the demand reduction equilibrium (100%).²¹ In the discriminatory auctions the newcomer enters more often than predicted. In both types of auctions entry levels do not vary with the level of the external effect.²²

²⁰For the ascending auctions we find $p \leq 0.01$ for all three comparisons, for the discriminatory auctions all $p = 0.00$ (Mann-Whitney rank tests with $m = n = 8$).

²¹Again note that the predictions appearing in Table 5 are based on the actual private value draws. For the theoretical $U[0, 100]$ distribution entry probabilities in the preemptive equilibria of the ascending auction equal 57.3% and 45.4% for $x = 50$ and $x = 100$, respectively (cf. Subsection 3.2). In the discriminatory auction these numbers equal 61.0% and 55.3%.

²²For the ascending auctions we find $p = 0.83$ when comparing $x = 50$ with $x = 100$, for the discriminatory auction we get $p = 0.34$ (Mann-Whitney rank tests with $m = n = 8$).

Table 5: Entry in %

			Ascending		Discriminatory		Mann-Whitney
Entry	$x = 50$	Actual	83.6	<i>37.2</i>	81.3	<i>39.2</i>	$p = 0.52$
		Nash preempt	60.2	<i>49.2</i>	61.7	<i>48.8</i>	
		Nash dem red	100.0	<i>0.0</i>			
	$x = 100$	Actual	82.8	<i>37.9</i>	85.2	<i>35.7</i>	$p = 0.48$
Nash preempt		46.1	<i>50.0</i>	57.8	<i>49.6</i>		
Nash dem red		100.0	<i>0.0</i>				
# goods entrant (given entry)	$x = 50$	Actual	2.14	<i>0.71</i>	2.27	<i>0.86</i>	$p = 0.34$
		Nash preempt	3.0	<i>0.0</i>	3.0	0.0	
		Nash dem red	2.0	<i>0.0</i>			
	$x = 100$	Actual	2.05	<i>0.77</i>	2.34	<i>0.82</i>	$p = 0.14$
Nash preempt		3.0	<i>0.0</i>	3.0	0.0		
Nash dem red		2.0	<i>0.0</i>				

Notes: Standard deviations in italics. The Mann-Whitney rank tests compare the realized efficiencies for the ascending and discriminatory auctions using the 8 average observations per independent group as data.

Table 5 also shows that, conditional on entry, the entrant wins slightly fewer licenses in the ascending auctions than in the discriminatory auctions. This observation is in line with the frequent play of the demand reduction equilibrium in the ascending auctions. The differences in number of licenses bought fail to reach significant levels however. The number of licenses the entrant gets (conditional on entry) is also independent of the extent of the external effect.²³

Summing up the findings of this subsection, the aggregate results reveal that the discriminatory auction is preferred – or better, not outperformed – in terms of revenue, efficiency, and entry. A plausible explanation for this is that the demand reduction equilibrium has considerable drawing power in the ascending auction. The aggregate results for this auction typically fall in between the theoretical predictions of the demand reduction equilibrium and those of the preemptive equilibrium. In the discriminatory auctions the aggregate results are fairly well in line with the theoretical predictions. The main difference is that entry occurs more frequently than predicted (cf. Table 5). This in turn results in efficiency levels that are somewhat lower than predicted (cf. Table 4). A potential explanation for the surprisingly high frequencies of entry is that bidders do not submit the flat bidding schedules predicted by Nash. This allows for the possibility that the entrant obtains 1 or 2 licenses, possibilities that will not materialize in the Nash equilibrium. In the next section we will come back to this aspect of the bidding process.

4.2 Individual bidding and equilibrium selection

Recall from section 3.2 that in the discriminatory auction, all three bidders bid on all three licenses. In the absence of an externality, the optimal bid functions are the same for the entrant and the incumbents:

$$B(v) = \frac{v}{3} \left(\frac{300 - 2v}{200 - v} \right). \quad (9)$$

where $0 \leq v \leq 100$ denotes the per-license private value of the bidder.²⁴ Figure 5 displays the average observed bids in treatment disc0 together with the Nash prediction reflected in (9). The Nash bids trace the average of the second-highest bids remarkably well. The absolute distance between the average of a bidder's three submitted bids and the corresponding Nash prediction is less than or equal to 3, 5 and 10 in respectively 39.8%, 59.9%

²³For the ascending auctions we find $p = 0.56$ when comparing $x = 50$ with $x = 100$, for the discriminatory auction the p-value equals $p = 0.53$ (Mann-Whitney rank tests with $m = n = 8$).

²⁴Recall that in section 3 the units were scaled down by a factor of 1/100.

and 86.4% of the cases. So a large proportion of the average bids are close to the Nash predictions and there are no systematic deviations in upward or downward direction.

