Theory, Experiment and the FCC Spectrum Auctions

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The US Congress has mandated an independent evaluation of the Simultaneous Multiple Round (SMR) auction mechanism used by the FCC to award spectrum licenses to bidders. This evaluation was required to include an experimental study of alternatives to the SMR procedures that might better facilitate the acquisition of efficient combinations of the elementary licenses where complimentarity is important, or in any case to increase understanding of the problems and the complexities of the SMR mechanism. This background report is the first that we expect to issue that provides such an evaluation; as the first such report, it provides a brief review of several issues and experimental findings that bear most directly on the conceptual and behavioral foundation of the FCC design problem.

I. Economics of English (Progressive) Auctions.

We begin with a general review of the theory of English[1] progressive auctions, under alternative assumptions about auction values: (A) individual valuations of the auctioned item are private and independent, or (B) the valuation is common across all individuals.

A. Independent private values

In this environment there are both advantages and disadvantages to the progressive procedure in comparison with sealed-bid (first or second price) or Dutch auctions.

The principal advantages of the progressive auction are the transparency of the optimal bidding strategy and, as corollaries, the procedure requires minimal bidder sophistication for choosing a noncollusive strategy, and none have an incentive to invest in acquiring information as to other bidders' values or strategies. A bidder who has estimated her maximum willingness-to-pay value for the item merely follows two simple (dominant strategy) rules: (i) after the first bid has been announced, and at all times until the auction ends, if the standing bid is below that value, the bid should be raised by the minimum bid increment such that the new bid is not greater than the bidder's value; (ii) never raise your own bid. This transparency and strategic simplicity accounts for the fact that the vast majority of auctions are of the English form both on and off the internet (Cassady, 1967; Lucking-Reiley, 1999). The implications of (i) and (ii) guarantee theoretically that the bidding will stop on each item auctioned when the bidder with the highest private value bids b^*, $v_2 \le b^* \le v_2 + \Delta$, where $v_2\,(< v_1 - \Delta)$ is the second highest value (v_1 the highest) among all the bidders, and $\Delta \ge 0$ is the minimum bid increment. No one will rationally invest in learning about the values or bidding strategies of other bidders because these will be revealed costlessly by the open bidding procedure. We note that the two-part strategy (i) and (ii) is not quite the same as stating that a bidder's dominant strategy is to bid actively until the price reaches the value of the object to him. The latter is correct for all but the highest value bidder, who, following rule (ii), discovers that he need bid only high enough to stop out the second highest valuation bidder, and rationally, will no longer remain active. Where bidders do not announce bids from the floor as in the English clock auction, which historically seems never to have been successfully adopted in the field (Cassady, 1967, p. 196), all remain active until one of the two last bidders drops out; then the clock stops and the price is set by the Clock reading. Experimentalists have regularly used this procedure for over a decade, as discussed below, when they want to implement an elicitation procedure for getting people to reveal true willingness-to-pay.

There are, however, prominent disadvantages of the progressive auction: (i) if bidders are risk averse then revenue will be higher in the first price sealed bid auction; (ii) the procedure has high transactions cost in the sense that bidders must be present at the auction, tending to it in real time[2], and (iii) it greatly facilitates collusive arrangements, or "rings" among the bidders, a fact that accounts for much of the colorful history of auctions. (See Cassady, 1967, pp. 177-192 on rings, and pp. 212-218 for other forms of collusion routine in the history of English auctions.)

The great transparency of the English auction, knowing who is bidding, and how much, enables the formation of collusive arrangements in real time, reducing uncertainty about who to communicate with in advance of the auction, as in sealed-bid auctions. With prior collusive agreements the English auction provides free real-time monitoring services enabling ring members to identify those who are not living up to their collusive agreements. Also, ring members can determine who among their competitors outside the ring should be included in their ring at subsequent auctions. The English auction enables collusion in the complete absence of prior agreements or communication at auction time: associates who know each other find it natural not to raise each other's bid. Parallel considerations apply to sealed-bid auctions where the seller announces all bids after the auction. Thus bidding rings can readily determine who is or is not complying with the agreement, and who are the outsiders that have won so that they can be included in subsequent rings. Outer continental shelf petroleum lease bids are publicized by the Government, thereby providing such costless services to any rings. (Cox, Isaac and Smith, 1983).

All of the above considerations apply to offers of multiple units in English auctions under either of the two simultaneous auction procedures suggested by Vickrey (1961, 1976). The case in which multiple units are offered, however, has led quite prominently to the phenomenon of "jump bidding," originally observed in laboratory experiments by McCabe, Rassenti and Smith (1988) leading them to study English Clock auctions for multiple unit auctions (one unit per bidder), as a means of controlling for jump bidding. The above problems are solved by removing the right of bidders to choose bids.

B. Common Value Auctions

In a path-breaking theoretical contribution Milgrom and Weber (1982) introduced the concept of the common value auction, as distinct from the independent private values auction. The paradigm here is the "mineral rights" problem: bidders for rights to explore for oil, gas and minerals on land or off-shore tracts, each estimate (e.g. by seismic readings in the oil and gas industry) the quantity of the recoverable mineral, if any, and base their bids on these estimates. Thus, Milgrom and Weber (1982, p. 1093) assume that "To a first approximation, the values of these mineral rights to the various bidders can be regarded as equal, but bidders may have differing estimates of the common value." If the value of an auctioned item to *i* is of the form

(1) $$\tilde{V}_i = \alpha \, \tilde{P}_i + (1-\alpha)\,\tilde{v}\,,$$

where $\tilde{P}_i$ is the item's uncertain, strictly private, value to *i*, and $\tilde{v}$ is the item's uncertain common value to all bidders, and $\tilde{v} = \tilde{v}(s_1, \ldots, s_N)$ is assumed to depend upon information (signals), s_i, available to each *i*. As indicated above, Milgrom and Weber (1982) assume as a first approximation, that α, a characteristic of the commodity, is approximately zero. Although this is a useful abstract exercise in developing the theory of auctions, and providing a more penetrating understanding of possible issues in auction design, we are lacking in objective, testable criteria for determining α. What we lack are systematic procedures for identifying α from the observed characteristics of an industry. That $\alpha \neq 0$ in applications to mineral extraction industries is indicated by the observation that oil and mineral companies buy and sell proven reserves. Thus an oil company whose marketing proficiency outstrips its supply capability may value a petroleum reserve more highly than the selling company. Indeed, it is unclear, empirically, that a is not closer to unity, rather than nearer to zero in the petroleum sector.

We not only have no theoretical guidelines from environments of the form (1), 0 < < 1, what results we do have are decisively negative: an equilibrium does not exist in auctions defined by this mixed environment. The difficulties are foundational. "With multidimensional types (as represented by $\tilde{P}_i$ and $\tilde{v}$ in (1), inference from prices may be non-monotone and complicated. It may not be possible to order the bids of agents with multidimensional information and incentives in a way that is consistent with what they can infer from prices and their resulting incentives." (Jackson, 1999, p. 8). An important implication of this is that it cannot be claimed that (although we have no equilibrium theory for the FCC auctions) game theoretic "intuition" developed from (complete information) examples, allows valuable guidelines to be articulated about auction design (McAfee and McMillan, 1996, pp. 172-3); another is that confidence in the postulated advantages of the English format is undermined.

The principle theoretical result that follows from the hypothesis that individual valuations are common can be stated as follows: prices are higher in the English auction than in the first and second price sealed bid auction (or Dutch auction, which is strategically equivalent to the first price). Prices are higher because each bidder's private information on the common value is valuable information to other bidders, and revealed in the open bidding process. This pooling of private information favors a higher revenue outcome, and is the essential feature that drives the judgement that English auction procedures dominate the alternatives. That judgement, however, is based on the assumption that a is near zero, and formal theory alone cannot say why this should be so.

We note several possible or potential contraindications that provide a basis for some amount of doubt concerning the apparent superiority of the English auction conditional on values being common.

1. If information not already publicly known is costly to acquire, and all bidders are both rational and sophisticated, then bidders are not well-motivated to invest in acquiring information if they will subsequently feel compelled to reveal it. It appears that all but the high bidder, given that the investment is a sunk cost, will reveal the value implications of their information. If so, then the decision problem devolves to assessing the probability of being the high bidder, then computing how much investment in information is justified by weighing cost against that expected benefit. Sophisticated bidders, using consulting firms and economic theorists, and applying the principle of backward induction, will anticipate this future state of the world and refrain from investing in the acquisition of information <u>that is not private</u> to their own special circumstances. We lack a theorem that addresses these needed extensions of the theory.

To the extent that the many sophisticated bidders in the FCC auctions expended resources for acquiring information on technology and demand information, we are led to deduce that this was a consequence of the judgement that the information enhanced the <u>private</u> value of the licenses to the individual bidder.

2. This line of reasoning suggests that the common value information that will be revealed in the bids will be that which is dispersed <u>initially</u> among the bidders as a consequence of technological, institutional and legal activities that had been undertaken for other business purposes, and are then discovered to be complimentary to the commodity or right that is proposed for auction. But investment in such activities is justified independently and prior to the sale of the commodity.

3. Ironically, it follows that buyer rings or consortia are not prima facie to be ruled out in common value auctions with costly information. Such consortia if they pool the information of their members, provide an incentive to invest in information acquisition by reducing the free-rider problem. This is especially the case if there are subsets of the bidders whose commonality is distinct from that of others. To the extent that such partitioning of $\tilde{v}$ among bidder subsets is a technological or marketing reality then allocations can be improved by allowing several consortia to each internalize these effects and then bid competitively against each other. Each consortium has a common private value distinct from the others, and optimality is restored by competition among the consortia who have alternative private uses for the resource.

4. Given the hypothesis that commodity 'X' has common value components, one can evaluate alternative auction procedures, deriving theorems, as in Milgrom and Weber (1982), showing the implication of common valuedness for auction performance. What the theory does not tell you is the answer to the following: given commodity 'X' and a description of its operating and technological characteristics, what is the value of a, $0 \leq a \leq 1$, in equation (1)? In particular, is a small enough to justify the choice of English over other auction forms especially given the implications above for investment in information acquisition? Clearly there must be a trade-off here. The fact that the English auction provides the greatest scope for collusion among sophisticated bidders, yielding lower prices and efficiency, and requires high transactions (monitoring/participation) costs, must be weighed against the effect of the postulated size of a. Is a low enough for the revenue advantages of the English auction, under common valuedness, to outweigh its disadvantages?

5. Finally, we note that in auction theory where the value of the auctioned item to oneself or others is uncertain, this uncertainty is resolved at the end of the auction. This is the basis on

which experimental studies have tested hypotheses derived from common value auction theory; i.e., we can create these artificial conditions in the lab. But suppose, after the sale of commodity 'X' at auction, the main uncertainty that is resolved is who won and who lost the rights awarded, with the winners still facing most of the uncertainty as to the value (common or private) of such rights. How should this reality affect the choice of auction format? Clearly, if most of the uncertainty will be resolved subsequently, based on "signals" subsequently purchased, this ex post auction information cannot be revealed for pooling purposes during the auction and the case for English procedures is compromised.

