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'The Favored but Flawed Simultaneous Multiple-Round Auctions'

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The Favored but Flawed Simultaneous Multiple-Round Auction*

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Abstract

We compare the first-price sealed-bid (FPSB) auction and the simultaneous multiple-round auction (SMRA) in an environment based on the planned sale of 900 MHz spectrum in Australia. Three bidders compete for five indivisible items. Bidders are permitted to obtain at most three items and need to obtain at least two to achieve profitable scale, i.e. items are complements. Value complementarities, which are a common feature of spectrum auctions, exacerbate the "fitting problem" and undermine the usual logic for superior price discovery in the SMRA. With substitutes, bidders reduce demands as prices rise and a tâtonnement-like dynamic produces market-clearing prices. With complements, however, all that bidders may be interested in at higher prices are *larger* packages. In addition, the SMRA assigns provisional winners each round, which exposes bidders to the risk of losses when they win only a subset of their desired package.

We find that the FPSB outperforms the SMRA across a range of bidding environments: in terms of efficiency, revenue, and protecting bidders from losses due to the exposure problem. Moreover, the FPSB exhibits superior price discovery in that it almost always results in competitive ("core") prices unlike the SMRA, which frequently produces prices that are too low because of demand-reduction or too high because of the exposure problem.

We demonstrate the robustness of our findings by considering two-stage variants of the FPSB and SMRA as well as environments in which bidders know their own values but not the distributions from which values are drawn.

Keywords: *Spectrum auctions, laboratory experiments, price discovery, exposure problem, market design*

JEL codes: *C78, C92, D47*

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1. Introduction

Since pioneered by the US Federal Communication Commission in 1994, the simultaneous multiple-round auction (SMRA) has come to dominate the allocation of radio spectrum, earning hundreds of billions of dollars for treasuries around the world (Milgrom, 2004). Its procedure is simple: all items are put up for sale simultaneously with a separate price associated with each item. Bidders can bid on any subset of items they wish and the auction ends only when no new bids are made on *any* of the items. At the end of the auction, bidders win the items they bid highest on and pay the price they bid. Analysis of the SMRA for allocating spectrum licenses since 1994 suggests that it has been extremely successful, with allocations generally thought to be efficient and revenues high (Cramton, 1997).

In computational terms, the SMRA can be seen as a "greedy algorithm" used to solve the following "fitting problem:" items need to be allocated to the bidders but it is not clear who gets what and at what prices. The algorithm starts at zero (or low reserve) prices at which aggregate demand does not fit into supply. As prices rise, the algorithm picks off demand that is no longer profitable for bidders and increases prices until excess demand is eliminated, i.e. until demand and supply fit.[1]

The use of the SMRA is typically motivated by its ability to produce correct prices, i.e. competitive prices that clear the market and allocate goods efficiently across agents (Ausubel & Cramton, 2004; Milgrom, 2004).[2] This motivation, however, rests on the assumption that goods are substitutes so that bidders reduce their demands over the rounds of the auction as prices rise until supply equals demand.[3] This logic breaks down when goods are complements, as they are in many spectrum auctions. The fitting problem the SMRA is intended to solve typically goes from bad – at low prices, total demand exceeds supply but individual bidders

[1]The algorithm is greedy in this sense, which makes it ideally suited to auctions with many items, such as many of the spectrum auctions in the US and Canada (often with hundreds of items). Greediness is less of an advantage when few items are being sold, as in the recent spectrum auctions in Australia and across Europe.

[2]When competitive prices do not exist in an auction environment, recent research suggests using the *core* as a proper benchmark for "reasonably" competitive outcomes. Core outcomes are reasonably competitive in the sense that there does not exist a coalition of players (including the seller) that would be better off exiting the market and trading amongst themselves; that is, prices reflect the opportunity costs of the allocation. These constraints are weaker than those imposed by competitive equilibrium. See for example (Milgrom, 2004; Day & Cramton, 2012; Day & Raghavan, 2007; Day & Milgrom, 2008; Goeree & Lien, 2016; Bichler & Goeree, 2017a).

[3]Milgrom (2004) and Gul and Stacchetti (1999) prove that when the items for sale are substitutes and bidders bid on subsets of items that provide the highest possible profit (i.e. straight-forward or myopic bidding), prices will be competitive and the allocation will be efficient if the bid increment between rounds is sufficiently small.

also compete for smaller packages – to worse – at high prices, bidders are *only* willing to bid on *large* packages making it harder, if not impossible, to balance demand and supply.[4]

Moreover, the SMRA assigns provisional winners for each item in each round, which exposes bidders to the risk of winning a subset of their desired package. This exposure problem may bias price discovery and lead to payoffs that are far from the core (i.e. minimally competitive payoffs).[5] The assignment of provisional winners can also inhibit bidders' ability to arbitrage across items if only certain items can be combined into valuable packages; for example, complementarities may exist only among electromagnetically adjacent licences in spectrum auctions.

While theoretical results indicate that the SMRA *may* fail to generate satisfactory outcomes, they do not suggest how frequent or how costly we should expect these failures to be in the real world. We conduct an experimental comparison of the SMRA and a first-price sealed-bid (FPSB) auction in which bidders are able to bid on any package of items they wish (subject to a bidding cap). Five indivisible items are available. Bidders can acquire at most three items and the items are complements: bidders need at least two items to earn significant value in the auction. We find that the FPSB is far superior to the SMRA across a range of bidding environments, in terms of efficiency, revenue, price discovery and protecting bidders from losses.[6]

To unpack and illustrate the forces at work in the laboratory, we first examine the SMRA in a simple analytical framework.

2. A Theoretical Analysis

2.1. Bidding Environment

Our experiment is based on the planned auction by the Australian Communications and Media Authority (ACMA) for five (paired) nationwide blocks of 2×5 MHz of spectrum in the 900

[4]This raises the broader question of how to design a practical vehicle for implementing efficient and competitive outcomes when complementarities cannot be ruled out and one cannot therefore rely on prices to guide participants to efficient and stable outcomes. In our setting, a first-price sealed-bid auction performs well relative to the SMRA. Comparing combinatorial designs, Munro and Rassenti (2019) suggest that a *descending* price auction can sometimes solve the fitting problem better than an ascending price auction.

[5]See e.g. (Goeree & Lien, 2014) for a theoretical analysis.

[6]Bidders' post-auction financial viability is essential to the efficient use of spectrum. For example, albeit not related to exposure risk, bankruptcy proceedings of a successful bidder in the 1994 American spectrum auctions precluded the use of valuable spectrum for nearly ten years (Cramton, Kwerel, Gregory, & Skrzypacz, 2011).

MHz band (Bichler & Goeree, 2017b; Goeree & Louis, 2019). Three bidders are expected to compete for five blocks and each will face a cap of three blocks. Bidders are thought to need at least two blocks to implement any profitable business plans. Complementarities between blocks are expected to be strong although it is not clear whether the strongest synergies occur when going from one to two blocks or from two to three blocks.

To keep this analysis tractable, we consider two types of bidders: type X bidders who need exactly two items (i.e. they place zero value on a single item and zero marginal value on each item above two), and type Y bidders who need exactly three items (i.e. they place zero value on a obtaining one or two items and zero marginal value on each item above three). We study multiple combinations of these bidder types: auctions with composition XXX, XXY, XYY, or YYY. An X type bidder draws a valuation for any pair of items uniformly from $[0, 1]$ and a Y type bidder draws a valuation for any three items uniformly from $[0, \alpha]$ for $\alpha > 1$. Bidders get zero value if they obtain less than what they need and zero additional value if they obtain more than what they need. We consider only equilibria wherein the same types bid the same way if such an equilibrium exists.

2.2. Bayesian Nash Equilibria

We summarize the structure of the equilibria for the various auctions here while relegating the technical details to the Appendix. We first discuss a common theoretical benchmark for auction performance.

2.2.1. The Vickrey-Clark-Groves Mechanism

An idealized benchmark to which auction formats are often compared is the Vickrey-Clark-Groves (VCG) mechanism (Vickrey, 1961). The VCG mechanism always allocates the items efficiently but has been criticized for, among other shortcomings, generating prices that are far too low when items are complementary for at least one bidder. As a result, the VCG mechanism has never been seriously considered for practical applications.(Rothkopf, 2007).[7] Nevertheless, the equilibrium outcome of the VCG mechanism is always in the core in our environment and therefore provides a useful comparison as a minimally-competitive mechanism.

[7] An exception is an early spectrum auction in New Zealand, widely seen as an embarrassment for the government. One firm paid only NZ$6 for a license, having bid NZ$100,000. See "The lovely but lonely Vickrey auction" (Ausubel & Milgrom, 2006), which provided inspiration for, among others, the title of this paper.

In the VCG mechanism, bidders report their values to the seller and, based on these reports, the seller chooses the allocation that maximizes total surplus (i.e. the efficient allocation). Payments are designed such that it is a dominant strategy for bidders to report their true values to the seller.

2.2.2. The First Price Auction

In the first price auction bidders submit one bid for every possible package (i.e. subset) of items, which they pay if and only if they win the package. Since the X type bidders only value a pair of items, we need only consider their bids for one item. Since the Y type bidders only value a package of three, we need only consider her bids for three items. An equilibrium in the first price auction in a particular environment will consist of a bidding function for each of the types present in the environment. The equilibrium calculations are described in Appendix A.2. The right-hand column of Figure 1 displays the equilibrium bid functions for each environment for the first price auction.

2.2.3. The Simultaneous Multiple-round Auction

The simultaneous multi-round auction (SMRA) is modelled using five price clocks (one for each item), each of which ticks upward from zero whenever two or more bidders demand (i.e. bid on) the associated item. Bidders can only decrease the number of items they bid on after the auction starts. Given bidders preferences, each bidder will either bid on her entire demand (i.e. two items for type X, three items for type Y) or on no items; in case of the latter we say the bidder is inactive or has dropped out. If only one bidder demands a particular item, its price clock is paused and this bidder is declared the provisional winner. If other bidders later demand this item, the price clock restarts and the item becomes provisionally unassigned. When demand on all items is at most one, the auction ends, items are assigned to their provisional winners and the winners pay the prices on the clocks for the items they won.

An equilibrium in the SMRA consists of a bidding function for each of the types present in the environment conditional on which types remain in the auction and at which prices others have dropped out. The equilibrium calculations are described in Appendix A.3. The left-hand column of Figure 1 displays the equilibrium bid functions for each environment for the SMRA. In environments XXX and XXY, as soon as any bidder drops out, the auctions ends. In the

XYY environment, the auction ends after a type Y bidder drops out but continues after the X type drops out. The dashed curve in the third panel in the left-hand column of Figure 1 represents the Y type's bidding function conditional on the X type staying in the auction and the other Y type dropping out at price $\hat{p}$. In the YYY environment, the auction ends only after two Y type bidders drop out. In equilibrium, one bidder is randomly chosen to abstain from the auction while the remaining bidders compete according to the bid function displayed the forth panel of the left-hand side of Figure 1.

2.3. Comparison of Auctions

Table 1 displays expected efficiency values as well as expected revenue and payoffs for the bidders for the three mechanisms in all four environments and for $\alpha = 1, \frac{3}{2}$ and 2.