[Figure 5 about here]

One aspect of observed bidding behavior that is not compatible with the theoretical predictions is that subjects tend to submit different bids for identical units.²⁵ In fact, Figure 5 shows that the three bidding functions fan out for higher private values. A similar pattern of fanning out is present in the discriminatory treatments with external effects. In only 17.7% of the cases without external effects did the subjects submit exactly the same three bids. This number increases a little to 19.3% in the treatment with $x = 50$ and to 22.1% in the treatment with $x = 100$. A hedging motive may be responsible for bidders' tendency to submit different bids for identical licenses: with the high bid a bidder plays safe and makes it less likely that she ends up without any profit. With the low bid the bidder then tries to "hit the jackpot."

Figures 6 and 7 show the bidding patterns for the discriminatory auctions with $x = 50$ and $x = 100$, respectively. In each of these figures we separated the bids of the incumbents and the entrants. We plotted the averages of subjects three submitted bids and the Nash predictions. The most striking departure from the theoretical predictions is that low-value incumbents bid too low. Theory predicts that when $x = 50$ all incumbents with $v \leq 13$ should bid above their value. In case $x = 100$ this applies to all types satisfying $v \leq 26$. For example, when $v = 0$, Nash incumbents should bid $50/6$ when $x = 50$ and $100/6$ when $x = 100$. In contrast to these predictions, low-value incumbents are unwilling to bid above their values. Perhaps they wish to avoid the worst-possible scenario in which they buy some licenses at prices above their values while still having to bear the negative externality caused by entry. Such an explanation may be compatible with the opposite deviation observed for high private values. Here incumbents bid below value but higher than the Nash prediction. Quite possible they do this to enhance the likelihood that the entrant is kept out.

The bidding behavior of the entrant is relatively closer to Nash. This is reflected by the relative frequency of bids close to the Nash predictions. In the treatment with weak external effects, 48.0% (82.7%) of the entrants' average bids are at most 5 (10) points away from the Nash predictions, while

²⁵The same anomaly shows up in the discriminatory auction treatment of Engelmann and Grimm (2003).

only 35.3% (72.2%) of the incumbents' bids are within a range of 5 (10) points from the Nash bids. In the treatment with strong externalities, the pattern is the same but the deviations are more pronounced. Here, 27.0% (60.7%) of the entrants average bids differ at most 5 (10) points from the Nash predictions, while only 15.9% (32.7%) of the incumbents' bids are within a range of 5 (10) points of the Nash bids.

[Figures 6 and 7 about here]

Theoretically, the introduction of an external effect in the discriminatory auctions should enhance the bids of both incumbents and entrants across the whole range of private values. The effect should be more pronounced for incumbents than for entrants. However, we do not observe any effect when bidders draw private values below 50. Pooled across all cases where bidders receive values below 50, they bid on average 11.7, 13.4 and 13.0 in the respective treatments with $x = 0$, $x = 50$ and $x = 100$. Neither the incumbents' nor the entrants' bids vary with the external effect for low private values. In contrast, when bidders draw private values above 50, their bids incorporate the external effect. Compared with the average bid of 29.3 observed in the absence of external effects, incumbents' bids increase to 36.7 while entrants' bids remain at 30.8 when $x = 50$. When the external effect is further enhanced to $x = 100$, incumbents' bids increase a little further to 38.7, while now the entrants' bids jump to 39.6. Thus the results suggest that the incumbents neglect the entrant when they have low private values, possibly because they think that they cannot prevent entry of the newcomer anyway. When they have high private values they are confident that their bids can make a difference and they bid more competitively than they do without external effects.

We summarize our main findings on bidding behavior in the discriminatory auctions in the following result:

Result 4. Individual bidding behavior in the discriminatory auctions deviates from equilibrium predictions in two important ways: (i) subjects tend to submit different bids for identical units and (ii) in the presence of negative externalities low-value incumbents bid too low.

Result 4 provides an explanation for our earlier observation that in the discriminatory auctions, entry occurs more often than predicted. First, because incumbents and entrants do not submit flat bidding schedules, actual bidding

allows for the possibility that the entrant obtains 1 or 2 licenses. This happens in 56.3% (52.3%) of the cases when $x = 50$ ($x = 100$). That an entrant ends up with only 1 or 2 licenses cannot happen in the Nash equilibrium where bidders are predicted to submit the same bid for all three licenses. Second, incumbents with low private values bid too low, also contributing to the higher frequencies of entry.

We next turn to the ascending auctions. These auctions present bidders with a coordination problem: do they split the market at low prices, thereby winning a moderate number of goods at high profit margins, or do they decide to bid competitively in an attempt to work out one of their opponents? If each of the three subjects in a group starts bidding on two goods only, then the clock does not even start rising and each of the bidders buys two goods at a price of zero. In the experiments, bidders often reduce their demand in exactly this way. We also observe many cases that are very close to this ‘ideal version’ of demand reduction. For instance, there are cases where two of the three bidders start bidding on two goods while the third starts bidding on three goods. The clock starts rising and at a very low price the third bidder stops the clock by reducing her demand from three to two goods. Table 6 lists the perfect cases of strategic demand reduction in the row labeled DR1, together with the close-to-perfect cases in the rows DR2 and DR3.