What can be said about the spectrum licenses as a commodity "X"? Here is the argument/evidence used to conclude that a is sufficiently small for common valuedness to be the primary consideration in the choice of auction form (CRA, 1997, p. 15):

> When there is uncertainty about technology and demand, as there certainly is for the new services involved in the spectrum auctions, *common value uncertainty* becomes an important factor. A bidder interested only in a license to serve Chicago may still learn something of value from observing others' bids for licenses to serve New York and Los Angeles. Those license prices reflect the estimates of other bidders about the profitability of those licenses, and those estimates depend on many of the same variables – penetration rates, equipment availability, demand growth rates, and so on – that determine its valuation of the Chicago license. When common value elements are important, the absence of communication about prices during a single-round Vickrey auction makes it more likely that mis-estimation by bidders will impair the efficiency of the license assignment, compared to the simultaneous ascending auction.

Again (CRA, 1997, p. 14):

> *Purely private values* refers to a situation in no which (sic, which no) bidder would ever be led to revise its own estimate of the value of a license or a package if it learned some of what its competitors know about the market covered by the license, markets covered by other licenses, equipment availability, new technologies, and so on.

These are not compelling evidential arguments, as can be seen by stating the obverse of the latter: *Purely common values* refers to a situation in which every bidder would always be led to revise their own estimate of the value of a license or a package if they learned some of what their competitors know about the market covered by the license, markets covered by other licenses, equipment availability, new technologies, and so on. So stated, you would not find such an extreme position attractive.

Finally, we note that in a common value auction environment efficiency is irrelevant – any allocation to any firm is efficient – the issue is exclusively one of maximizing revenue by incentivizing the public revelation of all information. There is thus a direct contradiction between the stated primary function of the FCC spectrum auctions – efficiency – and the interpretation argued above that common valuedness is the predominating characteristic of the commodity. Hence, when common value elements are important, as in the above quotation, alternatives to the English procedure are more likely to impair revenue, not efficiency.

These interpretations, however, are fragile, not only for the reasons indicated in 1-5 above, but also in terms of the theoretical predictions, given a small variation on the postulated environment. Klemperer (1998).

II. Review of Relevant Experimental Results

This section provides a short summary of those well established experimental findings that are directly relevant to the spectrum auctions. These findings cover: (A) behavior in standard single object auctions; (B) behavior in common value auctions; (C) jump bidding, impatience, inefficiency and manipulation attempts in claimed "incentive compatible" multiple unit English auctions; (D) information (Private vs. Complete) and Nash/Competitive outcomes; (E) effect of stakes and bidder sophistication on behavior; (F) sophisticated play by "unsophisticated" subjects: an example; (G) combinatorial auctions.

A. Standard Single Object Auction

Behavior in experimental private value English, Dutch, first and second price sealed bid auctions was originally reported in Coppinger, Smith and Titus (1980; reprinted in Smith, 1991; also see Kagel and Roth, 1995, Chapter 7 for a comprehensive survey). English auction prices, and efficiencies were found to vary insignificantly from the predictions of theory; i.e., most awards were to the highest value bidder at prices reasonably near to the second highest value. A very few awards, somewhat above the second highest value, could be attributable to minor "jump bidding" in the sense that bidders, free to select the amount by which they raised the standing bid, sometimes chose an increment larger than necessary. (Jump bidding is much more serious in multiple unit English auctions as discussed below). A few awards were at prices well below the second highest valuation (Coppinger, Smith and Titus, 1980, Chart 2). (These are believed due to subjects who knew each other and refrained from raising each other's bid, which was verified in one case). First price sealed-bid auction prices were significantly higher than those for the second price sealed bid auction.

A more extensive comparison of 780 Dutch, first and second price sealed bid auctions in an environment in which values are rectangularly distributed is reported by Cox, Roberson and Smith (1982; reprinted in Smith, 1991). Again, first price auctions yield higher prices than second. Also Dutch prices are found to be significantly lower than those in first price auctions. Efficiency was highest in second price auctions (94% of the awards were Pareto optimal), lower in first price auctions (88%) and lowest in Dutch auctions (80%). Possible behavioral reasons for the failure of Dutch and first price auctions to be isomorphic are modelled, and an explanation given, in Cox, Smith and Walker (1983; reprinted in Smith, 1991).

B. Common Value Auction Behavior

Initial experimental studies of first price sealed-bid auctions with common values (Kagel and Levin, 1986) identified serious problems with subjects not discounting properly their private information, except in small groups of 3-4 bidders, and suffering the "winner's curse." All bidders receive unbiased estimates of the value of the object, but the highest of several estimates is biased upward. This "order statistic" property requires that the optimal bid take this property into account. Hence, the Nash equilibrium bid of each bidder is below each bidder's private estimate. Inexperienced subjects tend to bid their signals' indicated value or more. Consequently, the highest signal bidder wins, but pays too much and on average loses money.

However, this preliminary finding in Kagel and Levin (1986) did not hold up with experienced bidders. Cox and Smith (1992) found that with experienced bidders, who could elect to enter the auction, or stay out and receive a modest return each period, subjects tended to bid below their estimates of value, and made positive profits. Subsequently, these results were confirmed by Garvin and Kagel (1994) in their study of "learning" (experience) in common value auctions. It is now well established that in most cases even unsophisticated bidders with training and experience have no significant difficulty overcoming the winner's curse in common value auctions. The few who do not, eliminate themselves by choice.

Kagel and Levin (see Kagel and Roth, p. 548) report common value auction results comparing first price with English auctions. Average prices in the English auctions were lower than in the first price sealed bid auctions, and both were higher than the expected common value, yielding negative profits under both auction procedures. But losses where lower in the English auction. Consequently, the winner's curse is reduced but not eliminated in English auctions. It is not known whether it would be eliminated using more experienced subjects choosing between bidding at auction and an alternative return activity.

C. A "Winner's Curse" in Private Value English Auctions for Gambles

Two studies have reported results from English auctions of objects of uncertain value – gambles yielding alternative monetary prizes with known stated probabilities. (Berg, Dickhaut and McCabe, 1996; hereafter BDMC); Chew and Nishimura, 1999, hereafter CN). The two sets of results are qualitatively very similar although the auction formats, and commodity gambles are quite different. Also, Cox and Grether (1996), incidental to their study of preferences reversals, report similar findings. All three report English auction prices in excess of the expected value of the auctioned gamble.

BDMC conduct English Clock auctions for the sale of a gamble by N = 4 sellers each of whom have been endowed with one unit of a gamble, identical for all sellers. Thus, in auction t each agent has one unit of a private prospect, G_t defined by

$$G_t = \begin{cases} M_t, \text{with probability } P_t = R_t / 30 \\ 0, \text{with probability } 1 - P_t \end{cases}$$

In each auction t, M_t is chosen independently from [1, 225] with constant probability for each event element. The cutoff range for winning M_t is determined from a 30-sided die with $R_t \in [1, 30]$ chosen at random to determine P_t. M_t and R_t are common information. An English Clock is set initially at price M_t for auction t, where all subjects want to sell. The clock decrements by 3 points $(M_t - 3,\ M_t - 6, \ldots)$ every 2 seconds. As the price declines each subject drops out when the price reaches a level hypothesized to represent each subject's cash equivalent for the gamble. When the third of four subjects drops out, the clock stops. The last subject is paid the clock price in return for her gamble, and the remaining three play the gamble based on a single role of the die yielding an outcome common to the three. Note that each unit of the good (gamble) is a private allocation, but the outcome is a common realization, like three prize winners in a lottery.

The results in this experiment show a strong "winner curse" in the sense that only 17% of the selling prices are below or equal to $E(G_t)$. This is consistent with risk preferring behavior for expected utility maximizers, but in controlled comparisons 94% of the same subjects bid as if risk averse in first price auctions, while 46% are risk averse when cash values are obtained using the second-price Becker-DeGroot-Marschak procedure.

In CN, subjects are endowed with cash, and bid to acquire a gamble, G_{it}, yielding private binary outcomes consisting of a high value, M_{it}, for subject *i* on auction *t*, or a low value, m_{it}:

$$G_{it} = \begin{cases} M_{it}, & \text{with probability } p_t = (1, 0.5, 0.75, 0.9) \\ m_{it}, & \text{with probability } 1 - p_t \end{cases}$$

where $M_{it} \in [M_{Lt}, M_{Ht}]$, $m_{it} \in [m_{Lt}, m_{Ht}]$ (or 0), each chosen from the indicated elements with constant probability. Thus, the prizes, true to the independent private values model, are known privately to each bidder i, on auction *t*, but bidders do not know the values assigned to competing bidders. The p_t values and interval $[M_{Lt}, M_{Ht}]$ and $[m_{Lt}, m_{Ht}]$ are common information for each *t*, e.g. $p_t = 0.5$, $M_{it} \in [8,10]$, and $m_{it} \in [2,3]$.

Subjects bid in an English ascending bid oral multiple round auction to acquire title to G_{it}. When no new higher bids are forthcoming on auction t, the procedure stops, and G_{jt} is awarded to the remaining bidder, *j*, at the standing bid price. Person j then plays the gamble, receiving the outcome; all $i \neq j$ receive only their original cash endowments.

NC find that English auction prices for their gambles are significantly greater than those in second-price auctions, and the risk neutral value $E(G_{it})$. This “winner curse,” however, is consistent with the NC model of non-expected-utility preferences based on Allais type choice behavior.

What we learn from these studies is that when there are uncertainties associate with the value outcomes of an auctioned commodity, English auction bidding behavior, whether bids are announced from the floor, or mechanized by clock, cannot be neatly dicotomized into the two classes: private valued uncertainty where there is no “winner’s curse” problem, and common valued uncertainty where there may be a “winner’s curse.”

D. "Jump Bidding" and other Behavioral Problems in Multiple Unit English Auctions

"Jump bidding" in the form of bid increases higher than the minimum required increment, and raising your own standing high bid (up yourself), occurred in all of the first three FCC auctions, most notably in the first two narrowband license offerings, but less in the third (wideband) auction, which might have been the result of "learning," the higher value of the widebands, or more likely, the scarcity of bidders. (MacAfee and McMillan, 1966, pp. 168-9). Standard theory views such bidding behavior as transparently irrational. Such bidding, however, had been observed as early as 1988 in multiple unit experimental auctions.

Vickrey (1961) proposed an extension of the single object English auction for the multiple unit case (each bidder desiring at most one of the m homogeneous units offered for sale) as follows:

> In simultaneous auctioning the m items can be put up simultaneously, and each bidder permitted to raise his bid even when this does not make his bid the highest. When a point is reached such that no bidder wishes to raise his bid further the items are awarded to the m highest bids. . . . Bidders with the top m values then secure the article at a uniform price equal to the $(m + 1)$st value; the result is again Pareto-optimal.

We note that this mechanism does not require or impose a uniform price. When $m = 1$ in the single object English auction, the highest value bidder, never raising the price by more than the minimum increment, will not need to bid higher, once her bid equals or just exceeds the second highest value. Similarly, in the above quotation, Vickrey is stating that the m highest value bidders will each raise their bid only to the level of the (m + 1)st highest value (or just above), and as a consequence, they will each be awarded an item at the common bid price equal to the (m + 1)st highest value.

In their comparison of eight variations on English multiple unit auctions, McCabe, Rassenti and Smith (1988; hereafter MRS)[3] refer to this version of the Vickrey procedure as the Simultaneous Bid (SIM) Auction, which is similar to the Japanese hand signal auction for selling fish in single lots, and the Japanese electronic auctions for fruit and vegetables. (See Cassady, 1967, pp. 63-66; 197-198).