2.3.1. Efficiency

Efficiency is calculated as

$$\text{efficiency}_a = \frac{V_a - V_{random}}{V_{opt} - V_{random}} \times 100\%$$

where V_a denote the total surplus generated by mechanism $a \in \{\text{SMRA, First Price}\}$, V_{opt} the total maximum surplus (generated by the VCG mechanism), and V_{random} the value of randomly assigning all the items to the bidders. This definition has the advantage that it is invariant when bidders' values are multiplied by a common number (i.e. when they are measured in cents rather than dollars) or when a common number is added to all of them. Subtracting surplus generated by randomly assigning all items helps to isolate the added value of mechanisms being studied; it reflects the fact that the relevant alternative to the auction is not the withdrawal of the items from the market but random assignment of all items.[8]

The first price auction is perfectly efficient in all but the XXY environment, where it is at least 98.6% for $\alpha \leq 2$. Meanwhile, the efficiency of the SMRA varies widely between environments, with a low of 66.7% in the YYY environment to a high of 100% in the XXX environment. Both auctions approach perfect efficiency in the XXY environment as α tends to infinity; for $\alpha \leq 2$, the first price auction is more efficient than the SMRA.

[8] In fact, radio spectrum was predominantly allocated via lottery prior to the introduction of auctions in 1994 by the FCC (Roth, 2002).

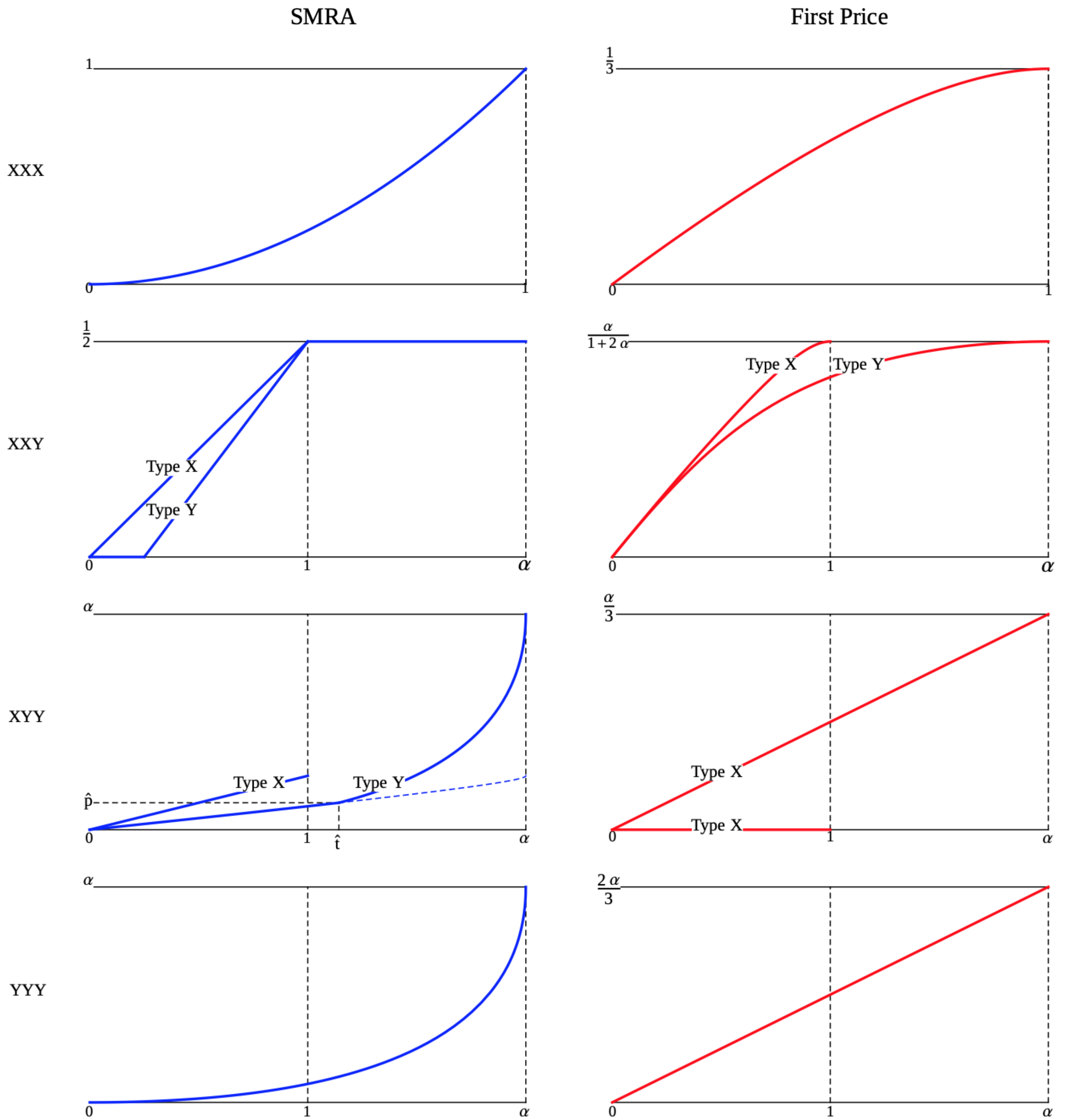

Figure 1: The left column displays the bidding functions of the first price auction by environment. The right column displays equilibrium bidding functions for the SMRA by environment. In the XYY environment, the bidding function for the Y type bidder in the SMRA is depicted when the X type bidder drops out at price $\hat{p}$. The dashed curve continues the Y type's bidding function conditional on the X type staying in the auction.

2.3.2. Seller Revenue and Bidder Profit

The seller's *revenue* is the sum of the winning bidders' payments while bidder *profit* is the difference between the value of what bidders won and the payments they made.

As with efficiency, payments in the first price auction closely track those of the VCG; in all but the XXY environment, expected seller revenue and bidders payoffs in the first price auction are equal to those in the VCG auction. In the XXY environment, the seller's expected revenue is higher in the first price auction while bidders' profits are lower; the bidders thus absorb the loss of efficiency in this environment. Since the VCG mechanism is minimally competitive (i.e. generates the lowest competitive equilibrium revenue for the seller and highest competitive equilibrium payoffs for the bidders), the first price auction can be said to be reasonably competitive in all our environments. The seller's revenue in the SMRA fluctuates around her first price/ VCG revenue between environments, being relatively low in the YYY environment and high in the XXY and XYY environments; the opposite pattern holds for bidders' profits. Thus, who bears the cost of the inefficiency in the SMRA depends on the environment; it is the seller in the YYY environment and the buyers in the XXY and XYY environments.

2.3.3. Price Discovery

The use of a multiple-round auction is often justified by appealing to its ability to discover or reveal prices; that is, the process of competitive bidding is expected to determine a set of prices for items and packages of items that are "correct", in the sense that they are close to what would prevail in a perfectly competitive environment with no uncertainty.[9] The intuition is that bidders will reduce their demands gradually over the rounds of the auction as prices rise until supply equals demand, as in the classical Walrasian *tâtonnement* process. As shown in (Milgrom, 2000), this process leads to competitive prices if bidders bid truthfully (i.e. myopically) and all items are substitutes for all bidders.

Items are complements for our bidders by design. We can see further, in Figure 1, that bidders do not bid truthfully when different types are mixed: for the same valuation, type Y bidders often bid lower than type X bidders. How good is price discovery in the SMRA in the absence of these assumptions? Figure 2 suggests that it is poor, relative to the first price

[9] Competitive equilibrium prices are prices for the items at which bidders want to purchase their efficient (i.e. value maximizing) allocation of items.

	Efficiency			**Revenue**			**Profits**		
	SMRA	First Price	VCG	SMRA	First Price	VCG	SMRA	First Price	VCG
XXX									
$\alpha = 1$	100%	100%	100%	0.500	0.500	0.500	0.750	0.750	0.750
$\alpha = \frac{3}{2}$	100%	100%	100%	0.500	0.500	0.500	0.750	0.750	0.750
$\alpha = 2$	100%	100%	100%	0.500	0.500	0.500	0.750	0.750	0.750
XXY									
$\alpha = 1$	93.8%	100%	100%	0.469	0.500	0.500	0.766	0.750	0.750
$\alpha = \frac{3}{2}$	96.6%	99.2%	100%	0.590	0.565	0.556	0.872	0.908	0.917
$\alpha = 2$	98.0%	98.6%	100%	0.651	0.607	0.583	1.050	1.103	1.125
XYY									
$\alpha = 1$	85.1%	100%	100%	0.459	0.333	0.333	0.673	0.833	0.833
$\alpha = \frac{3}{2}$	82.0%	100%	100%	0.646	0.500	0.500	0.803	1.000	1.000
$\alpha = 2$	80.5%	100%	100%	0.822	0.667	0.667	0.942	1.167	1.167
YYY									
$\alpha = 1$	66.7%	100%	100%	0.333	0.500	0.500	0.333	0.250	0.250
$\alpha = \frac{3}{2}$	66.7%	100%	100%	0.500	0.750	0.750	0.500	0.375	0.375
$\alpha = 2$	66.7%	100%	100%	0.667	1.000	1.000	0.667	0.500	0.500

Table 1: The table displays efficiency, revenue and bidder profit figures for the SMRA, first price and VCG auctions for $\alpha \in \{1, \frac{3}{2}, 2\}$.

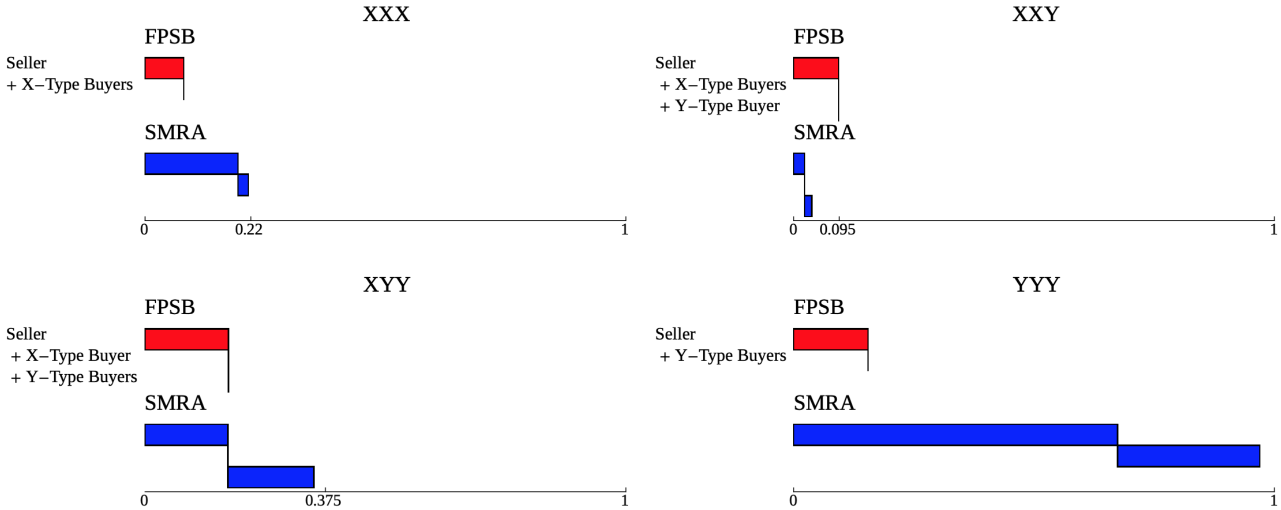

Figure 2: The figure shows the mean distance to the set of core payoffs for the first-price auction and the SMRA for each environment with $\alpha = 2$. The bar graphs are staggered over types to show the distance of each type to their core payoff.

auction. For each environment we drew 1000 valuations and calculated core payoffs for each draw. We then ran each auction and calculated the distance from the auction payoff to the set of core payoffs for each player. Figure 2 shows that mean distance over these 1000 draws, staggered over types to show the distance of each type to their set of core payoffs.