The second panel of Table 6 labeled ‘Preemption’ depicts how often subjects bid competitively in a serious attempt to get rid of a competitor. For the auctions without external effects, competitive bidding means that the realized price will at least be as high as the minimum private value in the group minus one. The three rows PR1, PR2 and PR3 list these cases; these rows differ in the actual price that results. In the treatments with external effects, preemptive bidding requires that each incumbent starts bidding on three goods, otherwise the external effect cannot be prevented. An ideal example of preemptive bidding occurs if the two incumbents successfully work out the entrant and thereby prevent the negative effect. These cases are listed in the rows PR4 and PR5. However, even in the preemptive equilibrium entrants will sometimes enter the market if they have a sufficiently better private value than each of the incumbents. So the class of preemption contains a subclass where the newcomer enters the market, despite the fact that each incumbent remained in the auction for three goods until the clock reached at least her private value (see row PR6). Among these cases we have also included the ‘close-to-perfect’ cases where the entrant made an unsuccessful attempt to seduce the incumbents to collude by reducing her demand at a low price.

The percentages in Table 6 reveal that both demand reduction and preemptive bidding are observed in all regimes. Without external effects demand

Table 6: Equilibrium selection in ascending auctions in %

		asc0	asc50	asc100
Demand Reduction	DR1	24.2	8.2	9.8
	DR2	30.6	6.6	14.8
	DR3	5.6	10.7	5.7
	Total	60.4	25.5	30.3
Preemption	PR1	0.8		
	PR2	3.2		
	PR3	3.2		
	PR4		0.8	1.6
	PR5		11.5	13.1
	PR6		2.5	5.7
Total	7.2	14.8	20.4	
Cheap Preemptive Attempt	PA1	8.1		
	PA2		22.1	18.9
	Total	8.1	22.1	18.9
Miscellaneous	Total	24.2	37.7	30.3

Notes: The categories are defined as follows. DR1: ‘Clock does not start rising because sum of initial demands ≤ 6 ’; DR2: ‘Sum of initial demands > 6 , but the clock is already stopped at a price of 0’; DR3: ‘ $0 < \text{realized price} \leq 3$ and minimum value of all bidders > 4 ’; PR1: ‘asc0, price=minimum value all bidders - 1’; PR2: ‘asc0, price=minimum value all bidders’; PR3: ‘asc0, price $>$ minimum value all bidders’; PR4: ‘asc50 or asc100, each incumbent wins 3 goods, realized price $>$ minimum private value incumbents’; PR5: ‘asc50 or asc100, each incumbent wins 3 goods, realized price \leq minimum private value incumbents’; PR6: ‘asc50 or asc100, each incumbent bids on 3 units until at least her private value, nevertheless entrant wins 1 or more goods’; PA1: ‘ascending $x=0$, each bidders starts bidding on 3 goods, each bidder wins at least 1 good, $0.2 \cdot \text{minimum value all bidders} \leq \text{realized price} \leq 0.8 \cdot \text{minimum value all bidders}$ ’; PA2: ‘ascending $x > 0$, each incumbent starts bidding on 3 goods, entrant wins at least 1 good, $0.2 \cdot \text{minimum value incumbents} \leq \text{realized price} \leq 0.8 \cdot \text{minimum value incumbents}$ ’.

reduction is by far the most frequently observed outcome. With external effects the relative frequency of demand reduction drops dramatically, but still remains the most observed outcome. Preemptive bidding becomes more likely when the negative external effect inflicted by the entrant increases, but even when $x = 100$ only 20.4% of the outcomes are characterized as preemptive bidding (while 30.3% of the outcomes correspond to demand reduction).

The weak appeal of the preemptive bidding equilibrium might be related to the fact that this equilibrium potentially results in the worst-case scenario for an incumbent. This happens when she bids above her value on all three licenses while the other incumbent reduces demand from three to zero licenses. In that case she has to bear the negative external effect caused by the entrant and at pay higher prices for the licenses than they are worth. Loss averse incumbents may only want to embark on the risky enterprise of preemptive bidding if they feel sufficiently confident that they will succeed in beating the entrant. If this reasoning is sound, then one would expect that incumbents only opt for the preemptive equilibrium when they have a high private value. Figure 8 shows that this indeed appears to be a driving force behind equilibrium selection. The figure considers only the outcomes that received the labels 'preemption' or 'demand reduction' in Table 6. For both regimes $x = 50$ and $x = 100$ the figure shows the percentage of preemptive outcomes as function of the minimum private value of the two incumbents. In both cases the demand reduction equilibrium prevails when the minimum private value is low while the preemptive equilibrium is dominant when this value is high. When the external effect is weak, incumbents embark on the preemptive equilibrium if both of them have a private value of at least 60.²⁶ In case $x = 100$ incumbents already opt for the preemptive equilibrium if both of them have private values higher than 40.