Subsequently, Vickrey (1976) modified his earlier proposed simultaneous auction – referred to as the Vickrey Matching (M) Auction by MRS (p. 52) – as follows:

> A Pareto optimal procedure is available, however, if all the items are auctioned simultaneously, with up to *n* bids permitted at any given level, the rule being that once *n* bids have been made equal to the highest bid, any further bid must be higher than this. Within the 'jitter' determined by the minimum acceptable bid increment, this assures optimal results, . . .

Table 1 lists all the multiple unit English auctions (2-8) reported in (MRS, 1988, 1991c, p. 46). In all experiments 4 units are offered for sale to 10 bidders, whose private resale values are drawn independently with replacement from a uniform distribution with support (0, 224]. These facts are common information to all subjects.

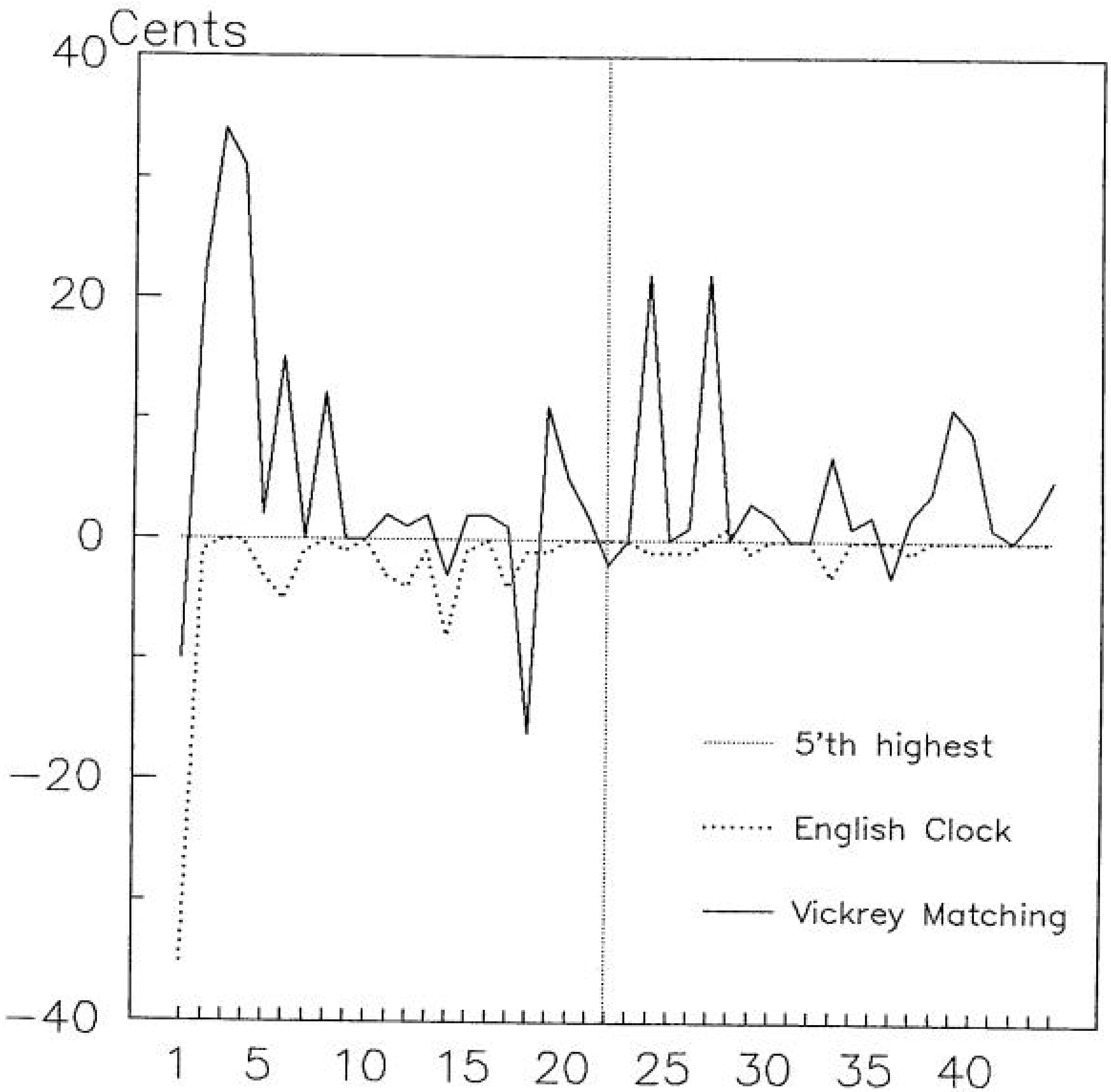
When MRS (1988, p. 54) ran the "Pareto optimal" Vickrey Matching Auction they "found that prices were higher than predicted, and in general, subjects were raising their bids by too large an amount. When a (one of the four highest) high value subject raises the suggested price p^t by too much all four units may not trade." (MRS, 1988; 1991c, p. 54) Their results, showing the effect of such jump bidding, are reproduced here as Figure 1 along with those for the English Clock auction emerging as uniformly the best procedure studied by MRS. This led MRS (1988; 1991c, pp. 54-58) to implement their Full Matching Auction, which we reproduce here as Figure 2. This mechanism uses two rows of four boxes. (Vickrey Matching used only one row). Initially, a standing bid of zero is placed next to one of the rows of boxes, the standing row. Buyers raise their ID cards if they are willing to purchase at this standing bid price and the IDs are entered from left to right. When four buyers indicate willingness to buy the standing bid and row are renamed the floor bid and row and a higher standing bid requested. If a new bid is made it is placed to the left of the remaining row of blank boxes, and the new bidder's ID is placed in the left-most box. Buyers are then asked to raise their ID cards if they want to buy at the new standing price. When the standing row is filled it is renamed the floor row, the data in the previous standing row is erased and a new standing bid is solicited. The auction continues until no new bids are forthcoming or there are an insufficient number (less than four) willing to pay the standing bid price. In Figure 2 the active bid is 75 made by buyer 5 and matched by 4. The old bid is 65 made by buyer 4 and matched by 8, 3 and 1 respectively. The current contract is at 65 with buyers 5, 4, 3 and 1 each buying a unit. A variation (not studied by MRS) would use a rule in which anyone who raised the standing bid would be the last to be bumped in the next round. Any disadvantage of being the first to be bumped must be weighed against the advantage that you get the lower price if the raise is not matched across the board. This is one of the many implementational details raising questions not clearly addressed by the theory that, in this context, was eminently reasonable as an abstract mechanism. It illustrates how an initial, theoretical sound, mechanism can lead to additional treatments suggested by the experimental results. In the field this leads to a parallel adjustment process across successive auctions without the benefit of observing efficiency, and at far higher cost.

Table 1. Types of Auctions

Auction Name	Type*	Description
1. Uniform Price	SB	Baseline (experiments in Cox, Smith, Walker [1986]).
2. English Clock	EC	Baseline (experiments in McCabe, Rassenti, Smith [1988]).
3. Vickrey Matching	M	Vickrey (1976) Uniform Price Variant of Multiple Unit English Auction
4. Full Matching	M	Modified Vickrey Matching guarantee's sale of all units.
5. Vickrey Backtracking	M	Modified Vickrey Matching allows bids to backtrack.
6. Simultaneous Bidding	SIM	Vickrey (1961) Variant of Multiple Unit English Auction.
7. First Rejected	SIM	Modified Simultaneous Bidding with Uniform Price equal to First Rejected Final Bid.
8. Last Accepted	SIM	Modified Simultaneous Bidding with Uniform Price equal to Last Accepted Final Bid.

Note: * SB = Sealed Bid.
EC = English Clock.
M = Matching.
SIM = Simultaneous Bidding.

Figure 1
Graph of price differences for the English Clock and Vickrey Matching Treatments*



Periods 1–22 (Experiments EC1* and VM1)
23–44 (Experiments EC2 and VM2)

* Each experiment used a new group of subjects, and subjects' values were replicated across experiments.

75	5	4		
65	4	8	3	1

1. The standing bid is 75.

2. The floor bid is 65.

3. The tentative contract is buyers 5, 4, 3, 1 buy at 65.

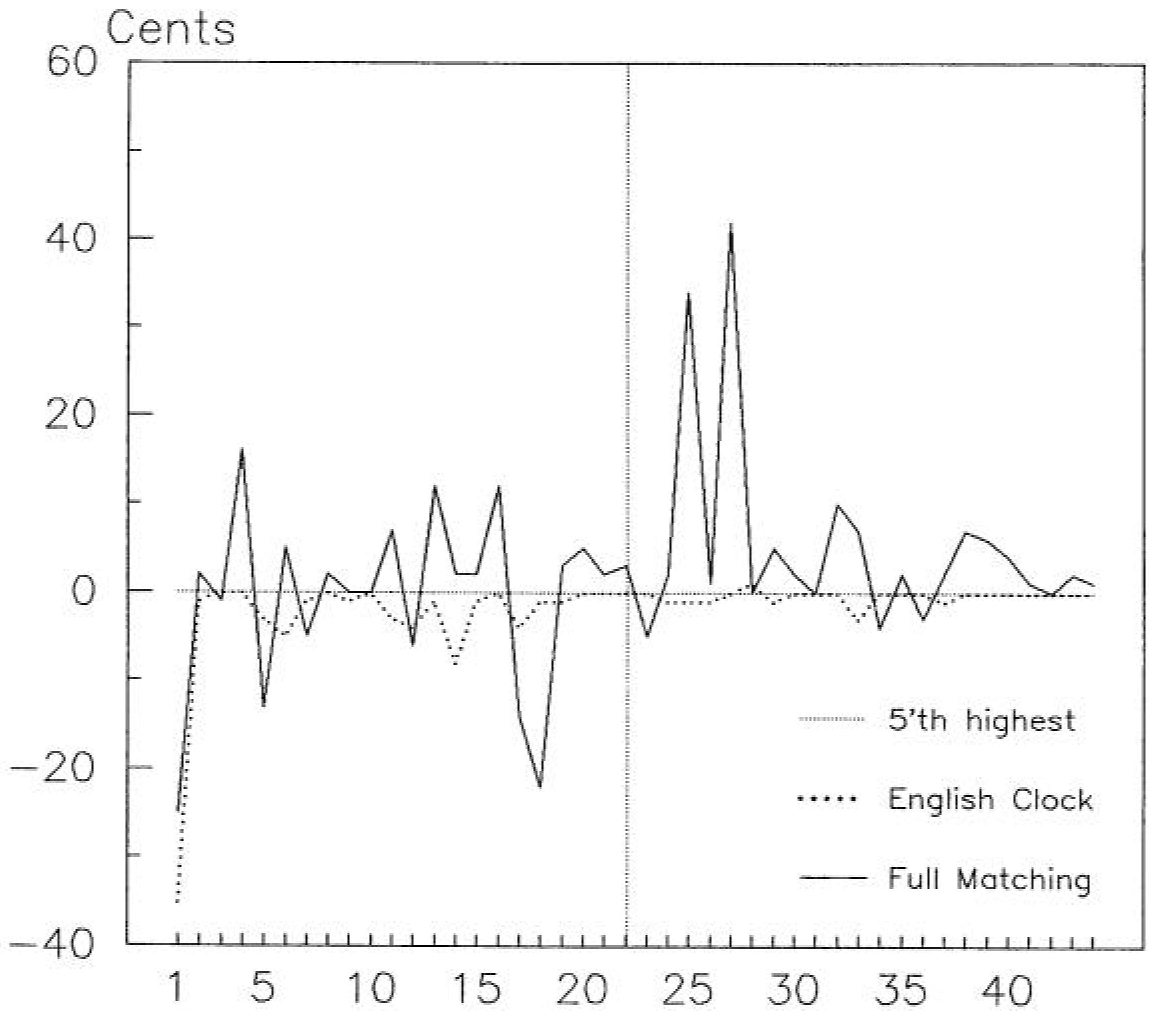
4. Notice that 4 was bumped by 5 making 4 eligible to bid. Buyer 4 then rematched at 75.