3. Experimental Design

3.1. Bidding Environment

Our design incorporates the main elements of the strategic environment of the planned Australian 900 MHz auction, in which five (paired) nationwide blocks of 2×5 MHz of spectrum will be offered for sale. The lowest of the five blocks is less valuable to bidders due to guard-band issues. We labelled the five items A through E and bidders were told that (any combination containing) item A was less valuable than (same-sized combinations containing) other blocks. As above, in the experiment three bidders compete for the five items and we consider two types of bidders: type X bidders whose per-item values peak at two items, and type Y bidders whose per-item values peak at three items. We study multiple combinations of these complementarities: two groups each with composition XXX, XXY, XYY, or YYY, for a total of eight groups. Each bidder faces a cap of three items. In the experiment, we eschew any association with

	Type X		Type Y	
# of Consecutive Items	With A	Without A	With A	Without A
1	5	10	5	10
2	10+1.5R	10+3R	10+0.5R	10+R
3	10+3.5R	10+4R	10+3R	10+5R

Table 2: Value specifications for bidders. R is an integer drawn uniformly between 25 and 35 inclusive.

radio spectrum, simply telling participants they can bid on five items that have some value to them. Each group participated in a series of 15 periods.

To generate bidder values, an integer R was drawn uniformly from between 25 and 35 (inclusive). Table 2 describes bidder values depending on draw, type, and whether item A is included. The draws differed across groups and periods, but the same draws were used across treatments (described below). Complementarities between items are realized only if items are consecutive. For example, if a bidder of type X wins items B, C and E, she earns $10 + 3R$ for B and C plus 10 for E rather than $10 + 4R$ for all three. Notice that the increase in value from winning a second item is higher for type X than for type Y. The increase in value from winning a third item is higher for type Y than for type X.

3.2. Treatments

Our main interest lies in the comparison of the SMRA mechanism with the FPSB. These were the mechanisms used in our two main treatments. A detailed description of each mechanism is as follows:

1. **First-price sealed bid auction (FPSB).** In this mechanism bidders place six bids: one for A, one for a single item other than A, one for pair of items including A, one for a pair of items not including A, one for a package of three items including A, and one for a package of three items not including A. At most one of the six bids placed by a bidder can become winning. A simple optimization algorithm finds the combination of bids that maximize revenue and the winning bidders pay their bids.

Treatment	Mechanism	Bids in 1st Stage	Bids in 2nd Stage	Bidder Information
FPSB	First price sealed bid	6: for 1, 2, and 3 items with or without item A	None	Value distributions and group types
SMRA	Simultaneous multiple-round ascending	5: for each item	None	Value distributions and group types
FPSB-2	First price sealed bid	3: for 1, 2, and 3 items	1: to not be assigned A	Value distributions and group types
SMRA-2	Simultaneous multiple-round ascending	3: for 1, 2, and 3	1: to not be assigned A	Value distributions and group types
FPSB-U	First price sealed bid	6: for 1, 2, and 3 items with or without item A	None	Own value only
SMRA-U	Simultaneous multiple-round ascending	5: for each item	None	Own value only
All treatments	3 bidders per group; 8 groups; 4 environments			

Table 3: Experimental Design. Each of the six treatments used one of the four different mechanisms: FPSB, SMRA or their two-stage variants. The third and fourth columns indicate the number of bids bidders need to submit in each stage. The final column indicates the information environment.

2. **Simultaneous multi-round auction (SMRA).** Here bidders compete directly for items A through E. A price clock is associated to each of the five items. The price in the first round is five for each item. In each round, bidders indicate whether they demand an item at the price displayed on its clock. For each round and each item, one of the bidders who demands the item is randomly designated the item's provisional winner. If more than one bidder demands an item, its price increases by 15. If only one bidder demands a particular item, its price clock is paused. If other bidders later demand this item, the price clock restarts and the item is randomly provisionally assigned to one of the new bidders. When demand on all items is one (or less), the auction ends and items are assigned to their provisional winners who pay the price displayed on their clock.

   An activity rule ensures that the auction progresses apace. The sum of items provisionally won by a bidder plus the items she is demanding is called her *activity*. Her activity *limit* in any round is her activity at the end of the previous round, or three if it is the first round. A bidder's activity cannot exceed her activity limit. Thus, for example, a bidder who fails to bid on any items in round one will be unable to bid in subsequent rounds.

The SMRA can result in fragmentation, i.e. a bidder winning non-contiguous items. Since value complementarities only apply to consecutive items, this is a potential source of inefficiency. In the FPSB this possibility is prevented by the algorithm that calculates the optimal allocation given bids. Also, the existence of separate price clocks for each item in the SMRA means that two bidders may pay very different prices for otherwise homogeneous (combinations of) items. To avoid these type of issues, practical applications of the SMRA have used a modified version of the mechanism described above, involving two stages.[10] We also run treatments using the two-stage format. For completeness we apply this modification to both the SMRA and the FPSB. The details are as follows:

3. **Two-stage FPSB (FPSB-2).** Bidders place three bids in the first stage: one for a single item, one for pair of items, and one for a package of three items. At most one of the three bids placed by a bidder can become winning. The winners pay their first-stage bids and proceed to the second-stage where they can bid for "not being assigned item A." In this stage, the lowest bidder is assigned A (by itself or as part of a package, depending on how many items the bidder won in the first stage) and does not pay the second-stage bid. The other bidder(s) pay(s) their second-stage bid(s).

4. **Two-stage SMRA (SMRA-2).** Bidders first compete for a generic item. A single price clock is associated to the item. In each round, bidders indicate whether they demand zero, one, two, or three units of the item at the current round price. If the total demand in the round plus total units provisionally assigned for items at the current round price is fewer than five, all bidders are provisionally assigned the quantity they demanded. Otherwise, provisional winners are established in the following way. First, any current provisional winners are reassigned their provisional winnings if the round price has not increased since they were assigned. Second, the bidders demanding items at the current round price are declared provisional winners of the number of goods they demanded in random order until all five units are assigned. The last bidder provisionally assigned items in this process may be assigned fewer items than she demanded. If, at the end of the round, all provisional winners were assigned their items at the current round price, the clock price increases by ten for the next round. Otherwise the round price stays the same. The auction ends after any round with zero new demand, i.e. demand not including provisional winners.

[10] See for example the UK 2.3 GHz and 3.4-3.6 GHz spectrum auction in 2018.

An activity rule ensures that the auction progresses apace. A bidder's *activity* is the maximum of the number of items she is provisionally winning and the quantity she demands. Her activity *limit* in any round is her activity at the end of the previous round, or three if it is the first round. A bidder's activity cannot exceed her activity limit. Thus, for example, if a bidder bids for three items in round one, is provisionally assigned two items, and refrains from bidding in round two, her activity limit in round three is two. Furthermore, bidders cannot demand fewer items than they are provisionally assigned.

The winners pay their first-stage bids and proceed to the second-stage where they can bid for "not being assigned item A." The lowest bidder in the second stage is assigned A and does not pay her second-stage bid. The other bidder(s) pay(s) their second-stage bid(s).

In the initial experiments bidders are provided information about others' valuations. In particular, we describe to bidders how values are generated and the distribution of draws. On the bidding screen, each bidder is shown a table with values as well as the types (X or Y), but not the values, of the two other bidders in the group. In a series of follow-up treatments, bidders know their own value but not how these values are generated. We dub these treatments **FPSB-U** and **SMRA-U**, where the U stands for *uninformed*. These follow up experiments served as stress tests for the single-stage formats, which performed much better than the two-stage experiments in the initial experiments. Except for the informational environment, they were otherwise identical to the FPSB and SMRA respectively.

In total there were six treatments. These are summarized in Table 3.

3.3. Experimental Procedures

A total of 144 subjects participated in the experiment. Subjects were recruited from University of Technology, Sydney using ORSEE (Greiner, 2015). The experiment was programmed and conducted with z-Tree (Fischbacher, 2007) and MATLAB.[11] Subjects received instructions, answered a quiz and competed in a practice period, before participating in fifteen paid auctions. The experiments lasted from a little over an hour for the FPSB to 2.5 hours for the SMRA-2. Participants were paid the earnings that accumulated over the 15 periods of the experiment if

[11]The user interface was designed and implemented in zTree. In the background, MATLAB was used to calculate allocations dynamically based on the bids.

these were positive plus a 10 AUD show-up fee. If their cumulative earnings were negative at the end of the experiment, they were only paid the 10 AUD show-up fee. The conversion rate used in the experiment was 1 Australian dollar (AUD) for every 4 experimental points. The average earnings were 39.95 AUD including a 10 AUD show-up fee.

4. Experimental Results

Figure 3 displays efficiency, seller revenue and bidder profits for all treatments by each environment, as well as pooled over all environments. The first row displays results for the one-stage FPSB and SMRA when bidders are told the types in their groups and how values are drawn. The second row displays results for the one-stage mechanisms when bidders are told only their values: FPSB-U and SMRA-U. The third row displays results for FPSB-2 and SMRA-2.

Figure 4 shares the same structure as the previous one, but gives a more detailed look at the distributions of efficiency, seller revenue and bidder profits for all mechanisms, pooled over all environments.

4.1. Comparing single-stage auctions

From the top-left panel of Figure 3 it is clear that the one-stage FPSB delivers substantially higher efficiency than the corresponding SMRA. Irrespectively of the type distribution, efficiency in FPSB comes very close to the theoretical maximum achieved by the VCG and remained on average above 90%. In SMRA it does not go above 75% under any type distribution, and even drops below 50% when types are XXY. In the other two graphs of the first row one sees that the FPSB also achieves, on average, higher seller revenue and lower bidder profits than the SMRA. This can be attributed to demand reduction on the part of bidders in the SMRA. Note however that in our experiment bidders in this mechanism frequently make losses. For example, In environment XXY, bidders' profits are negative on average. This is a consequence of the inability to protect themselves from the exposure problem. In the SMRA, bidders competing aggressively for a package of two or three items may end up winning only one. In addition, there may be fragmentation, i.e. a bidder winning non-contiguous items.