[Figure 8 about here]

There is an interesting pattern in the bidding of many of the experimental auction outcomes that do not belong to the class of demand reduction or the class of preemption. With negative external effects, the incumbents often start bidding on three goods each, like they are supposed to do in a preemptive bidding equilibrium. When it turns out that it is not possible to work out the entrant at low prices, one of the incumbents reduces her demand well before the clock has reached her private value. Usually the

²⁶Notice that rather counterintuitively the curve for $x=50$ bends downward for very high minimum private values. This part of the figure is based on few datapoints only, however.

other incumbent follows suit and the clock stops below the level that would have been reached in a preemptive equilibrium. As a result, the entrant is able to enter the market at a price below the minimum private value of the incumbents. We include these 'cheap preemptive attempts' at the bottom of Table 6 in the row labeled CPA2.²⁷

A remarkable result is that we observe an approximately equal number of 'cheap preemptive attempts' and true preemptive cases. When faced with a stubborn entrant, many incumbents chicken out and settle for an outcome that still gives them a positive profit margin on the goods purchased. Notice that these outcomes have a self-enforcing character. If one incumbent reduces her demand there is no way that the other incumbent can avoid the negative external effect of the entrant. Consequently, it may be in the interest of the other incumbent to reduce demand as well and split the market at an interior price level.²⁸ Our overall findings on equilibrium selection are summarized in Result 5.

Result 5. (i) In the ascending auction strategic demand reduction is observed more often than preemptive bidding, although the presence of negative externalities makes demand reduction less focal. (ii) Around 20% of the observed outcomes can be classified as 'cheap preemptive attempts'; incumbents first try to get rid of the entrant at low prices, but then turn to demand reduction when this appears unsuccessful.

5 Conclusion

In situations where there are multiple licenses up for sale and both incumbent firms and potential entrants are among the interested bidders, the ascending auction allows for multiple equilibria. In one compelling equilibrium all bidders collude and strategically reduce their demand. By doing so each bidder pays a very low price for the license(s) she obtains. A potential drawback for the incumbent firms is that in this type of equilibrium also entrants obtain

²⁷The row labeled CPA1 contains the corresponding cases for situation without external effects. Because in that regime the three bidders are symmetric, the cheap preemptive attempt may be directed at either one of them.

²⁸The self-enforcing character of interior price levels also applies in the situation without external effects ($x = 0$). Then the following strategies (i.e. for each bidder i) constitute an equilibrium for any $c \in [0, 100]$: if $v_i < c$, then start bidding on three units and drop out at v_i for three units, while if $v_i \geq c$ then drop out at c for 1 unit. If all bidders have a valuation that exceeds c , an interior price of c results in this equilibrium. The two polar cases of $c = 0$ and $c = 100$ correspond to the demand reduction equilibrium and preemptive equilibrium respectively.

a license. This imposes an identity-dependent negative externality on the incumbents when the entrant starts competing in the (post auction) market through low prices. Therefore, another compelling equilibrium outcome of the ascending auction is the one where incumbents engage in preemptive bidding in order to keep the entrant out of the market. The attractiveness of using the ascending auction crucially depends on which of these two equilibria is most compelling; both revenue and efficiency are much higher in the preemptive equilibrium than in the demand reduction equilibrium. Entry by newcomers is rather limited under preemption though.

A practical and much used alternative to the ascending auction is the discriminatory ‘pay-your-bid’ auction. This format has the advantage that it does not support demand reduction as an equilibrium phenomenon and hence collusion among all bidders is (in theory) excluded. At the same time, however, preemptive bidding becomes much more involved because incumbent bidders cannot track the bidding behavior of their fellow incumbents while the auction progresses. Theoretically, the discriminatory auction is therefore less prone to predatory bidding than the preemptive equilibrium of the ascending auction; the probability that a newcomer enters the market is higher in the former. A comparison of the performance of the two auction formats depends to a large extent on which type of equilibrium is selected in the ascending auction. By means of a controlled laboratory experiment we shine light on this issue.

In the experiments the ascending auction generates less revenue and a less efficient allocation than the discriminatory auction does. This results from the fact that in the ascending auction demand reduction is wide-spread. For every level of the external effect considered, the demand reduction outcome is observed more often than the preemptive bidding outcome. Both auction formats appear to induce the same high frequencies of entry. In the ascending auction this is due to the frequent occurrence of demand reduction. In the discriminatory auction entry is higher than predicted because bidders do not submit the same bid for identical units as they are supposed to do in the Nash equilibrium.

The bidding data of the ascending auction reveal an intuitive empirical equilibrium selection device. Incumbents let their decision to pursue the demand reduction equilibrium instead of the preemptive equilibrium depend on their private value. With low private values they figure they have no chance to work the entrant out and they settle for demand reduction. With high private values they give preemption a try, conditional on the cooperation of the other incumbent. Interestingly, the threshold above which subjects opt for preemption decreases with the negative external effect, that is, with a stronger negative external effect subjects sooner pursue the preemptive

path.