Figure 2. Example Full Matching Board

The Vickrey Full Matching data are shown in Figure 3, and we note that there were still serious jump bidding problems. MRS (1988) then implemented a backtracking procedure (Vickrey Backtracking), allowing the price to fall, whenever there was an overshoot with less than four bidders in the contract. This "fix" greatly improved allocations, but there was gaming by some subjects who anticipated that the price would overshoot then fall, and less-cautiously jumped the bid by too much. The major problem with the procedure was that it took a long time relative to the other auctions, as backtracking was widely employed, and transactions cost escalated. These experiments illustrate the following: you have a nice theoretically "optimal" procedure, but in testing you encounter behavioral incentive or "strategic" problems not part of the original theory or even considered. You come up with a rule "fix," creating a new problem requiring a new rule adjustment, and so on. In this case all problems arose from a common feature: bidder control over bids from the floor. These are all issues, not readily anticipated by formal analysis, that can surface naturally in experiments, and make <u>ex post</u> sense.

Vickrey's (1961) Simultaneous Bid Auction was also found by MRS to be plagued by jump bidding. The bottom line, transparently evident in Figures 1 and 3, is that if you want to do English multiple unit (incentive compatible) auctions the way to do them is to use the English Clock. In 45 English Clock auctions only one failed to award the item to the highest value buyer. This method dominates all others in terms of efficiency (percent of maximum possible joint payoff that is realized by the participants), as shown in Table 2. There can be no jump bidding <u>because no one can bid a price</u>. Thus, MRS (1988; 1991c, p. 70) conclude "that the English Clock is our best implementation and is likely to find acceptance in the field. This auction gives participants feedback during the auction, . . . , produces consistent pricing and very high efficiency, (and) can accommodate programmed (or electronic) . . . bidding".

Figure 3
Graph of price differences for the English Clock and Full Matching Treatments*



Periods 1–22 (Experiments EC1* and FM1)
23–44 (Experiments EC2 and FM2)

* Each experiment used a new group of subjects, and subjects' values were replicated across experiments.

Essentially, the procedure works well because it removes from bidders the right to announce bids from the floor – they can only indicate willingness to be in at the standing price, or out, and once out they (in the MRS implementation) cannot reenter. Bidding from the floor invites jump bidding, collusion and longer auctions. Jump bidding is encouraged by impatient bidders who desire to speed up the pace of the auction, but sacrifice price (and efficiency). (MRS, 1988, p. 70-72, offer a model of impatience). Some may jump bid as a bluff: "I intend to win so you might as well give up," but this is entirely conjectural. Such "signals," however, are not rational, and we think are not a plausible explanation of jump bidding. Among sophisticated bidders, we would conjecture that, where it is not seen as too costly for a bidder to jump, it is a way of drawing the attention of other bidders away from that which is essential and causes speculation about why they did it.

E. Information (Private versus Complete) and Nash/Competitive Outcomes

Experimentalists have known since the early 1960s that private information is the payoff condition under which Nash, and dominant strategy, outcomes are most likely to be observed. These well-established results, replicated in many environments with a variety of different levels of subject sophistication, and with increased payoff stakes, originated in the work of Siegel and Fouraker in bilateral monopoly, and Bertrand and Cournot oligopoly competition (See McCabe, Rassenti and Smith 1991a for a review and the earlier references, and McCabe, Rassenti and Smith, 1998, for its extension to extensive form bargaining). Theorists (e.g. Sonnenschein, 1983, p. 13) have commonly supposed, that the "requirement" of complete information on preferences is a "weakness" of the Nash equilibrium concept. The fundamental problem with this construction is that complete information permits agents to identify more lucrative outcomes

Table 2. Summary Measures of Efficiency

	EC	***UP***	***VM***	***FM***	***VB***	***SB***	***FR***	***LA***	
					Statistics				
Avg.	99.99	97.36	97.77	99.36	99.88	99.03	98.5	99.84	
Std.	.149	4.023	7.233	2.45	.319	4.782	5.038	.767	
N	44	44	44	44	26	31	44	44	
					***t*-Tests**				
EC		4.317	2.026	1.676	1.504	1.106	1.948	1.189	*t*-value
		.0001	.049	.1011	.142	.2776	.058	.2407	Probability
UP	-4.317		-.329	-2.816	-4.133	-1.637	-1.173	-4.017	
	.0001		.7435	.0063	.0002	.1060	.2441	.0002	

Notes: EC = English Clock; UP = Uniform Price Sealed Bid } Baselines

VM = Vickrey Matching
FM = Full Matching
VB = Vickrey Backtracking

SB = Simultaneous Bidding
FR = First Rejected
LA = Last Accepted

than are available at Nash and dominant strategy equilibrium outcomes. Essentially, agents Nash behave much more reliably when they cannot identify who is doing what for how much, and each only knows what must be done to respond in their own private interest. This is a fundamental design principle.

F. Effect of Stakes and Bidder "Sophistication" on Equilibrium Behavior

When experimental results fail to conform to equilibrium theory, two common ex post hoc arguments are that (i) the stakes were not large enough, or (ii) the subjects were not sophisticated. But if one increases the stakes 3-fold (or 10-fold) and the results still fail to support the theory, it can again be argued that the stakes were inadequate. No matter what the stakes, it can always be argued that they were inadequate. This makes it transparent that the theory is not testable because it is not capable of being falsified. This is the Duhem-Quine problem: every test of a theory requires auxiliary hypotheses; if the theory fails a test, the auxiliary hypotheses can be blamed, protecting the theory from refutation. (Lakatos, 1978). It is because stakes can be important that they need to be addressed by theory.

Stakes

We do not propose to review the literature on stakes and decision in experiments, but we will provide a brief report of some of the findings concerning issues likely to continue to be investigated by experimentalists. We begin by noting that it is somewhat of a surprise for economists to suggest that in any application of theory the stakes were inadequate. This is because if any theories should explicitly incorporate the stakes as a parameter it ought to be those developed by economists. Yet it is a common characteristic of such theory to imply that the equilibrium is independent of a scalar increase in payoffs, l , across agents. Risk averse models are an exception, but the central results are typically derived assuming risk neutrality with perhaps a subsection devoted to the effect of risk aversion. The latter effect tends to be qualitative only, and such analysis says nothing about how the equilibrium itself might be made more (or less) probable, if the stakes are increased. In particular, equilibria are independent of whether individual payoff functions are flat (i.e., very gently rounded) or sharply peaked, and therefore the opportunity cost of failing to optimize is not a factor in formal theory.

The effect of increases (including large increases) in the payoff scale in a substantial range of different experiments has produced findings as follows: (a) performance, relative to theoretical predictions, is sometimes improved, with the central tendencies of the data providing stronger support for the theory; (b) where there was already significant support for the theory, increased payoffs sometimes reduce the variance around the predictions; (c) finally, in many cases increased payoffs have no effect in improving performance. (For a summary, see Smith and Walker, 1993). These results can be derived from a model which includes a cognitive decision cost of effort, in which more effort improves performance. Hence, there is a cost/benefit tradeoff. With interior optima, a scalar increase in rewards improves performance on average and lowers the variance of outcomes relative to predictions. But if decision cost is high enough, it is not worth the effort and you get a boundary solution that is insensitive to increased rewards. (Smith and Szidarovszky, 1999). In field applications of the model, where stakes are substantial, decision cost includes the time and resources, such as consultants, devoted to decision, such costs being weighed against the value of improved performance.

Bidder Sophistication

It is taken as an axiom that the behavior of subjects in experiments is sensitive to their sophistication. "Sophistication," however can have any one of (at least) two meanings: (1) subject experience as business persons in industry; (2) subject knowledge of game theory, and strategic analysis in interactive games whose payoff outcomes are paid to the participants in real money.

This axiom, however, requires examination. A number of experimental studies make it plain that here, as elsewhere, in the study of behavior prior conceptions do not always bear up under systematic comparisons.

Siegel and Harnett (1961) compared GE executives with college undergraduates in bilateral monopoly (Price, Quantity) bargaining. The formal comparisons showed no significant difference – statistically or economically – in the cooperative versus noncooperative bargaining outcomes. Impressionistically, however, the GE executives were reported to pick up on the instructions, and understanding of the task and payoff displays more quickly, with fewer questions, than the undergraduates.

King, et al. (1993) compared middle level corporate and business executives, and over-the-counter stock traders, with undergraduates in finite horizon laboratory stock market experiments where the (expected) fundamental value of the shares was known to all subjects period by period. Contrary to rational expectations theory, all three groups deviate substantially from fundamental value in sessions where all subjects were inexperienced. Subjects from all three subject pools produce price bubbles that typically collapse to fundamental value near the end of the horizon. In these cases common information is not sufficient to yield common expectations of value (although in three successive experiments the same undergraduate subject group will come to have common expectations through experience and trade near fundamental value). But McCabe and Smith (1999) report a replication of this same experiment with advanced (3rd and 4th year) graduate students, from around the world, attending an experimental workshop. They also were inexperienced in the stock market experiment, but fundamental value is tracked very closely by prices in their experiment. Hence, these subjects had no difficulty discerning the nature of rational play; but also (knowing who were the other subjects and their background) inferred that others would behave rationally.

Some of us have conducted electric power workshops for industry executives, and have noted no material positive differences in their behavior compared with college undergraduates. In our work with the Australians, who ran extensive experiments on market mechanisms for trading privatized electricity in wholesale markets, we recommended against using industry subjects, and instead using paid, trained, professionals in two-week, 7 hours a say, trading sessions. This is because deregulation was politically controversial and opposed by the industry. We think the possibilities for political contamination of the integrity of experiments is potentially much more important than conjectured differences in subject pools which seem not to have found general support where examined. This, of course, does not mean that we think there exists no cases and contexts in which such subject pool differences can be identified.

Particularly revealing comparisons of subject pool effects have been reported by McCabe and Smith (1999), which together with earlier findings in McCabe, Rassenti and Smith (1996), suggest that the above axiom is simplistic and fundamentally flawed. If we define sophisticated play as the ability to increase earnings over that obtained by unsophisticated play, then it is clear that this distinction contradicts one based on play that follows the prescriptions of game theory – one that applies noncooperative equilibrium analysis to games of complete payoff information.