The top panels of Figure 5 illuminate the shortcomings of the SMRA: this format often leads to allocations where one or two bidders get a single unit. The bottom panel of Figure 5

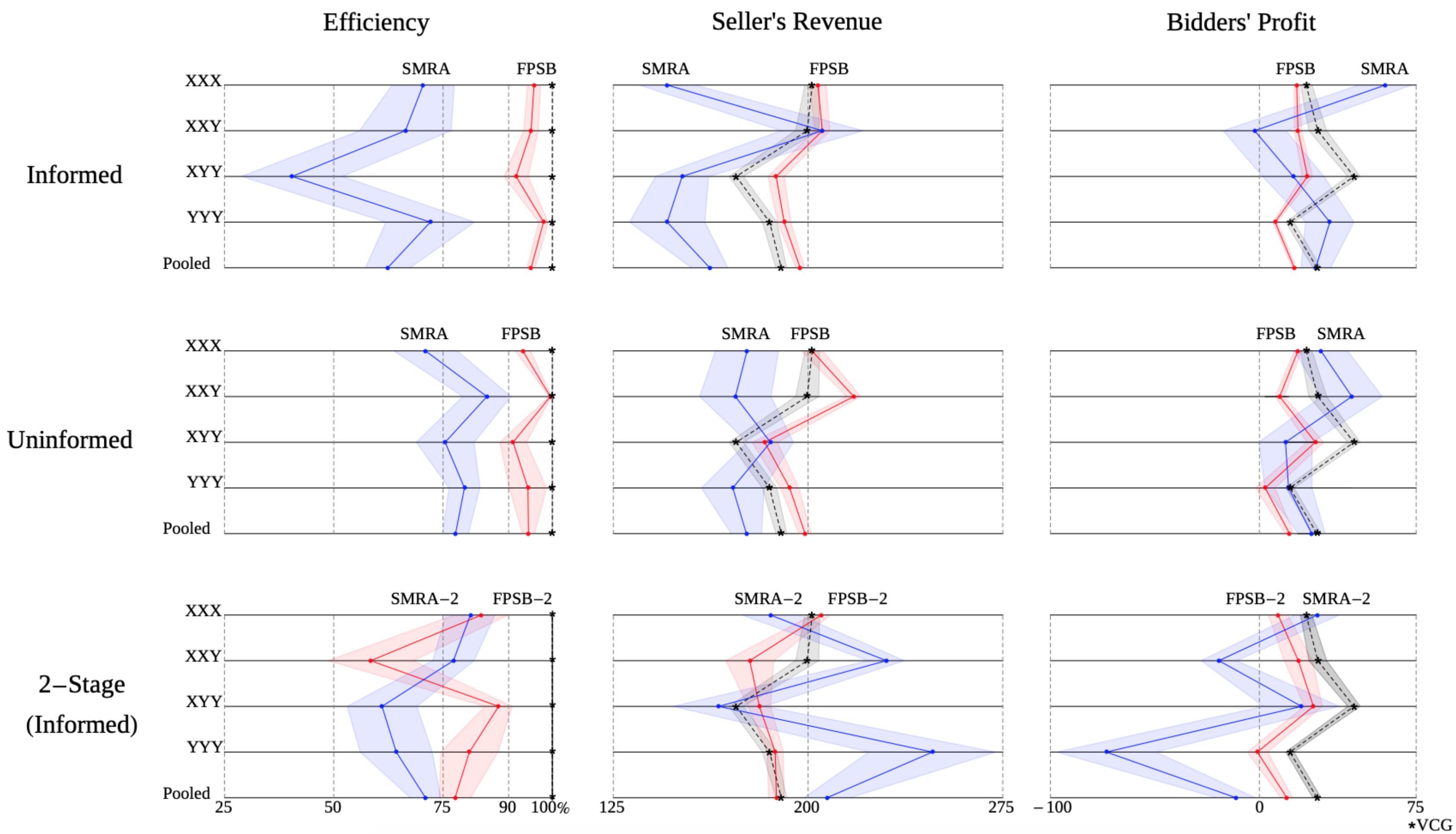

Figure 3: Summary statistics. Observations are pooled over all environments for periods 6 to 15. The first row displays results for the one-stage mechanisms when bidders are told the types in their groups and how values are drawn. The second row displays results for the one-stage mechanisms when bidders are told only their values. The third row displays results for the two-stage mechanisms when bidders are told the types in their groups and how values are drawn. All graphs include the corresponding predictions for the VCG mechanism as a benchmark.

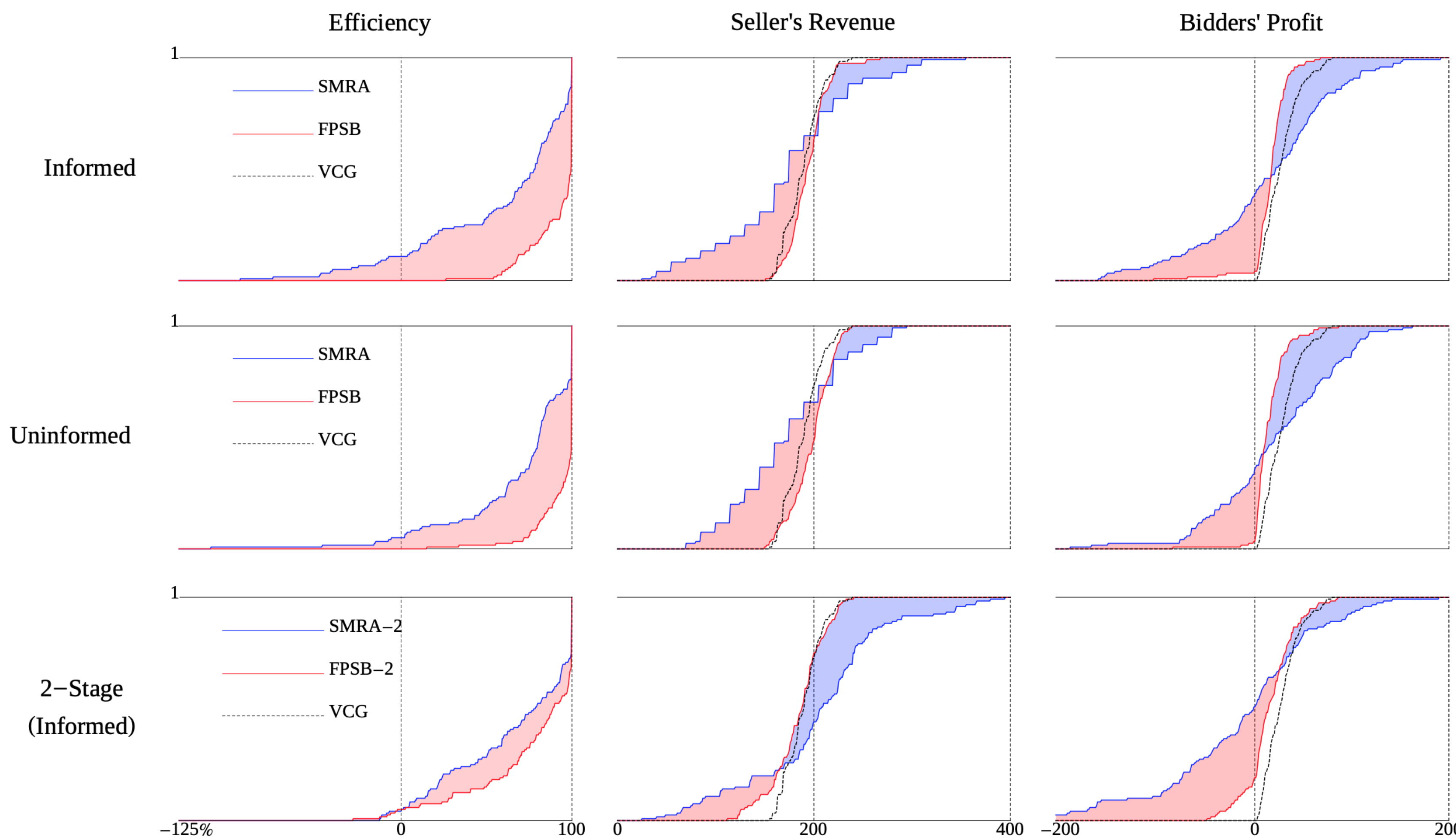

Figure 4: Cumulative distributions of key variables. Observations are pooled over all environments for periods 6 to 15. The first row displays results for the treatments where bidders are told the types in their groups and how values are drawn. The second row displays results for the treatments where bidders are told only their values. All graphs include the corresponding distributions for the VCG mechanism as a benchmark.

displays the degree to which items are sold in non-consecutive packages or remain unsold in the standard SMRA; evidently, bidders had difficulty coordinating their bids effectively to form packages of consecutive items in the single-stage SMRA.

Note that FPSB yields higher revenue on average than VCG despite its efficiency being less than VCG's 100%. Moreover, this difference in revenue is statistically significant. This comes at a cost to the bidders who make less than under VCG. Importantly, bidders' profits are always positive under FPSB. The reason is that FPSB fully protects bidders from the exposure problem: they can specify a separate bid for each of the (combination of) items they might win and by submitting bids that are less than values, never risk a loss.

Result 1 *Compared to the SMRA the FPSB is more efficient, yields more revenue and lower bidder profit. Bidders frequently incur losses in the SMRA due to exposure problems.*

Support. The result is supported by the data shown in the graphs in the top row of Figure 3. Further support is given in Figure 4, where the top row graphs display the distributions for efficiency, revenue, and bidder profits for the SMRA and FPSB. For the Wilcoxon Signed-Rank test comparing mean efficiency in FPSB and SMRA we get $p-value < 0.001$. For the same test comparing revenues in the two treatments we get $p-value < 0.001$ and for the test comparing bidder profits we get $p-value = 0.049$. ■

4.2. Comparing two-stage auctions

The two-stage SMRA is used in practice to help bidders overcome some of the problems with its single-stage counterpart. First, it avoids fragmentation, as items won are contiguous by design. It also requires bidders to focus on a specific attribute in each stage: first the number of items, then on their location. Unfortunately, it has a double exposure problem: bidders who compete aggressively for a package may end up winning only a subset (as in the single-stage SMRA) and when competing for the number of items, bidders do not know whether item A will be included or not. In fact, this second exposure problem is independent of the underlying mechanism and inherent to the two-stage process. It can therefore also affect results in the two-stage FPSB.

The bottom row of Figure 3 allows us to compare efficiency, revenue and bidder profits between FPSB-2 and SMRA-2. In both cases we observe a substantial efficiency loss, but on

Figure 5: Observed outcomes in the different mechanisms (top panel) and fragmentation in the SMRA (bottom panel).

average efficiency is higher in the FPSB-2. The comparison of revenues and bidder profits seems to indicate that SMRA-2 suffers from a larger exposure problem. Bidders make high losses that translate to high seller revenues. In FPSB-2, while bidder profits are significantly lower than the ones in the VCG theoretical benchmark, losses are not very common. In fact, seller revenues are not significantly different than what they are in the VCG benchmark.