Another interesting (and unanticipated) outcome of the ascending actions that is observed quite often corresponds to what we have labeled ‘cheap preemptive attempts’. Incumbents first try to keep the entrant out of the market at low prices. When this appears unsuccessful, one of the incumbents chickens out and tries to settle for a demand reduction like outcome. Given that a coordinated preemptive attempt has failed, the other incumbent follows suit. When the level of the external effect is mild (rather than strong), cheap preemptive attempts are even more frequent than true preemptive outcomes. The introduction of preemptive motives thus initially frustrates bidders’ attempts to keep prices low. But when it becomes clear to incumbents that preemption has a rather high price, they quickly try to split the market again.

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Appendix A

Besides the on-screen instructions subjects also received a summary of these instructions on paper. Below a direct translation of this summary sheet is given for both the asc50 and disc50 treatments.

Summary of the instructions Today's experiment consists of two parts. At the beginning of part 1 you are assigned to a group of 3 participants. During the 15 rounds of part 1 the group composition remains unchanged. The three participants within a group are labeled type A, type B and type X. At the start of the experiment you will learn your type. You will keep the same type during the complete first part.

Products. Within each group there are in each round 6 identical products up for sale. For each group member the value of each product lies in between 0 and 100 points, and every integer number between 0 and 100 is equally likely. The value a particular group member has is independent of the values of the other group members. At the start of a round you will only learn your own value for each product. Your value of a product in one round does not depend on your value of a product in any other round.

Bidding and prices. After you have learnt your value, you indicate on how many products you would like to start bidding. You can start bidding on 0, 1, 2, or 3 products. We label this amount your "demanded quantity". If the sum of demanded quantities within a group is smaller than or equal to 6, then each group member is assigned his/her demanded quantity and pays a price of 0 points per product. The products that are possibly left over remain unsold.

In case the sum the demanded quantities exceeds 6, a "thermometer" starts rising from 0 points onwards. The thermometer indicates the price. At every price each group member has the opportunity to adapt the demanded quantity downwards. As soon as the sum of demanded quantities equals 6, the thermometer stops. The position of the thermometer determines the price that is paid for each product. All group members are assigned the number of products they demand at the time the thermometer comes to a stop.

From the moment the thermometer starts rising, you can decrease your demand quantity only such that the sum of the demand quantities remains larger than or equal to 6. In case a participant lowers his/her demanded quantity during a round, the other group members are informed immediately about this.

[In disc50: *Bidding and prices*. After you have learnt your value, you indicate for each of the products how much you would like to bid for it. You can make a bid on three products at most. A bid has to be in between 0 and 125 points. For each product you indicate how much you are willing to pay for it. You can decide yourself whether you make the same or different bids. You can also decide not to make a bid on one or more products.

After every group member has made his/her bids, the six products are assigned to the six highest bids. In case there are less than 6 bids in total, the products are assigned to all the bids that are made. The remaining products remain unsold. In case a product is assigned to you, your bid determines the price you pay for this product.]

Earnings. Your returns are equal the number of products that you buy multiplied by the difference between the value assigned to each of your products and the price you pay for each product:

$$\text{Your returns} = \text{number of products} * (\text{your value} - \text{the price})$$

[In disc50: *Earnings*. For each product that you bought your returns are equal the difference between the value of the product and the price you pay for this product. Your overall returns equal the sum of the returns per product purchased. For example, if you buy 3 products, then your returns are equal to:

$$\begin{aligned} \text{Your returns} = & (\text{your value} - \text{the price of } 1^{\text{st}} \text{ product you bought}) + \\ & (\text{your value} - \text{the price of } 2^{\text{nd}} \text{ product you bought}) + \\ & (\text{your value} - \text{the price of } 3^{\text{rd}} \text{ product you bought}) \quad] \end{aligned}$$

If you are a participant with type X, then your earnings within a round equal your returns. In case you have either type A or type B, your earnings also depend on whether type X bought any products or not. If type X has bought one or more products, then the returns of both type A and type B are in that round reduced with 50 points. Only when type X buys no products at all there is no reduction on the returns of types A and B in that round.

At the beginning of part 1 you receive a starting capital of 750 points. Your total number of points at the end of part 1 will be equal to the sum of this starting capital and your earnings in all 15 rounds. At the end of the experiment your points are exchanged into euros. Here it holds that 80 points correspond with 1 euro in money. Part 1 starts with a practice round. Your profits or losses during this practice round are not counted.