Thus in McCabe, Rassenti and Smith (1996) subjects who risk defection and play cooperatively in single play games, realize higher average payoffs than those who apply the principles of backward induction and the choice of dominant outcomes. In McCabe and Smith (1999) 3rd and 4th year graduate students, from across the United States and Europe, with training in economic and game theory, also cooperate "too much" in anonymous play, and produce outcomes indistinguishable from naïve undergraduates. In Coricelli, McCabe and Smith (1999) undergraduates are compared with young faculty. In one extensive form two person 'trust' game, the latter take longer to decide and make less money than the undergraduates.

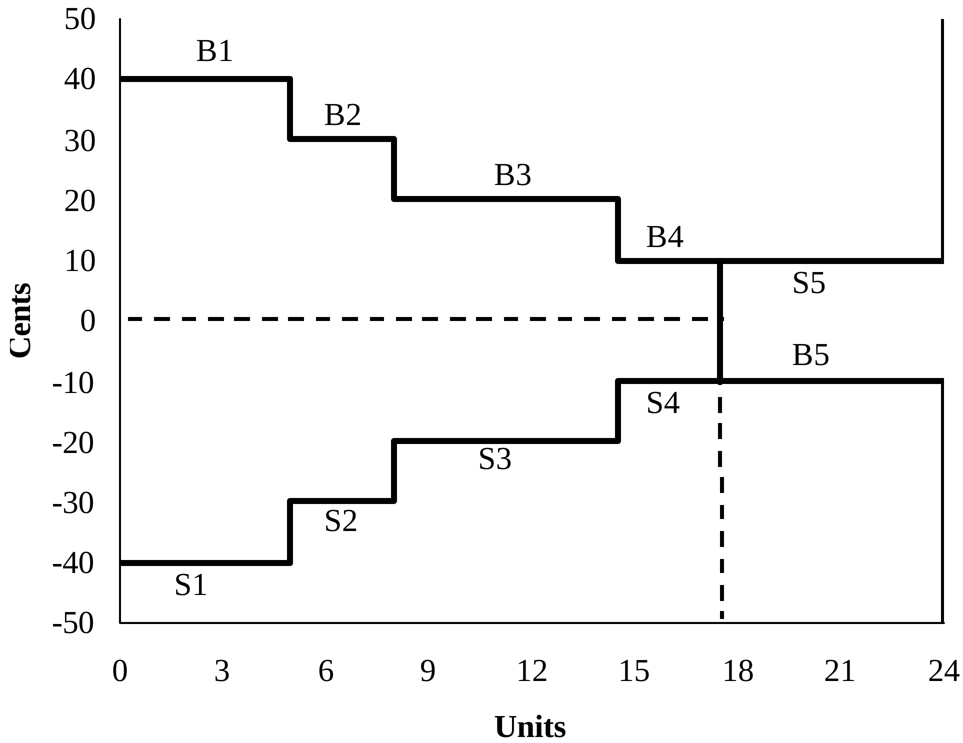
G. Sophisticated Play by "Unsophisticated" Subjects: An Example

In this section we provide an example of a uniform price market mechanism in which: (1) allocations frequently are 100% efficient, although demand (supply) revelation is low (less than 10% of total surplus); (2) the realized equilibria are strategy proof in the sense that no subject can manipulate price to her advantage; (3) demand reduction as a theoretical problem is not typically a behavioral problem; (4) subjects do not use marginal units to set price, while revealing other units; (5) the solution to this problem is provided by unsophisticated subjects who discover the effectiveness of the principles they use using only private information.

The mechanism, uniform price double auction (UPDA) receives bids and offers in real time, continuously resorting the bids from high to low and the offers from low of high, which are crossed and a price and quantity that clears the market is displayed publicly. (McCabe, Rassenti and Smith, 1991b). There are two different rule systems for processing incoming bids (offers): (1) the both-sides rule in which a new bid (offer) is accepted in the cross if it is higher (lower) than at least one of the currently accepted bids (offers); (2) the other-side rule under which a new bid (offer) is accepted in the cross only if it meets the terms of an offer (bid) on the other side of the market which is not currently in the acceptance set – only then do such bids (offers) enter the cross, both being accepted or one or the other accepted depending upon whether it provides better terms than a currently accepted bid or offer. Rule (2) provides a form of temporary time priority for any bid (offer) that has been accepted; it can only be displaced by an order that has first met the terms of an unaccepted order on the other side of the market. This provides an incentive to transact early, and not wait until near the end. Each trading period has a fixed close time under one stopping rule, or, in another, the period closes endogenously if 45 seconds elapse without a change in the tentative allocation.

Figure 4 shows one of the environments using UPDA. (We have also used an alternative environment in which all values and costs are drawn randomly from a constant density). Each buyer (seller) is randomly assigned a 6 (or 3) unit value (cost) step in each period. A random constant is added to all value (cost) steps each period, and then the steps are reassigned among the buyers (sellers). The result is a stochastically changing strictly private information supply and demand environment at the beginning of each trading period, as indicated by the plot of the midpoint clearing price in each of 15 trading periods in Figure 4.

Observe that the environment in Figure 4 invites demand reduction based on the standard game-theoretic postulate of full information. (Ausubel and Cramton, 1996). Thus, suppose all agents, except buyer B1, with the highest value step, reveal true values and costs. Then buyer B1 can bid his value on his first 5 units, and bid the cost of seller S4 on his sixth unit. As a consequence he gets the price at S4's cost and collects more of the surplus. But the condition of the world is that all agents are free to underreveal in this way, making the outcome of such strategic actions problematic; if any one agent on one side of the market underreveals, than it


B1
B2
B3
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S5
B5
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Cents
Units
50
40
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3
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21
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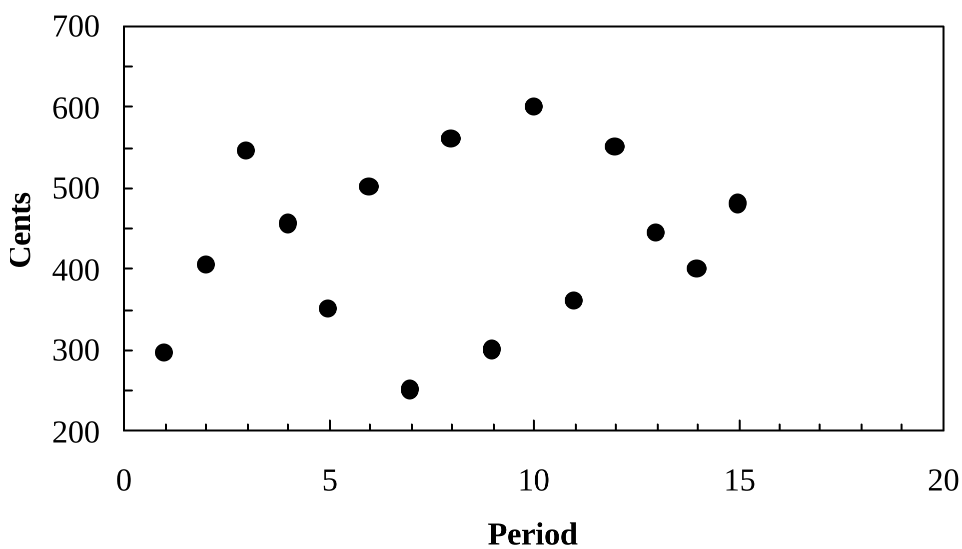
Cents
Period
700
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20

pays her side's competition to free-ride on this "demand reduction;" also, artificial analysis based on full information does not do justice to the incomplete information nature of the world. Under such conditions what do real, motivated, subjects do?

Figure 5 shows a typical plot, in one period, of the reported demand and supply superimposed on true demand and supply. In this period the surplus revealed was only 5% of the true surplus, but 100% of the gains from exchange were realized. Table 3 lists the midpoint equilibrium clearing price and quantity (P_e,Q_e), in the first and second data columns while the realized price and quantities are (P_r,Q_r) in the third and fourth column. Efficiency, and the percent of surplus revealed are shown in the last two columns (Eff_e, Eff_r). In tracking the stochastically changing environment each period, 100% efficiency occurs frequently with an average of less than one-third (27%) of the true surplus being revealed.

In Figure 5 we reproduce the strategic behavior that constitutes the observed equilibrium each period: most bidders match closely other bids and offers at the clearing price. So long as the number of tied bids and offers exceeds the trading capacity of any one agent, no agent acting alone can move the price. Each side erects a wall of price quotations that the other side is helpless to manipulate. In saying this we remind the reader that no subject sees or knows the true environment. Hence strategic analysis based on such knowledge is not feasible. If at any time t before the close there is excess supply (demand), then of course agents can move the market and the competition for surplus leads to an increase in the bids (decrease in the offers) in response to the excess demand (supply). The UPDA mechanism allows this price discovery process to occur in real time within each period while withholding final determination of all

Figure 5

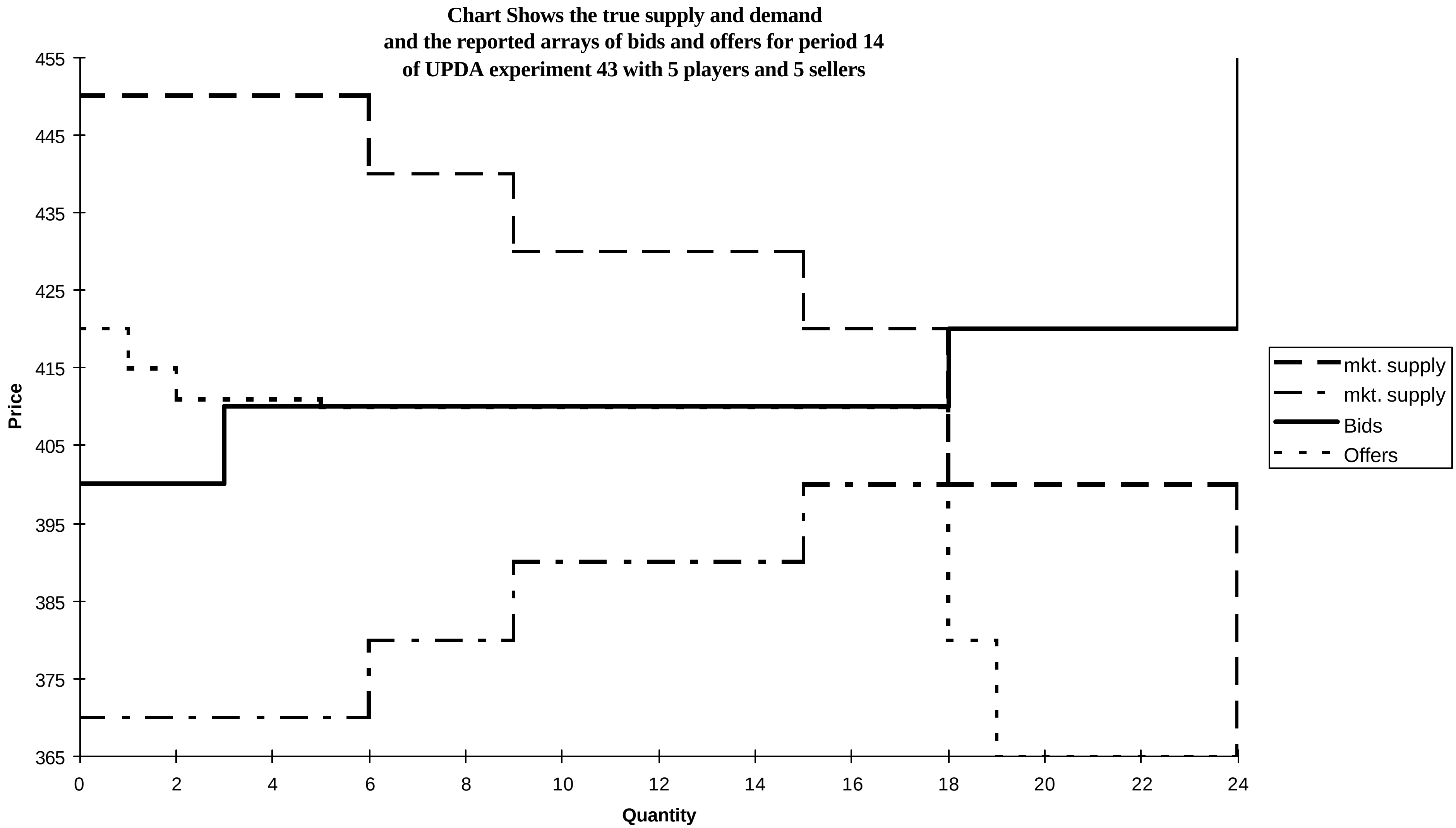


Chart Shows the true supply and demand
and the reported arrays of bids and offers for period 14
of UPDA experiment 43 with 5 players and 5 sellers
455
445
435
425
415
405
395
385
375
365
Price
0
2
4
6
8
10
12
14
16
18
20
22
24
Quantity
mkt. supply
mkt. supply
Bids
Offers