Result 2 *Compared to the SMRA-2 the FPSB-2 is more efficient. But SMRA-2 yields higher revenue and lower bidder profit mainly because bidders incur losses due to exposure problems.*

Support. The result is supported by the data shown in the graphs in the bottom row of Figure 3. Further support is given in Figure 4, where the bottom row graphs display the distributions for efficiency, revenue, and bidder profits for the SMRA-2 and FPSB-2. For the Wilcoxon Signed-Rank test comparing mean efficiency in FPSB and SMRA we get $p - value = 0.072$. For the same test comparing revenues in the two treatments we get $p - value < 0.001$ and for the test comparing bidder profits we get $p - value = 0.024$. ■

4.3. Comparing single-stage and two-stage auctions

Looking at the top and bottom rows of Figure 3 it becomes clear that the two-stage process did not help bidders in our experiment. For the SMRA efficiency did not improve significantly moving from one stage to two. At the same time, it seems that the exposure problem intensified, leading to much higher seller revenues and losses for bidders in the two-stage mechanism compared to the one-stage SMRA. As an illustration of what is going on, consider a case where in the first stage, a type Y bidder might compete fiercely to win three items but finally give in (at high prices) and settle for two items. In the second stage, the value of what was won may depreciate further if the type Y bidder places the lowest bid. As a result, bidder losses in the two-stage SMRA are common and substantial. In terms of protecting bidders' from exposure risk, this format is least desirable. This is an important finding as regulators have started using such a two-stage format in spectrum applications. For example, Ofcom in the UK used two stages in the 2.3 GHz and 3.4-3.6 GHz auction in 2018.[12]

For the FPSB efficiency decreased. Apparently, bidders are able to deal well with the relatively high number of bids required in the one-stage FPSB (6 bids in total). Breaking down

[12] https://www.ofcom.org.uk/spectrum/spectrum-management/spectrum-awards/awards-archive/2-3-and-3-4-ghz-auction

the process in two stages does not bring additional benefits, but introduces a new exposure problem. Unlike in SMRA-2, bidders in FPSB-2 do appear to protect themselves against this problem, as their profits are not significantly different than those in FPSB. Still, seller revenues are lower.

Result 3 *The two-stage mechanisms result in lower efficiency (FPSB) or an exarcebated exposure problem (SMRA).*

Support. The result is supported by the data shown in the graphs in the top and bottom rows of Figure 3. For the Wilcoxon Signed-Rank test comparing mean efficiency in SMRA and SMRA-2 we get $p - value = 0.329$ and for mean efficiency in FPSB vs. FPSB-2 we get $p - value < 0.001$. For the same test comparing revenues in SMRA vs. SMRA-2 we get $p - value < 0.001$ and for FPSB vs. FPSB-2 we get $p - value = 0.031$. For the test comparing bidder profits in the SMRA vs. SMRA-2 we get $p - value = 0.001$ and for FPSB vs. FPSB-2 we get $p - value = 0.135$. ■

4.4. Robustness to the informational environment

In the baseline SMRA and FPSB treatments subjects knew not only their own type and valuations, but also the type of the other bidders in their group. In real applications it is not unreasonable to think that telecom companies may have some information about their competitors preferences and the degree of complementarity they face. Nevertheless, it is a valid concern that the problematic performance of the SMRA in our experiment, as stated in Result 1, may be driven by this design feature combined with the particular choice of valuation distributions used. To test the robustness of our main result with respect to the informational environment, we conducted additional treatments of the one-stage mechanisms in which bidders know their valuations but are entirely uninformed about the distribution of other bidders' valuations. These treatments are dubbed FPSB-U and SMRA-U respectively.

The second row in Figure 3 presents the results for these additional treatments. We find that the comparison between FPSB-U and SMRA-U yields very similar results as that between FPSB and SMRA. The signs of the differences remain unchanged for all three measures: efficiency, revenue and bidders' profit. In terms of magnitudes, the difference in efficiency is reduced but remains substantial: the FPSB-U is approximately 20% more efficient than the SMRA-U. There is also a reduction in the difference in revenue between the two mechanisms, but it remains significant. Bidders' profit is again higher in the SMRA, although now the difference in not statistically significant.

Result 4 *The FPSB's better performance compared to the SMRA is robust to changes in the information available to bidders about others' distribution of valuations.*

Support. The result is supported by the data shown in the graphs in the middle row of Figure 3. Further support is given in Figure 4, where the middle row graphs display the distributions for efficiency, revenue, and bidder profits for the SMRA-U and FPSB-U. For the Wilcoxon Signed-Rank test comparing mean efficiency in SMRA-U and FPSB-U we get $p - value < 0.001$. For the same test comparing revenues in SMRA-U and FPSB-U we get $p - value < 0.001$. For the test comparing bidder profits in the SMRA-U and FPSB-U we get $p - value = 0.362$. ■

Overall, the change in the information available to bidders does not seem to have any effect on the average outcomes of the FPSB mechanism. For SMRA, the only statistically significant change is the improvement in efficiency, which on average climbs at just above 75%. This difference is significant only at the 10% level.[13]. Based on this, and to facilitate the presentation of results regarding price discovery, in the analysis in the following section we pool the data for each mechanism across the two informational environments. If anything, this would work in favour of the SMRA.

5. Price Discovery

One justification for the use of auctions is that they are *price discovery* mechanisms. Through a competitive bidding process, prices for items and combinations thereof are determined. Ideally, auction prices are competitive equilibrium prices that clear the market (i.e. prices such that auction losers are happy not to be assigned any items and auction winners are happy with their assignment). Notice that in this environment, the prices for items B through E must be identical. Therefore, competitive prices consist of a set of two prices p_A and $p_{\neg A} = p_\ell$ for $\ell \in \{B, C, D, E\}$. As we will see, however, such prices do not always exist, which complicates the notion of what proper price discovery entails.

[13]The tables in appendix B provide the results of formal tests to support these statements.

	Bidder 1			Bidder 2			Bidder 3		
# items	1	2	3	1	2	3	1	2	3
including A	5	47.5	97.5	5	49	101	5	61	**129**
not including A	10	85	110	10	**88**	114	10	112	146

Table 4: Example of bidders' valuations in the *XXX* environment.

To illustrate this, consider the valuations in Table 4 that were used in one of the *XXX* groups where the numbers in bold indicate the best allocation for a total surplus of 217. For the *XXX* environment, competitive equilibrium prices do always exist. For the example in Table 4 the following prices clear the market: $p_A = 13$ and $p_{\neg A} = 42.5$. It is readily verified that at these prices it is optimal for bidder 1 to demand nothing, for bidder 2 to demand two items without A, and for bidder 3 to demand three items including A. Competitive equilibrium prices are typically not unique, e.g. $p_A = 17$ and $p_{\neg A} = 44$ also clear the market. Indeed, any combination of prices $(p_A, p_{\neg A})$ satisfying $13 \leq p_A \leq 17$ and $42.5 \leq p_{\neg A} \leq 44$ are competitive equilibrium prices.

This example might suggest that the proper definition of price discovery is for the auction to produce prices somewhere in the range of competitive equilibrium prices. But this definition is too narrow since competitive equilibrium prices do not necessarily exist in environments with complementarities (e.g. with one or more Y types). Consider, for instance, the valuations in Table 5, which were used in one of the *YYY* groups. Now the inequalities defining competitive equilibrium prices have no solution, e.g. $p_A + p_{\neg A} \leq 23$ conflicts with $3p_{\neg A} \geq 135$.

Because competitive equilibrium prices do not always exist in the presence of complementarities, attention has turned to the *core* as a proper benchmark for "reasonably" competitive outcomes.[14] The core is defined by combinations of seller and buyers' payoffs that satisfy certain stability constraints. The intuition is that auction payoffs are in the core when no coalition of bidders and/or seller can all do better than their auction payoffs. If we index the seller by $i = 0$ and the three bidders by $i = 1, 2, 3$ then the possible coalitions are the non-empty elements of

[14] See for example (Milgrom, 2004; Day & Cramton, 2012; Day & Raghavan, 2007; Day & Milgrom, 2008), each of which study mechanisms to achieve core outcomes in complete information environments. (Goeree & Lien, 2016) note that, when bidders values are private information, if the VCG outcome is not in the core, no core-selecting auction exists.

	Bidder 1			Bidder 2			Bidder 3		
# items	1	2	3	1	2	3	1	2	3
including A	5	24.5	97	5	22.5	85	5	**23**	88
not including A	10	39	**155**	10	35	135	10	36	140

Table 5: Example of bidders' valuations in the *YYY* environment.

the powerset of $\{0, 1, 2, 3\}$.[15] A vector of payoffs $\{\pi_0, \pi_1, \pi_2, \pi_3\}$ is in the core if

$$\sum_{i \in S} \pi_i \geq v(S)$$

for all $S \subseteq \{0, 1, 2, 3\}$ where π_i is the auction profit for coalition member $i \in S$, and $v(S)$ is the maximum surplus that coalition S can generate. Competitive equilibrium prices, when they exist, always produce core payoffs. But while competitive equilibrium prices may not exist, the core is always non-empty in auction applications. As such it seems the right benchmark for competitive outcomes in settings with complementarities.

Of course, simply because the core is non-empty does not mean that it is easy for a particular auction format to discover prices that lead to core payoffs. For the environments considered in our experiment, the VCG auction produces core outcomes.[16] In fact, the VCG outcome corresponds to the point in the core that assigns the lowest revenue to the seller and the highest profits to the bidders. In this format, truthful bidding is a (weakly) dominant strategy and the outcomes are fully efficient. For the example of Table 4, the bidders payoffs are $(0, 3, 31)$ and the seller's revenue is 183. Note that these payoffs correspond to the lowest competitive equilibrium prices: $p_A = 13$ and $p_{\neg A} = 42.5$.

Figure 6 shows core payoffs for each of the four environments: *XXX*, *XXY*, *XYY*, and *YYY*. To produce a two-dimensional graph, the sum of bidders' profits is shown on the horizontal axis and the seller's revenue is shown on the vertical axis. All payoffs are normalized by the maximum surplus, $v(\bar{S})$, and the negatively sloped dashed line corresponds to all possible divisions of the maximum surplus among the bidders and the seller. The subset of core constraints that dictate

[15] They are $\{0\}$, $\{1\}$, $\{2\}$, $\{3\}$, $\{0, 1\}$, $\{0, 2\}$, $\{0, 3\}$, $\{1, 2\}$, $\{1, 3\}$, $\{2, 3\}$, $\{0, 1, 2\}$, $\{0, 1, 3\}$, $\{0, 2, 3\}$, $\{1, 2, 3\}$, and the grand coalition $\bar{S} = \{0, 1, 2, 3\}$.

[16] This is not necessarily the case in the presence of complementarities. In our example of Section 2, VCG prices are often below core prices.