Figure 1: Incumbents' bidding behavior in the ascending auction

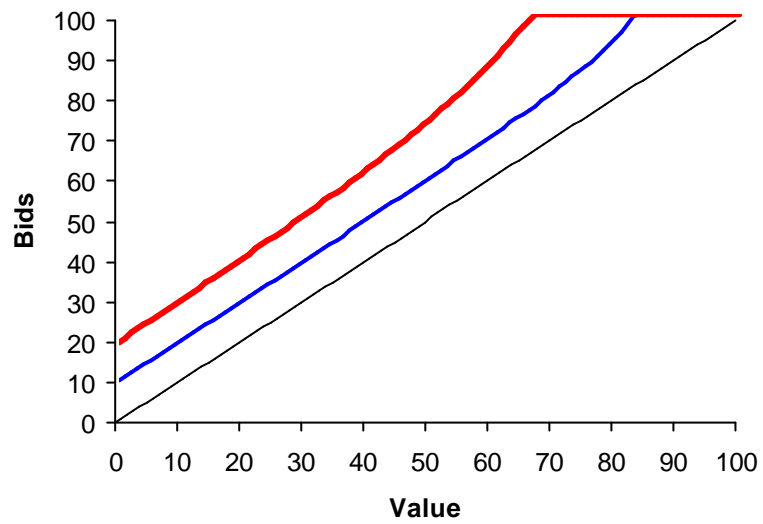
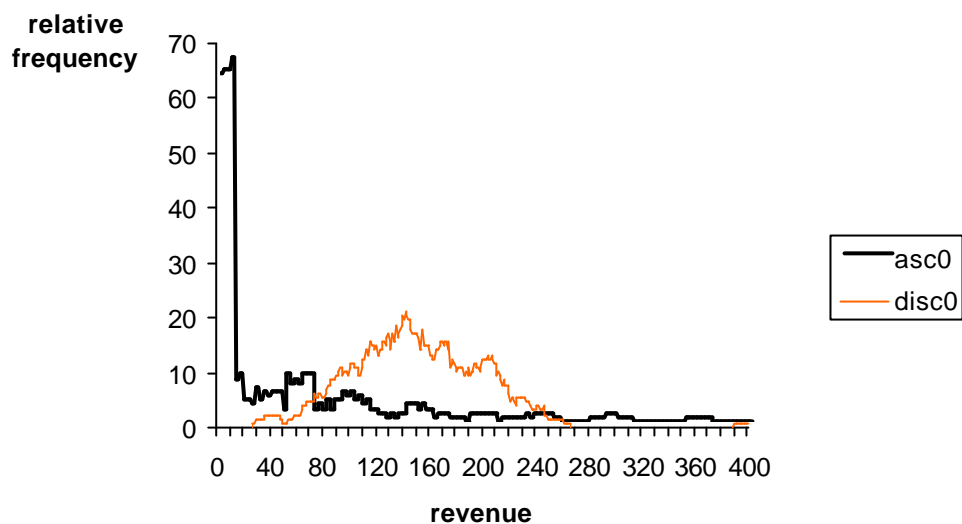
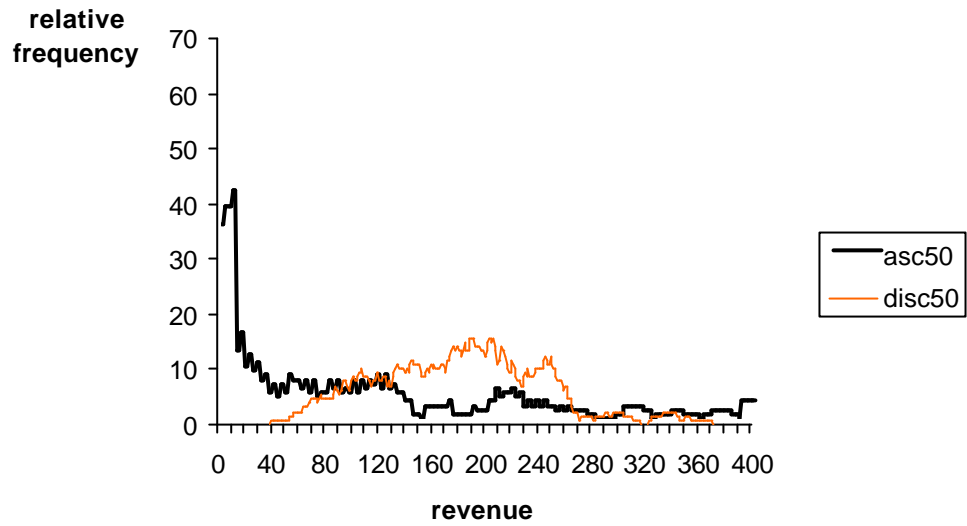