exchange contracts. These results are remarkable in showing that in these low information markets, agents can track the unpredictable changes in the environment so effectively. They solve with ease a problem posed in the theory literature as one that is fraught with problems of incentive incompatibility and strategic manipulation. Thus, with no prior experience, and working only with the tools defined by UPDA's bidding and real time display rules, the market in Table 3 produces efficient outcomes in 7 of 15 periods yielding as little as 5, 7 or 9% of the surplus. Across all periods in this stochastic environment, efficiency averages 95%. The mechanism gives plenty of scope for bidders to express their innate protective instincts to underreveal, while minimizing the amount of money left on the table.

These results will obviously not be independent of the value/cost environment. In electric power market experiments using UPDA, generators upstream from a constrained line face inelastic demand. Without knowing that the line is constrained, they quickly learn under UPDA rules to raise their offer prices, and divert some of the transmission congestion rent to their own profit account. (Backerman, Rassenti and Smith, 1997, to appear).

Table 3

Summary of Results: up43;5,5

	P_e	Q_e	P_r	Q_r	Eff_e	Eff_r
1	295	18	300	16	91%	22%
2	405	18	400	18	100%	7%
3	545	18	540	18	100%	14%
4	460	18	448	18	92%	14%
5	360	18	350	18	100%	9%
6	500	18	500	18	98%	12%
7	260	18	250	17	96%	26%
8	565	18	553	15	92%	28%
9	300	18	300	18	100%	28%
10	610	18	610	18	100%	33%
11	365	18	350	15	85%	88%
12	550	18	558	15	88%	55%
13	450	18	450	18	100%	31%
14	410	18	410	18	100%	5%
15	485	18	484	19	89%	39%
			μ = 17.3		95%	27%
			σ = 1.3		5	21

H. Combinatorial Auctions

The general concept of smart computer-assisted markets, and the specific version known as a "combinatorial auction," originated in the early 1980s. (Rassenti, 1981; Rassenti, Smith and Bulfin, 1982; hereafter RSB). As noted by RSB (p. 672):

> To our knowledge, this study constitutes the first attempt to design a "smart" computer-assisted exchange institution. In all the computer-assisted markets known to us in the field, as well as those studied in laboratory experiments, the computer passively records bids and contracts and routinely enforces the trading rules of the institution.[4] The RSB mechanism has potential application to any market in which commodities are composed of combinations of elemental items (or characteristics). The distinguishing feature of our combinatorial auction is that it allows *consumers* to define the commodity by means of the bids tendered for alternative packages of elemental items. It eliminates the necessity for producers to anticipate, perhaps at substantial risk and cost, the commodity packages valued most highly in the market. Provided that bids are demand revealing, and that income effects can be ignored, the mechanism guarantees Pareto optimality in the commodity packages that will be "produced" and in the allocation of the elemental resources. The experimental results suggest that: (a) the procedures of the mechanism are operational, i.e., motivated individuals can execute the required task with a minimum of instruction and training; (b) the extent of demand underrevelation by participants is not large, i.e., allocative efficiencies of 98-99% of the possible surplus seem to be achievable

over time with experienced bidders. This occurred despite repeated early attempts by inexperienced subjects to manipulate the mechanism and to engage in speculative purchases.

Subsequently, the idea of smart computer-assisted markets was applied in a proposal to deregulate the electric power industry in Arizona by separating the "wires business" from energy sales, and create a smart market in the form of the Arizona Energy Exchange.[5] (Economic Science Laboratory Research Group, February 1985); in a Federal Energy Regulatory Commission study of the application of linear programming algorithms to the processing of node-specific bids to buy delivered gas and offers to sell wellhead gas, and leg-specific offers of pipeline capacity by multiple rights holders (McCabe, Rassenti and Smith, 1989); in a two-sided combinatorial auction for trading pollution permits. (Ledyard, Porter and Rangel, 1997).

The RSB (1982) mechanism addressed three problems generic to the combinatorial features of the commodity space: (i) separating prices (Lagrange multipliers) in the optimization do not exist; (ii) in view of this what information should be reported to the bidders after each sealed bid auction allocation (or round in the case of multiple round auction mechanisms)?; (iii) what are the behavioral incentive properties of the resulting rules? An integer programming algorithm was devised that allocated integer elements {0, 1} to packages that maximized reported surplus as contained in the bids submitted for the packages, subject to constraints on the supply of each elemental resource. Two pseudo-dual programs to this primal problem were used to define a set of accepted packages, A, and a set of rejected packages, R; also a set of lower bound prices $\{w_i^*\}$ and a set of upper bound package prices $\{v_i^*\}$ were determined. Then, (a) if a package bid was greater than the sum of its component values in the set $\{v_i^*\}$, it was in A, and, except in rare marginal cases, the bidder paid less for the package than her bid, providing good incentives not to underreveal true value; (b) if it was less than the sum of its component prices in $\{w_i^*\}$ it was in R; (c) all bids in between A and R were in a region where acceptance or rejection were critically dependent upon the integer constraints on the allocation of the elemental resources. Thus, each bidder knew that in a subsequent auction (or round if an iterated procedure is used) whether a best reply would certainly be accepted, certainly be rejected, or depended on the integral "fitness" of the bid.[6] An after-market open English auction board was used to allow subjects to further adjust elements needed to fill out packages after each primary auction using the combinatorial auction (CA) mechanism. This was compared with an independent auction (IA) in which resources were auctioned simultaneously in a sealed bid uniform price auction, followed by the English after market.

Table 4 shows the "easy" (little interdependence) combinatorial environment while Table 5 shows the "difficult" (lots of interdependence) environment.

Results

(1) This computational and feedback reporting process in RSB yielded efficiencies for experienced bidders no lower than 97.8% in a difficult combinatorial environment (Figure 7, lower panel), and no lower than 83.2% in an easy combinatorial environment (Figure 6, lower panel).

(2) Efficiency in the difficult environment with experienced subjects weakly dominated efficiency in the easy environment. (Compare Figures 6 and 7).

(3) In both environments efficiency in the RSB mechanism tended to be higher than a control mechanism which independently auctioned the elemental resources in a uniform price sealed-bid auction and used an after-market board for bidders to adjust their allocations to

Table 4

□ Easy resource utilization design

Agent	Package	Value	Item A	Item B	Item C	Item D	Item E	Item F
1	1	598	1	1				
1	2	946	1	1	1			
1	3	517		1	1			
2	4	632	1			1		
2	5	663		1	1			
2	6	951	1	1	1			
3	7	877	1	1				1
3	8	595	1		1			
3	9	515		1	1			
3	10	885	1	1	1			
4	11	546	1		1			
4	12	983	1		1			1
4	13	569	1	1				
4	14	603		1	1			
5	15	642	1	1				
5	16	450	1				1	
5	17	498		1	1			
5	18	913	1		1		1	
5	19	476	1		1			
6	20	576	1		1			
6	21	802		1	1	1		
6	22	439		1	1			
6	23	945	1		1			1
6	24	617	1		1			
6	25	520	1	1				
Units Demanded			18	15	18	2	2	3
Units Available			13	11	15	1	2	3

Table 5

⌧ Difficult resource utilization design

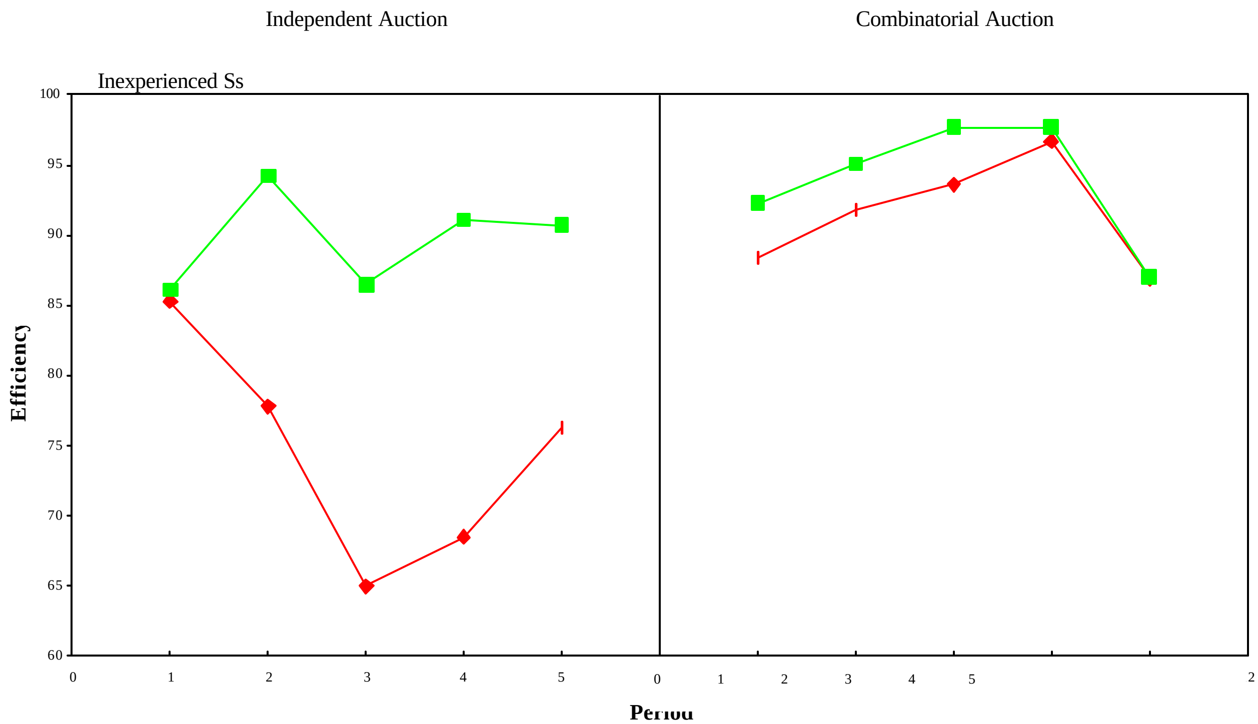
Agent	Package	Value	Item A	Item B	Item C	Item D	Item E	Item F
1	1	627	1	1				
1	2	577			1	1		
1	3	506	1				1	
1	4	825	1		1			1
1	5	834		1	1		1	
2	6	531	1	1				
2	7	556			1	1		
2	8	576	1		1			
2	9	644		1			1	
2	10	584			1		1	
2	11	886	1				1	1
3	12	517	1	1				
3	13	576			1	1		
3	14	887	1		1		1	
3	15	940		1	1			1
4	16	598	1	1				
4	17	627			1	1		
4	18	578	1					1
4	19	578		1		1		
4	20	556				1		1
4	21	861		1			1	1
5	22	560	1	1				
5	23	582			1	1		
5	24	565		1				1
5	25	834		1		1	1	
5	26	782	1			1		1
6	27	507	1	1				
6	28	565			1	1		
6	29	833		1		1		1
6	30	959	1			1	1	
# Units Demanded			14	14	12	12	9	9
# Units Available			7	7	7	7	7	7

fill out the needed packages of complementary items. (Compare left and right panels in Figures 6 and 7).