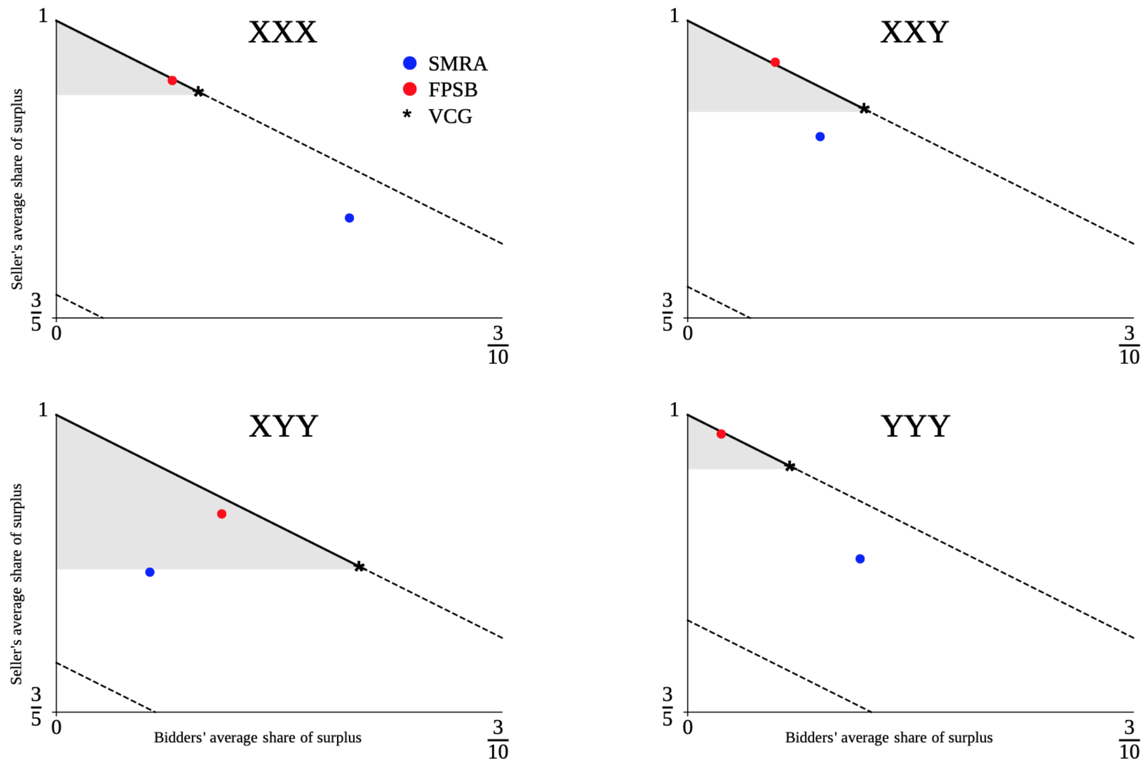

Figure 6: Each panel shows the seller's revenue (y-axis) and average buyer payoff (x-axis) normalized by total surplus and averaged over the last ten periods. The upper dashed line corresponds to efficient outcomes with the solid segment indicating core outcomes. The lower dashed lines correspond to random allocations of the items. These figures use pooled observations from both information treatments for the one-stage mechanisms.

individual rationality (i.e. $\pi_i \geq 0$ for $i = 0, 1, 2, 3$) imply that the core is part of the positive orthant. The other core constraints set a minimum revenue for the seller, here given by R^{VCG}. So in each of the four panels of Figure 6, the core corresponds to the solid segment that runs from the VCG payoff point to (0,1).

The grey triangles in each of the panels reflect alternatives to the VCG outcome that might interest a seller. These alternatives are not all fully efficient but do yield higher seller revenue than the VCG auction and generate positive profits for the bidders. As such they reflect a trade-off between efficiency and revenue that sellers typically face (e.g. in the use of reserve prices). The markers for the first price auctions are red and for the SMRA are blue.

Note that the FPSB does a remarkable job at price discovery: the red points are always close to fully efficient outcomes while providing more than VCG revenues for the seller. The SMRA formats on the other hand consistently either under perform the VCG from the seller's

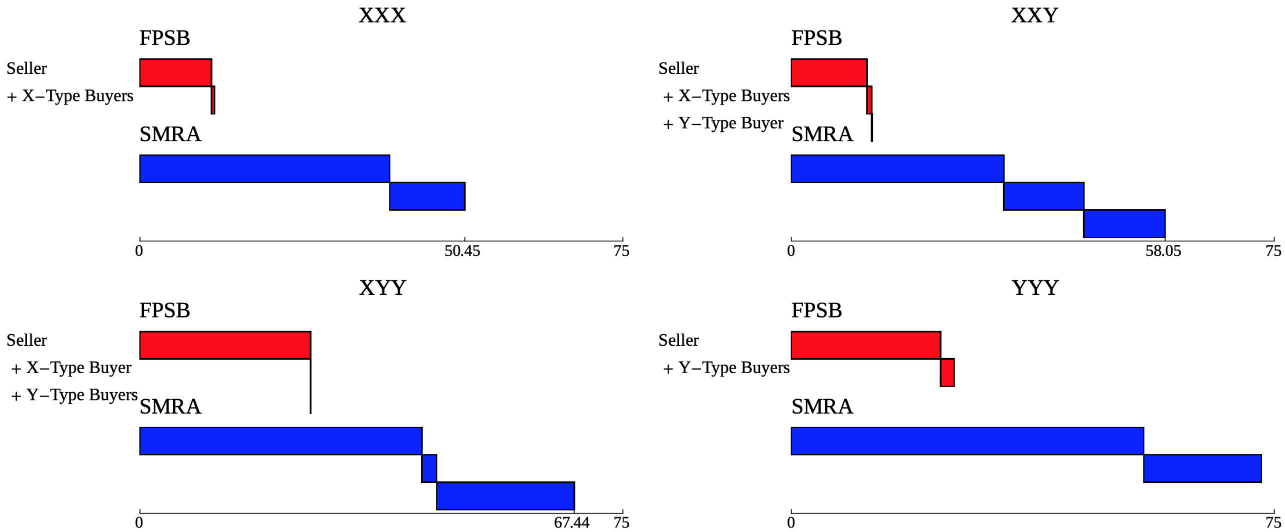

Figure 7: The figure shows the mean distance to the set of core payoffs for the (one-stage) FPSB and SMRA treatments for each environment. Data is pooled over periods 6 to 15 and over both information treatments. The bar graphs are staggered over types to show the distance of each type to their core payoff.

perspective or generate losses for the bidders (i.e. are outside the grey triangles in the figures).

Result 5 *The FPSB results in closer-to-core prices than the SMRA.*

Support. See Figure 7, which parallels the theoretical Figure 2, and demonstrates that average deviations from core prices are smaller for both X and Y type bidders as well as the seller. This is true for all environments including XXY for which the SMRA is theoretically predicted to yield closer-to-core prices. ■

6. Conclusion

It is posited that, in practice, the same forces in the SMRA that generate competitive prices for substitutable goods will at least mitigate any problems caused by complementarities as well as provide the seller with sufficiently competitive revenues (Cramton, 2006). Indeed, there have been notable spectrum auctions involving complements that appear to have performed quite well, such as the US regional narrowband auction in 1994 (Milgrom, 2000). Nevertheless, we show that the flaws in the SMRA can be significant in an important setting. Our motivation for the experimental framework is Australia's upcoming sale of blocks of spectrum in the 900 MHz band, see (Goeree & Louis, 2019). However, the environment – a small number of licenses on offer, hard limits on the number of licenses each bidder can win and a small number of bidders – is typical, with similar auctions planned or having taken place in Canada, Denmark, Italy, Austria, Switzerland, Belgium, Greece, the Netherlands and the UK (Klemperer, 2002; Earle & Sosa, 2013). Moreover, industry commentary in Australia and elsewhere has suggested that firms, depending on their current holdings, often need to acquire multiple licenses to achieve profitable scale; that is, the licenses are complements for some bidders. Our result is therefore an important evidentiary critique of the SMRA in an important setting.

Theoretical analysis shows that bidders in the SMRA are highly susceptible to the exposure problem. For a bidder whose per-item value increases in the number of items she wins, bidding up to her value for two items, for example, exposes her to the risk of having to pay a large amount for a single item that she places little value on. In equilibrium, bidders reduce their demands too early in the auction resulting in low prices and low efficiency (Goeree & Lien, 2014). The experimental results reported in this paper confirm these theoretical predictions. Price discovery in the SMRA is poor, see Figures 6 and 7, and efficiency and revenue are low, see Figure 3. This poor performance cannot be attributed to using the "wrong" subject pool since it aligns with equilibrium predictions, e.g. compare Figures 2 and 7.

The FPSB protects bidders from the exposure problem as it lets them place bids for every possible package they may win (six bids in total). As a result, efficiency is high, revenue is high, bidders make no losses and payoffs are virtually always in the core. Based on our findings, the Australian Communications and Media Authority (ACMA) is considering replacing the SMRA in favor of the FPSB for the sales of 900 MHz spectrum. More generally, with relatively few items for sale, complementarities, and binding caps, the FPSB seems the preferable choice.

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A. Bayes Nash Equilibrium Calculations

A.1. The Vickrey-Clark-Groves Mechanism

For $S \subseteq \{0,1,2,3\}$, let $v(S)$ indicate the maximum surplus that the coalition of players S can generate (where the seller is player 0). Then VCG profits for bidders $i = 1,2,3$ are

$$\pi_i^{\text{VCG}} \;=\; v(\bar{S}) - v(\bar{S}\setminus\{i\}) \tag{1}$$

where $\bar{S} = \{0,1,2,3\}$ is the grand coalition and $\bar{S}\setminus\{i\}$ is the grand coalition without bidder i. Given these payoffs, it is a dominant strategy for the bidders (of any type) to report their valuations truthfully to the seller. The seller's revenue in the VCG auction is

$$R^{\text{VCG}} \;=\; V_{opt} - \sum_{i=1}^{3} \pi_i^{\text{VCG}}.$$

A.2. The First Price Auction

Since the X-type bidders only value a pair of item, we need only consider their bids for two items; denote the equilibrium bid function for X-type bidder $b : [0,1] \to \mathbb{R}_+$ and let $\phi(b) = b^{-1}(b)$ be its inverse for $b \in [0,\bar{b}]$ with the upper bound $\bar{b}$ to be determined. Since the the Y-type bidders only value a package of three items, we need only consider her bids for three items; denote equilibrium bid function for type Y $B : [0,\alpha] \to \mathbb{R}_+$ for valuation and let $\Phi(b) = B^{-1}(b)$ be its inverse on $b \in [0,\bar{b}]$. As will be confirmed below for each environment, assume for now that the bidding functions are strictly increasing and their inverse functions are therefore well defined.

A.2.1. XXX Environment

Exactly two bidders will be awarded their desired packages in the auction. Therefore, each bidder wins if and only if she bids higher than the lowest of her two rivals. Supposing her rivals play according to their equilibrium strategies, let $\pi_X(b,w)$ denote the expected payoff of a bidder with valuation w when she bids b. Payoffs are

$$\pi_X(b,w) \;=\; (w-b)\big(1-(1-\phi(b))^2\big)$$

Equilibrium requires that $\frac{\partial}{\partial b}\pi_X(b,w) = 0$ when evaluated at the equilibrium strategies. This gives us the differential equation:

$$-\big(1-(1-\phi(b))^2\big) + 2\big(1-\phi(b)\big)\phi'(b) \;=\; -(2-w)w - 2(1-w)\big(b(w)-w\big)/b'(w) \;=\; 0$$

together with terminal condition $b(1) = \bar{b}$. This has the solution $b(w) = \frac{w(3-2w)}{3(2-w)}$.