Figure 2: Revenue histograms when $x = 0$



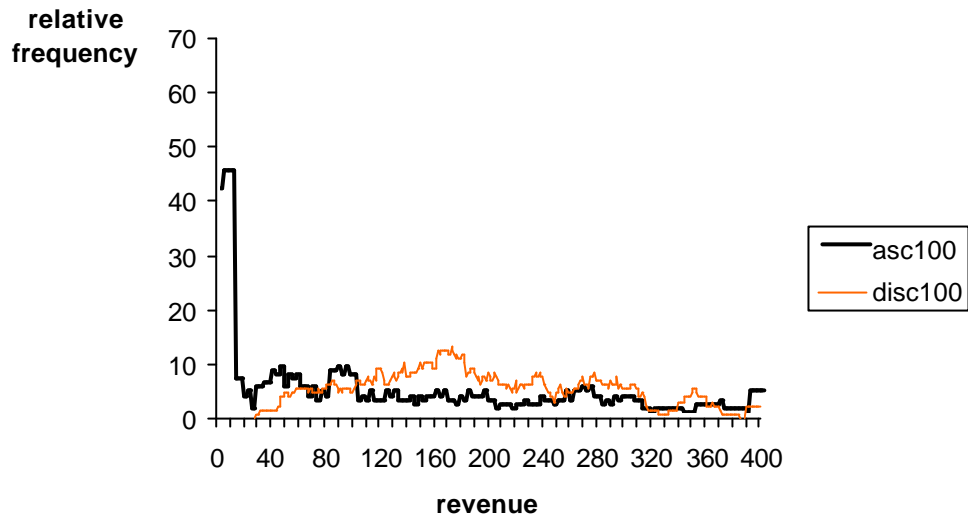
Notes: For every revenue level the % of outcomes that fall in the interval $[\text{revenue}-10, \text{revenue}+10]$ is displayed.

Figure 3: Revenue histograms when $x = 50$



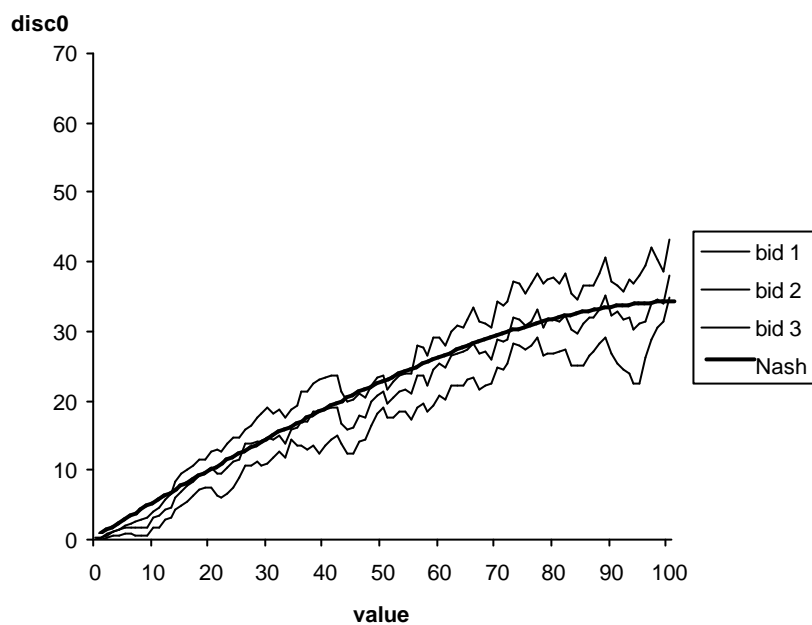
Notes: For every revenue level the % of outcomes that fall in the interval $[\text{revenue}-10, \text{revenue}+10]$ is displayed.

Figure 4: Revenue histograms when $x = 100$



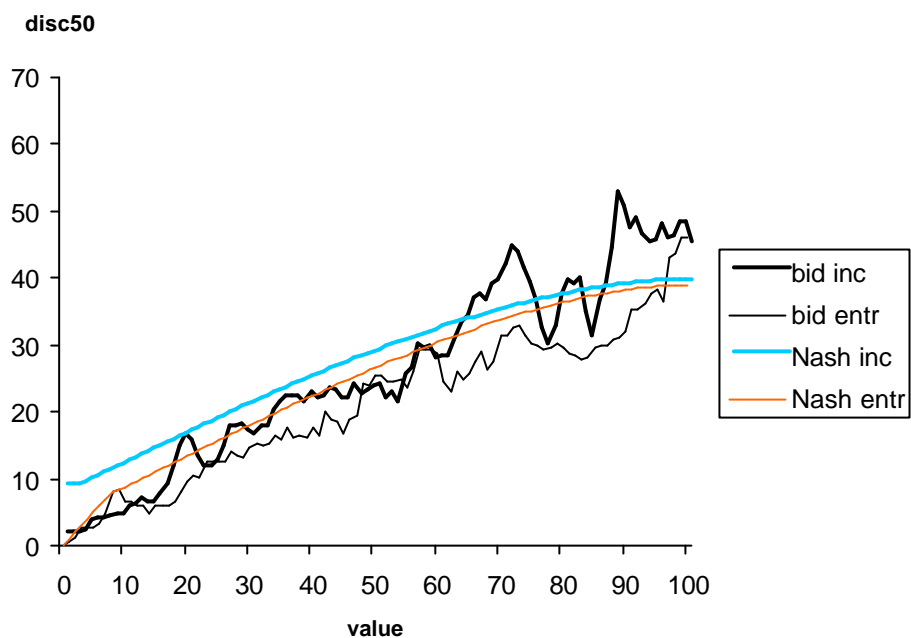
Notes: For every revenue level the % of outcomes that fall in the interval $[\text{revenue}-10, \text{revenue}+10]$ is displayed.