(4) The lower efficiencies indicated in (2) and (3) were a consequence of subject attempts to strategically acquire units in the primary auction for resale in the after market. The independent auction invited these manipulative attempts much more prominently than RSB in both the easy and difficult combinatorial environments. With experienced subjects the RSB mechanism invited it slightly more in the easy than the difficult environment. (Figure 8 shows the average percent of subjects showing a deficit across all periods by treatment and experience). This small difference was conjectured to be due to increased transparency when combinatorial complexity is minimal. In more complex environments it is especially costly to fail to obtain the desired packages, bidders are motivated to better reveal true package value and thereby rely on computer assistance to put together valuable packages. This was the primary learning experience that subjects went through in using the RSB mechanism. The fact that RSB performed better (relative to the independent auction) in the more complex combinatorial environment is consistent with the findings reported in Ledyard, Porter and Rangel (1997) in which single-item commodity awards were less efficient than package-item awards. We suggest that the more transparent environments simply invite manipulation attempts more readily than complex environments where with private information it is more difficult to capture benefits that outweigh the cost risk of manipulation. The easiest way to control for gaming between the primary and after markets is to abolish the latter. The combinatorial auction performed so well in the primary auction that there was little room left for improvement in the after market.

Figure 6. For the easy combinatorial environment, each of the four panels plots efficiency by period in the primary market, and efficiency for each period following the after market. For inexperienced subjects in the top panels, the declines shown in periods 1 to 3 for the independent auction (IA), and in period 5 for the combinatorial auction (CA) are the result of speculation: subjects purchase items in excess of their own demands in an attempt to profit from resale in the after market. These speculations caused losses (see Figure 8) and use of this behavioral strategy was much reduced when subjects become experienced. Overall the CA provided only slightly improved after market efficiency relative to IA in this simple environment. With inexperienced subjects, CA efficiency was higher in periods 1 to 4 than in IA, but below it in period 5. With experienced subjects in periods 1 and 4 IA efficiency was higher than CA, while in periods 2 and 3 this ranking was reversed.

Easy Environment



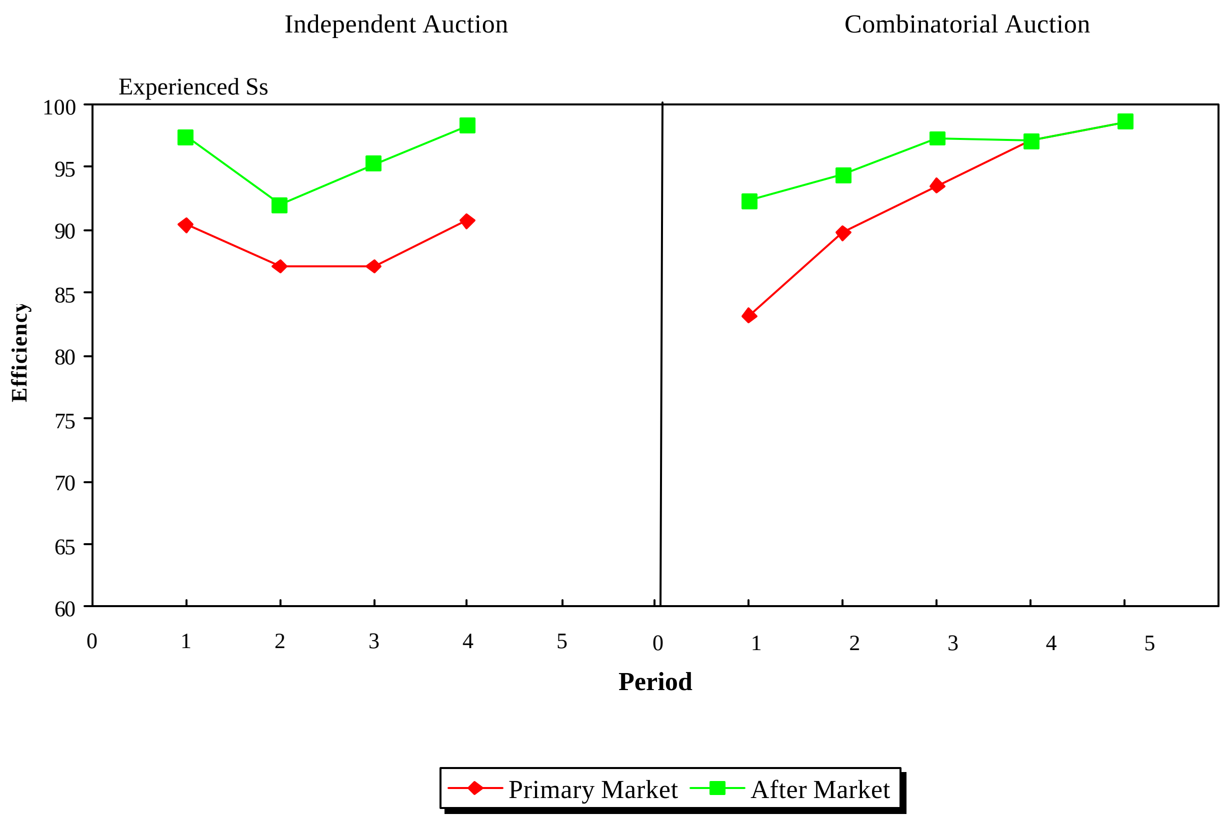


Figure 7. Efficiency is plotted by period for each treatment using the difficult combinatorial environment for the primary market and the after market. Note that the improvement in efficiency going from the primary market to the after market is much more pronounced in IA than CA. Even for inexperienced subjects the primary market CA easily solves the coordination problem in a complex environment, leaving little room for efficiency improvement in an after market. In IA the low primary market efficiencies were a consequence of speculative attempts by subjects to buy elements in excess of their individual demand needs in the hope of reselling at a profit in the after market. This was a much less severe problem in CA where the complexity of the environment led subjects to rely on the support of computer coordination in the primary market and to avoid using the after market to piece together valuable packages.

Difficult Environment

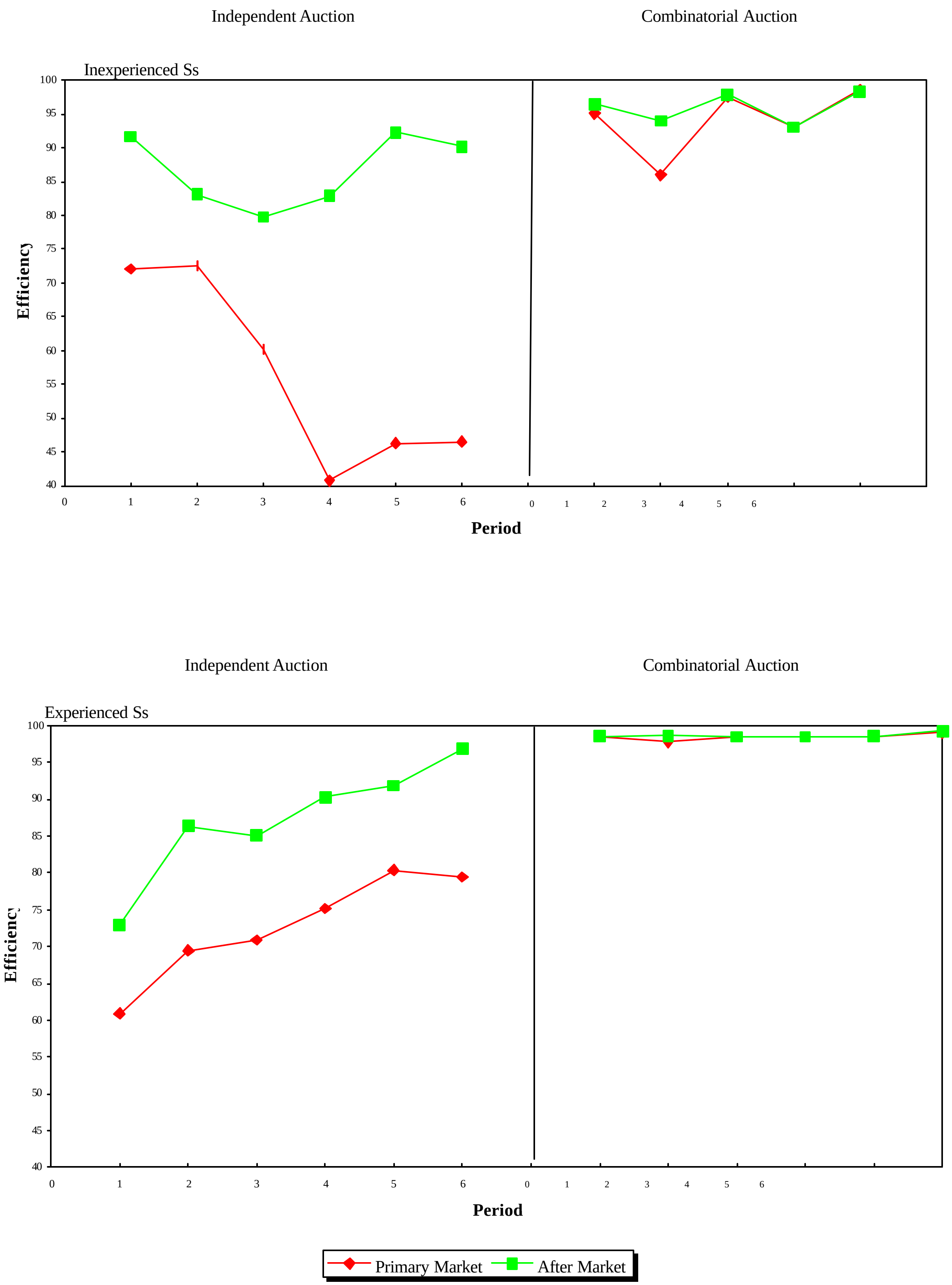
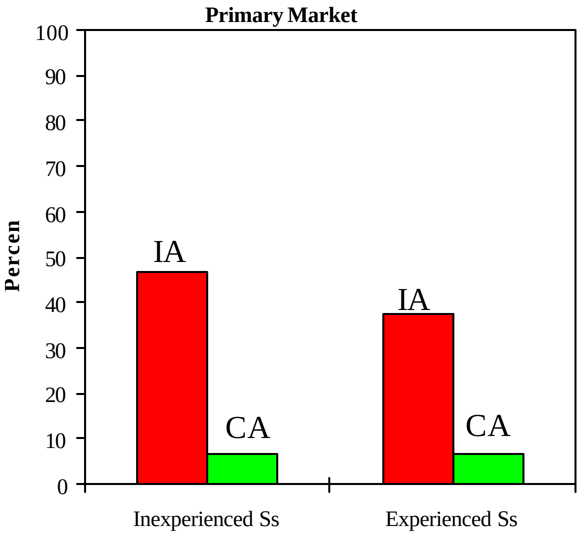
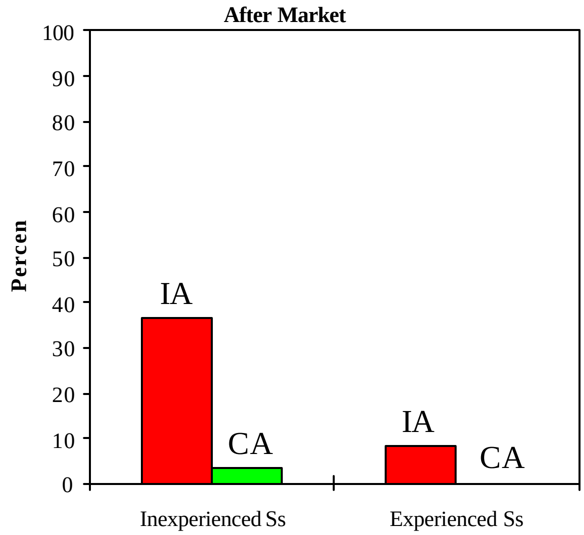