A.2.2. XXY Environment

Exactly two bidders will be awarded their desired packages in the auction. Therefore, each bidder wins if and only if she bids higher than the lowest of her two rivals. Supposing her rivals play according to their equilibrium strategies, let $\pi_i(b,w)$ denote the expected payoff of the type i bidder with valuation w when she bids b. Payoffs are

$$\begin{aligned} \pi_X(b,w) &= (w-b)(1-(1-\phi(b))(1-\Phi(b)/\alpha) \\ \pi_Y(b,W) &= (W-b)(1-(1-\phi(b))^2) \end{aligned}$$

Equilibrium requires that $\frac{\partial}{\partial b}\pi_i(b,w) = 0$ when evaluated at the equilibrium strategies. This gives us two differential equations to satisfy:

$$\big(1-\phi(b)\big)\Big(1-\frac{\Phi(b)}{\alpha}\Big) - \big(1-\phi(b)\big)\left(\Big(1-\frac{\Phi(b)}{\alpha}\Big)\phi'(b) + \big(1-\phi(b)\big)\frac{\Phi'(b)}{\alpha}\right) - 1 = 0 \tag{2}$$

$$\big(1-\phi(b)\big)^2 + 2\big(1-\phi(b)\big)\big(\Phi(b)-b\big)\phi'(b) - 1 = 0 \tag{3}$$

together with the terminal conditions $\phi(\bar{b}) = 1$ and $\Phi(\bar{b}) = \alpha$. We can solve equations (2) and (3) for $\Phi(b)$ as a function of $\phi(b)$ and b only:

$$\Phi(b) = \frac{\phi(b)\big((\alpha+b)\phi(b) - 2b(1+\alpha)\big)}{2\big(1-\phi(b)\big)\big(\phi(b)-b\big)} \tag{4}$$

We need $\Phi(\bar{b}) = \alpha$; then (4) implies $\bar{b} = \frac{\alpha}{2+2\alpha}$. Substituting this back into (2) or (3), we arrive at a single differential equation

$$\phi'(b) = \frac{\big(\phi(b)-b\big)\big(2-\phi(b)\big)\phi(b)}{\big(\alpha-b\big)\big(\phi(b)^2+2b\phi(b)\big) - 2b^2}. \tag{5}$$

Unfortunately, (5) does not admit a (clean) analytical solution but its numeric solution is simple to generate.

A.2.3. XYY Environment

For any set of bids, the seller will allocate two items to the X type bidder and three items to the highest Y type bidder. Therefore, $b(w) \equiv 0$ and a Y type bidder wins only if she out bids the other Y type bidder. Supposing her rivals play according to their equilibrium strategies, let $\pi_Y(b,W)$ denote the expected payoff of the type Y bidder with valuation W when she bids b. Payoffs are

$$\pi_Y(b,W) = (W-b)\Phi(b)$$

Equilibrium requires that $\frac{\partial}{\partial b}\pi_Y(b,w) = 0$ whenever $b > 0$ evaluated at the equilibrium strategies. This gives us the differential equation

$$-\Phi(b) + (W-b)\Phi'(b) = -W + (W - B(W))/B'(W) = 0 \tag{6}$$

together with the terminal conditions $B(\alpha) = \bar{b}$. This has solution $B(W) = \frac{W}{2}$.

A.2.4. YYY Environment

The seller will allocated three items to the bidder submitting the highest bid. Therefore, a type Y bidder wins if she out bits both of her rivals. Supposing her rivals play according to their equilibrium strategies, let $\pi_Y(b, W)$ denote the expected payoff of the type Y bidder with valuation W when she bids b. Payoffs are

$$\pi_Y(b, W) = (W - b)\frac{\Phi(b)^2}{\alpha^2}$$

Equilibrium requires that $\frac{\partial}{\partial b}\pi_Y(b, w) = 0$ whenever $b > 0$ when evaluated at the equilibrium strategies. After multiplying by $\frac{\alpha^2}{W}$, this gives us the differential equation

$$-\Phi(b)^2 + 2(W - b)\Phi(b)\Phi'(b) = -W + 2\big(W - B(W)\big)/B'(W) = 0 \tag{7}$$

together with the terminal conditions $B(\alpha) = \bar{b}$. This has solution $B(W) = \frac{2W}{3}$.

A.3. The Simultaneous Multiple-round Auction

Since the items within a package are substitutes for the bidders and they can freely switch demand between items throughout the auction, the price clocks will always display the same price. A bid function specifies the price level at which the bidder drops out of the auction; it will depend on the number and types of bidders still bidding in the auction. Beliefs are updated via Bayes rule and according to the equilibrium bid functions when a bidder observes a rival drop out of an auction.

A.3.1. XXX environment

Once any bidder stops bidding the auction ends; therefore, bidding functions depend only on the price level and the bidder's draw. A bidder wins if she outbids the lowest bid of her rivals.

Let $b : [0, 1] \to \mathbb{R}_+$ denote a bidder's equilibrium bidding function and let $\phi(b) = b^{-1}(b)$ be its inverse for $b \in [0, \bar{b}]$ with the upper bound $\bar{b}$ to be determined. Supposing her rivals play according to their equilibrium strategies, let $\pi_X(b, w)$ denote her expected payoff when she bids b and her draw is $w \in [0, 1]$. Equilibrium payoffs are

$$\hat{\pi}_X(b, w) = 2\int_0^{\phi(b)}\int_y^1 \Big(W - 2b(y)\Big)dzdy - b(1 - \phi(b))^2. \tag{8}$$

The last term arises when the bidder drops out first at $p = b$ and is forced to purchase one good. Equilibrium requires that $\frac{\partial}{\partial b}\hat{\pi}_X(b, w) = 0$ whenever $b > 0$ when evaluated at the equilibrium strategies. This gives us the differential equation

$$2\phi'(b)(1 - \phi(b))\big(w - 2b\big) - (1 - \phi(b))^2 + 2b(1 - \phi(b)) = \frac{(1 - w)}{b'(w)}(2(w - b(w)) - b'(w)(1 - w)) = 0$$

together with the terminal conditions $b(0) = 0$. This gives $b(w) = w^2$.

A.3.2. XXY environment

Once any bidder stops bidding the auction ends; therefore, bidding functions depend only on the price level and the bidder's draw.

For a type X bidder with draw w, it is a dominant strategy to bid on two items if $p \leq \frac{w}{2}$

and otherwise to stop bidding on any items.[17]

Let B denote the Y type's equilibrium bidding function and let $\pi_Y(b,w)$ denote her expected payoff when she bids B and her draw is $w \in [0,\alpha]$. Given the X-types' strategy

$$\hat{\pi}_Y(b,W) = 2\int_0^{2b}\int_w^1 \Big(W - 3\frac{w}{2}\Big)dzdw - b(1-2b)^2. \tag{9}$$

The last term arises when the Y type drops out at $p = b$ and is forced to purchase one item. Equilibrium requires that $\frac{\partial}{\partial b}\hat{\pi}_Y(b,w) = 0$ when evaluated at $b = B(W)$ whenever $B(W) > 0$ and $\frac{\partial}{\partial b}\pi_Y(b,w) \leq 0$ when evaluated at $b = B(W)$ whenever $B(W) = 0$. Since

$$\frac{\partial}{\partial b}\pi_Y\big(B(W),W\big) = \Big(4\big(W-2B(W)\big)-\big(1-2B(W)\big)\Big)\big(1-2B(W)\big) = \big(4W-1-6B(W)\big)\big(1-2B(W)\big) \geq 0$$

if and only if $W \geq \frac{1}{2}$, we have

$$B(W) = \begin{cases} 0 & \text{if } 0 \leq W < \frac{1}{4} \\ \frac{1}{3}\big(2W - \frac{1}{2}\big) & \text{if } \frac{1}{4} \leq W \leq \frac{3}{4} \\ 1 & \text{if } \frac{3}{4} \leq W \leq \alpha \end{cases}.$$

The second panel of the left hand side of Figure 1 plots this bid function and the type X bid function.

A.3.3. XYY environment

For a type X bidder with draw w, it is a dominant strategy to bid on two items if $p \leq \frac{w}{2}$ and otherwise to stop bidding on any items.

The auction ends only after a Y type drops out; therefore, a bidding functions for the Y type bidder will one her draw, the price level, and who remains in the auction – i.e. whether or not the X type bidder had dropped out. A Y can win if the type X bidder drops out *then* the rival type Y bidder drops out, or if the rival type Y bidder drops out while the type X type is still actively bidding.

Proceeding by backward induction, let $B^Y(W,p)$ denote the price level in equilibrium at which they type Y bidder drops out when her draw is W and the X type bidder has dropped out at the price level p and define $\Phi^Y(b,p)$ such that $B^Y(\Phi^Y(b,p),p) = b$. Supposing her rivals play according to their equilibrium strategies, let $\pi_Y^Y(b,W)$ denote a Y type bidder's expected payoff when she bids drops out at price level b and her draw is $W \in [0,\alpha]$. Equilibrium payoffs are

$$\pi_Y^Y(b,p,W) = \int_0^{\Phi^Y(b,p)} \Big(W - 3B^Y(V,p)\Big)\frac{dV}{\alpha} - 2b\Big(1 - \frac{\Phi(b,p)}{\alpha}\Big) \tag{10}$$

The last term arises when the bidder drops out at $p = b$ and is forced to purchase two items. Equilibrium requires that $\frac{\partial}{\partial b}\pi_Y(b,p,W) = 0$ whenever $b > 0$ when evaluated at the equilibrium strategies. This gives us the differential equation

$$\frac{\partial\Phi^Y(b,p)}{\partial b}(W-3b) - 2\Big(1-\frac{\Phi(b,p)}{\alpha}\Big) + \frac{2b}{\alpha}\frac{\partial\Phi^Y(b,p)}{\partial b} = \frac{1}{\frac{\partial B^Y(W,p)}{\partial W}}\Big(W - B^Y(W,p)\Big) - 2\Big(1-\frac{W}{\alpha}\Big)$$

[17] The auction for a type X bidder is mathematically identical to a second price sealed bid auction; a type X bidder's dominant strategy is to bid her valuation.

together with the terminal conditions $B(\alpha) = \bar{b}$. This gives

$$B^Y(W,p) = W - 2\sqrt{\alpha - W}\Big(\sqrt{\alpha - p} - \sqrt{\alpha - W}\Big).$$

Expected equilibrium profits for at Y type bidder with a draw of W in this stage – i.e. supposing that the X type bidder dropped out at p – are

$$\pi_Y^Y(p,W) = \pi_Y^Y(B^Y(W,p),p,W) = \frac{(W-p)^2}{2(\alpha - p)} - 2p$$

Let $B^{XY}(W)$ denote the price level in equilibrium at which they type Y bidder drops out when her draw is W and neither rival has dropped out and define $\Phi^{XY}(b)$ such that $B^Y(\Phi^{XY}(b)) = b$. Supposing her rivals play according to their equilibrium strategies, let $\pi_Y^{XY}(b,w)$ denote a Y type bidder's expected payoff when she bids drops out at price level b, neither rival has dropped out and her draw is $W \in [0,\alpha]$. Payoffs are

$$\pi_Y^Y(b,p,W) = \int_0^{\Phi^Y(b)} \int_{2b}^1 \Big(W - 3B^{XY}(V)\Big)dy\frac{dV}{\alpha} - \int_{\Phi^Y(b,\frac{v}{2})}^{\alpha} \int_{2b}^1 \pi_Y^Y\Big(\Phi^{XY}(b,\frac{y}{2}),\frac{y}{2},W\Big)dv\frac{dV}{\alpha} \tag{11}$$

Equilibrium requires that $\frac{\partial}{\partial b}\pi_Y^{XY}(b,p,W) = 0$ whenever $b > 0$ when evaluated at the equilibrium strategies. After some manipulation, this gives us the differential equation

$$\big(W - 3B^{XY}(W)\big)\big(1 - 2B^{XY}(W)\big) - 4\frac{\partial B^{XY}(W)}{\partial W}B^{XY}(W)\big(\alpha - W\big) = 0$$

together with the terminal conditions $B(\alpha) = \bar{b}$. This equation has no simple analytical solution. Its numeric solution is display in the fourth panel of the left-hand side of Figure 1 for the case where the X type bidder drops out at price $\hat{p}$.