Figure 5: Bidding behavior in the discriminatory auction with $x = 0$



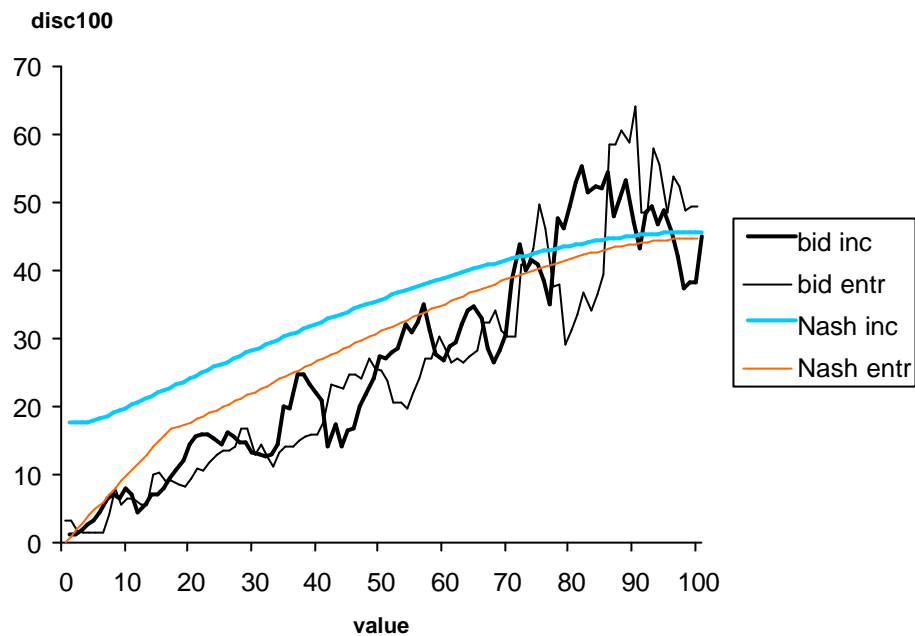
Notes: Bid 1 graphs the average highest bids submitted as function of the values. Likewise, bid 2 and bid 3 show the middle highest bids and the lowest bids respectively. For every value the average of bids in the interval $[\text{value}-2, \text{value}+2]$ is reported.

Figure 6: Bidding behavior in the discriminatory auction with $x = 50$



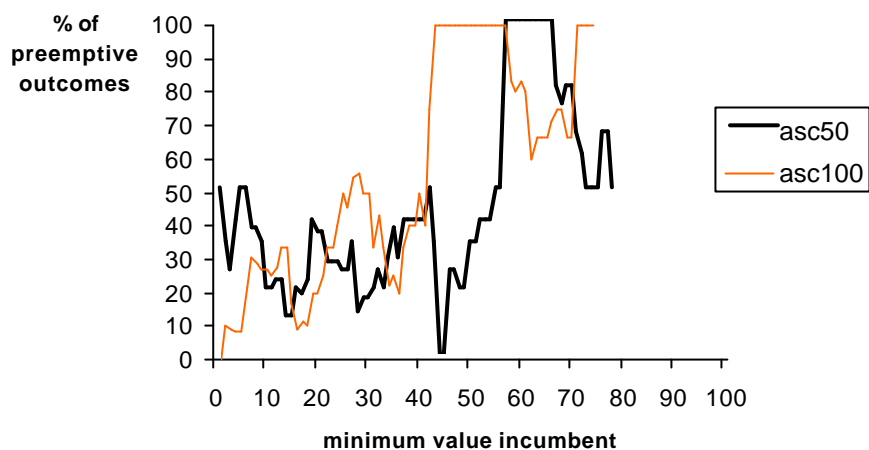
Notes: Bid inc (bid entr) graphs the average of the three bids submitted by incumbents (entrants) as function of value. For every value the average of bids in the interval $[\text{value}-2, \text{value}+2]$ is reported. Nash inc (Nash entr) shows the Nash bids of incumbents (entrants) of value.

Figure 7: Bidding behavior in the discriminatory auction with $x = 100$



Notes: Bid inc (bid entr) graphs the average of the three bids submitted by incumbents (entrants) as function of value. For every value the average of bids in the interval $[\text{value}-2, \text{value}+2]$ is reported. Nash inc (Nash entr) shows the Nash bids of incumbents (entrants) of value.

Figure 8: Preemptive bidding versus demand reduction



Notes: For every minimum value of the incumbents the % of preemptive outcomes in the interval [minimum value incumbents-4, minimum value incumbents+4] is reported. The relative frequency of demand reduction outcomes equals 100% - the % of preemptive outcomes.