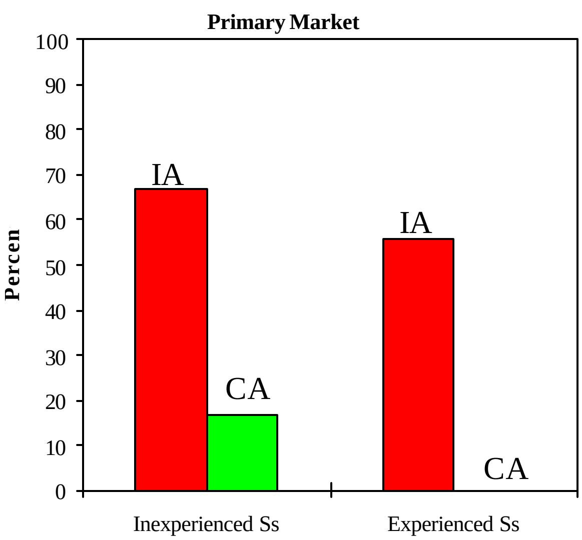
Figure 8. The average percent of subject agents incurring a deficit across all periods is shown for the independent auctions (IA) and for the combinatorial auction (CA). Deficits are common in the IA primary market, even with experienced subjects, and persist into the after market, especially in the difficult combinatorial environment shown in the lower panels. Thus over 20% of agent periods end in deficit with experienced subjects in the IA. (Lower right panel). Such deficit problems are minor in the CA with inexperienced subjects, and disappear entirely with experience in both the easy and difficult environments.

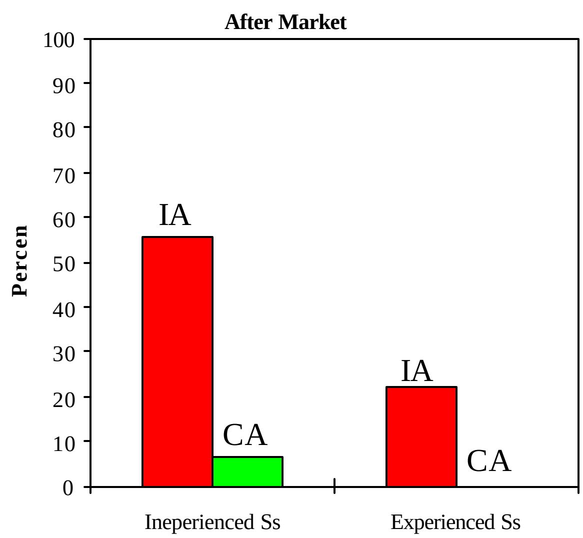
Average Percent of Agents in Deficit





Difficult Environment
Average Percent of Agents in Deficit





III. Implications for the Design of Spectrum Auctions

Our discussion suggests a number of potential implications for the design of spectrum auctions, or similarly complex allocation problems. Auction design requires a balancing of a number of competing considerations, each one of which has an uncertain weight in the final specification of the mechanism to be used. Consequently, the implications listed here should be viewed primarily as a basis for further theoretical, experimental and empirical investigation, and for discussion among the growing number of scholars associated with applied mechanism design.

1. If the open English bidding mechanism continues to be the primary procedure of choice, we believe it should eliminate iterative price bidding by the participants. Rather, all price bids should be supplied by the English Clock procedure, with bidders simply indicating whether they are active, or no longer active in expressing their demand for any licenses (or combination of licenses) in real time. This is straight forward for licenses that are independent, which is the environment to which the FCC's SMR procedure applies. Where licenses are complementary or otherwise show synergies, the same considerations apply, although the design features of such an implementation requires articulation. Such a procedure would not require a bidder to be present during the life of an auction. The bidder need only submit bench-mark bids for all units and combinations below which he desires to remain active, and above which he wishes to become inactive.

2. The motivation for the English procedural form of the SMR is poor, as it is derived essentially from stories about why common valuedness is the key feature of spectrum licenses: uncertainty about technology and demand, similarities among applications in different regions, and so on. We have no rigorous models of how common valuedness can be derived from more

elementary characteristics of commodities, knowledge of which is inherently dispersed, and requires pooling through the revelation properties of the English auction format. Given a solution to this problem, and the identification of a core of common valuedness in spectrum auctions, we have no theorems showing why a bidder, using backward induction, would be motivated to invest in the acquisition of improved common value information if in the subsequent SMR auction she would be forced to reveal all or most of it. These considerations, in the absence of the indicated fundamental research, call for laboratory and field tests of alternatives to SMR, including the sealed-bid format.

3. The examination of alternatives to the SMR auction is further indicated by the high transactions cost of participation, requiring advice from a wide range of consultants to deal with the strategic issues that arise in real time as the bidding proceeds. The ideal incentive mechanism design should lead to a two step procedure: (1) an estimation of the value of the auctioned item(s), followed by (2) the submission of this value in the form of a bid, such action being a fair approximation to that which serves the interest of the bidder. Thus, in the combinatorial auction summarized above, which was only approximately incentive compatible, a difficult interdependent environment yielded 98-99% efficiency with experienced bidders.

The key question for the SMR, and for combinatorial mechanisms based on open bidding, is the following: do the benefits, based on the judgement as to the importance of common valuedness, outweigh the costs of higher complexity induced by the desire to control manipulation. All the examples of strategic behavior – exposure, free rider, demand reduction, etc., problems – are based on postulated common information, known to the analyst and/or revealed in open English bidding. Consequently, the chain of causality is that common valuedness implies English format implies strategic behavior implies higher transaction cost design complexity to control the behavior. This chain needs fundamental examination.

The SMR auction has evolved over a sequence of field applications in which weaknesses and defects revealed in each application led to “fine tuning,” followed by the observation of further problems leading to new “fixes,” and so on. Each “fix,” designed to limit strategic exploitation, tended also to generate complexity and its attendant higher transactions cost. This is reminiscent of the MRS (1998, 1989) series of experiments leading to a sequence of increasingly complicated modifications of English procedures until all such fine tuning attempts were abandon in favor of the elimination of price bidding – the feature which historically has been the defining characteristic of the English auction.

4. In the spectrum auctions probably very little of the ultimate technological, antitrust and demand uncertainty is resolved at the end of the auction. This feature is not formally part of the theory that led to the original conclusion that the English auction procedure should be used. But whatever might be the consequence of reexamining the basis for the SMR in the light of this feature, a more important consequence, we think, is the challenge to the assumption that these licenses should be privatized by a single initial one-sided auction. More appropriate, we think, is for the FCC to consider periodic two-sided auction exchange mechanisms in which misallocations caused by bidding errors or mechanism design faults in earlier auctions, together with subsequent resolution of earlier uncertainties about technology, demand and antitrust, allow spectrum title holders to participate in the sale of incumbent rights in new auctions. This would facilitate repackaging old as well as new rights in response to changing information, whatever might be the auction format that is used.

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Footnotes

1. The so-called "English" auction was imported to the British Islands by the Romans. This is indicated by word origins. Thus, the word auction is derived from the Latin root auctio meaning "an increasing"(procedure). More revealing, the Oxford English Dictionary notes that an old English word, fallen into disuse, is subhasta, which is still used in Spain to refer to an auction or auction house. This word is compounded from the Latin words sub hasta meaning (a sale) "under the spear" which refers to the practice of the auctioneers who followed the Roman army to auction the spoils of war so that the soldiers would not have to be paid in kind.

2. Some auctions reduce transaction cost by defining off-floor bidding procedures: stamp (and some fish) auctions permit "book bids" by buyers not present at the auction, and Southby's, for example, allows buyers to monitor by telephone and submit oral bids to the auctioneer for paintings and collectibles. Book bids are of theoretical interest because they long ago made it transparent to practicing auction houses that the second price sealed bid auction is isomorphic to the English auction. Hence, the rule that if there is one book bid, the auctioneer calls for a bid from the floor. Given a bid from the floor the auctioneer advances the bid, for the account of the book bidder by the standard increment, Δ. If this bid is advanced from the floor, the auctioneer again advances the bid by Δ for the book bidder, and so on, until either the book bidder is stopped out by a floor bidder, or bidding from the floor ceases, in which case the item is knocked down to the book bidder at a price equal to the last standing floor bid plus Δ. If there are two (or more) book bids, then the auctioneer starts the bidding at the second highest book bid plus Δ. If there are no counter bids from the floor, the award is to the highest book bid at Δ over the second book bid.

3. In McCabe, Rassenti and Smith (1991a) a ninth mechanism – the multiple unit uniform price Dutch auction –is modelled theoretically, and tested.
4. An exception is in several market-like public good mechanisms that appeared in the period 1977-1984 using the Groves-Ledyard and other mechanisms. (See Smith, 1991, Part III, pp. 375-506; also Chapter 2 by Ledyard in Kagel and Roth, 1995.)
5. In the early 1990s some of us served as consultants for New Zealand in the application of combinatorial methods to the auctioning of cutting rights to Crown timber lands, and in New Zealand and Australia on the application of smart markets and experimental methods to the design of energy markets for the privatization of electric power.
6. All the indicated value information is private for each agent. The mechanism allows bids of the form: "Accept no more than p of the following q packages;" "don't spend more than \$$M$; accept package A only if B is accepted." Any logical constraints linear in the x_i are acceptable. The experiments did not utilize these bid options.