A.3.4. YYY environment

The auction ends only after two Y types drop out; therefore, a bidding functions for a Y type bidder will depend both on her draw, and how many bidders remains in the auction.

Proceeding by backward induction, let $B^Y(W)$ denote the price level in equilibrium at which they type Y bidder drops out when her draw is W and only one Y type bidder remains active in the auction. Define $\Phi^Y(b)$ such that $B^Y(\Phi^Y(b)) = b$. This is strategically identical to the stage in the XYY environment after the X type has dropped out. Therefore, as derived above,

$$B^Y(W,p) = W - 2\sqrt{\alpha - W}\Big(\sqrt{\alpha - p} - \sqrt{\alpha - W}\Big).$$

and expected equilibrium profits for a Y type bidder with a draw of W in this stage – i.e. supposing that first bidder dropped out at price p – are

$$\pi_Y^Y(p,W) = \pi_Y^Y(B^Y(W),p,W) = \frac{(W-p)^2}{2(\alpha - p)} - 2p$$

Let $B^{YY}(W,p)$ denote the price level in equilibrium at which the type Y bidder drops out when her draw is W and neither rival has dropped out and define $\Phi^{YY}(b)$ such that $B^{YY}(\Phi^{YY}(b)) = b$. Supposing her rivals play according to their equilibrium strategies, let $\pi_Y^{XY}(b, W)$ denote a Y type bidder's expected payoff when she bids drops out at price level b, neither rival has dropped out and her draw is $W \in [0, \alpha]$. Payoffs are

$$\pi_Y^Y(b, p, W) = \int_0^{\Phi^Y(b,p)} \int_V^W \pi_Y^Y(B^{YY}(V), W) \frac{dZ}{\alpha} \frac{dV}{\alpha} \tag{12}$$

Equilibrium requires that $\frac{\partial}{\partial b} \pi_Y^{YY}(b, p, W) = 0$ whenever $b > 0$ when evaluated at the equilibrium strategies. After some manipulation, this gives us the equation

$$-2(\alpha - W)B(W) = 0.$$

But this is negative whenever $B(W) > 0$. Thus, there is no symmetric equilibrium (in pure strategies) wherein all three Y type bidders bid above zero in the auction. Instead, we assume one bidder randomly drops out at any price $p \geq 0$. The remaining two bidders play the equilibrium strategy $B^Y(W, p)$ defined above.

B. Statistical test results

	FPSB	FPSB-2	FPSB-4U	SMRA	SMRA-2	SMRA-U	VCG
FPSB-2	0.0002	1	-	-	-	-	-
FPSB-U	0.5509	0.0001	1	-	-	-	-
SMRA	0	0.0059	0	1	-	-	-
SMRA-2	0	0.0924	0	0.3287	1	-	-
SMRA-U	0	0.3440	0	0.0667	0.2480	1	-
VCG	0	0	0	0	0	0	1

Table 6: p-values for the Wilcoxon Signed-Rank test where H_0: mean efficiency$_i$ = mean efficiency$_j$ for $i, j \in$ {FPSB, FPSB-2, FPSB-U SMRA, SMRA-2, SMRA-U, VCG}.

	FPSB	FPSB-2	FPSB-U	SMRA	SMRA-2	SMRA-U	VCG
FPSB-2	0.0313	1	-	-	-	-	-
FPSB-U	0.3639	0.0100	1	-	-	-	-
SMRA	0	0.0002	0	1	-	-	-
SMRA-2	0.0077	0.0008	0.0373	0	1	-	-
SMRA-U	0.0025	0.0620	0.0008	0.1786	0.0010	1	-
VCG	0.0105	0.9619	0.0038	0	0.0003	0.0373	1

Table 7: p-values for the Wilcoxon Signed-Rank test where H_0: mean revenue$_i$ = mean revenue$_j$ for $i, j \in$ {FPSB, FPSB-2, FPSB-U, SMRA, SMRA-2, SMRA-U, VCG}.

	FPSB	FPSB-2	FPSB-U	SMRA	SMRA-2	SMRA-U	VCG
FPSB-2	0.1354	1	-	-	-	-	-
FPSB-U	0.1006	0.6972	1	-	-	-	-
SMRA	0.0493	0.0196	0.0381	1	-	-	-
SMRA-2	0.0014	0.0241	0.0071	0.0011	1	-	-
SMRA-U	0.5211	0.2350	0.3622	0.6352	0.0065	1	-
VCG	0.0001	0	0	0.7432	0	0.4206	1

Table 8: p-values for the Wilcoxon Signed-Rank test where H_0: mean earnings$_i$ = mean earnings$_j$ for $i, j \in$ {FPSB, FPSB-2, FPSB-U, SMRA, SMRA-2, SMRA-U, VCG}.

C. Instructions for SMRA

Welcome to the UTS Behavioural Laboratory

Welcome and thank you for participating in today's experiment.

Place all of your personal belongings away, so we can have your complete attention. In particular, please turn off your phone and put it away.

Please sit at the computer you have been assigned to and log on using your usual UTS username and password. Click once on the grey screen and await further instructions.

The Experiment

The experiment you will be participating in today will involve a series of auctions. At the end of the experiment you will be paid in cash for your participation. Each of you may earn different amounts. The amount you earn depends on your decisions, chance, and on the decisions of others.

You will be using the computer for the entire experiment, and all interaction between you and others will be through computer terminals. Please DO NOT socialize or talk during the experiment.

If you have any questions, raise your hand and your question will be answered so everyone can hear.

The Auction

The experiment consists of a series of **15 periods.** In each period, there will be an auction.

In the auction, you will be in a group of **3 bidders** (you and 2 other bidders). You will remain in the same group for all 15 periods.

In each auction, there will be **5 items** for sale, labeled A through E.

A B C D E

Each bidder can win a **maximum of 3 items.**

We will explain the details of the auction later. We first explain the items' values to you.

Bidder Values

Each bidder has values for winning a single item, two items or three items. These values depend on the following:

- Your type: **X** or **Y.** Your type will remain the same throughout the experiment.
- Whether item A is among the items you won. Item A has a lower value than the other items.
- Whether winning items are consecutive, e.g. AB or CDE (but not AC or ACE). The value for winning consecutive items is higher than the sum of individual item values.
- A random number **R** between 25 and 35, with all numbers in this range being equally likely. In each period, each bidder will get their own random number, so the random number will likely differ from bidder to bidder. Also, each bidder will get a new draw when a new period starts, so your random number will likely differ from period to period.

Bidder Values

The value of winning **consecutive** items, e.g. AB or CDE (but not AC or ACE), is higher than the sum of individual item values.

For type X:

# of items	Value **WITH** item A	Value **WITHOUT** item A
1 item	5	10
2 **consecutive** items	10 + 1.5 **R**	10 + 3 **R**
3 **consecutive** items	10 + 3.5 **R**	10 + 4 **R**

For type Y:

# of items	Value **WITH** item A	Value **WITHOUT** item A
1 item	5	10
2 **consecutive** items	10 + 0.5 **R**	10 + **R**
3 **consecutive** items	10 + 3 **R**	10 + 5 **R**

Bidder Values

Example: **If R = 30, the tables become**

Type X:

# of items	Value **WITH** item A	Value **WITHOUT** item A
1 item	5	10
2 **consecutive** items	55	100
3 **consecutive** items	115	130

Type Y:

# of items	Value **WITH** item A	Value **WITHOUT** item A
1 item	5	10
2 **consecutive** items	25	40
3 **consecutive** items	100	160

Bidder Values

Note that:

- The increase in value from winning a 2nd item is higher for type **X** than for type **Y**.
- The increase in value from winning a 3rd item is higher for type **Y** than for type **X**.

In each period, you will be shown a table with your values like the one shown before. You will not be shown the R you draw.

You will know your type and the type of the other bidders in your group.

You will not know the exact values of the other bidders.

Bidding

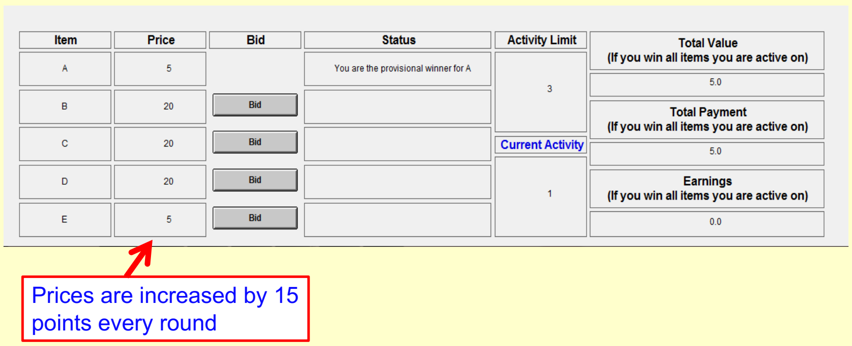
Each auction proceeds in a series of rounds. In each round of the auction, you will see a **price for each item**.

You can then **bid for the items** you want at the given prices by clicking a button.

After submitting your bids, the computer assigns a **provisional winner** for each item, chosen randomly among the bidders that bid for it. If the auction ends, provisional winners become actual winners for the items.

In the next round you are informed about the items for which you are the provisional winner, **prices are increased by 15 points** and you can place bids for the other items.

Bidding



Activity

Your **activity** is the number of items you are provisionally winning plus the number of other items you bid for.

Your activity cannot exceed your **activity limit.** Your initial activity limit is **3**.

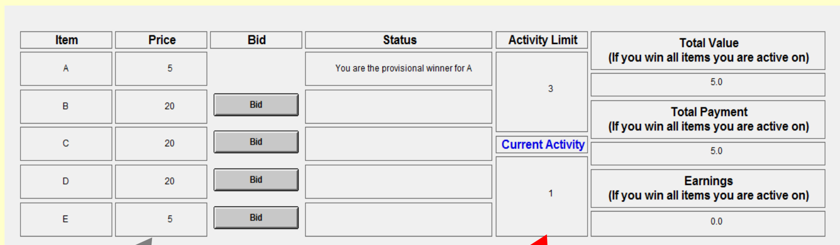
In each round, your activity limit is reset to your previous round activity. Therefore, if you do not use all your available activity in a given round, your activity limit is reduced in the next round.

<u>Example 1:</u> Suppose your **activity limit is 3** and you are the provisional winner on 1 item. So you have 2 units of spare activity.

- If you bid on 2 more items, your next-round activity limit will again be 3
- If you bid on 1 more item, your next-round activity limit will decrease to 2
- If you do not place any bid, your next-round activity limit will decrease to 1

<u>Example 2:</u> Suppose your **activity limit is 1** and you are the provisional winner on 1 item. In this case, you have no spare activity and cannot place bids on additional items.

Bidding



Prices are increased by 15 points every round

If you do not use all your available activity in a given round, your activity limit is reduced in the next round.

Auction end and payments

Depending on the bids submitted in the group, each auction will proceed in multiple rounds. The auction ends if no bidder places a new bid, or if no bidder has any spare activity left to bid (i.e. if all bidders are provisional winners for as many items as their activity limits)

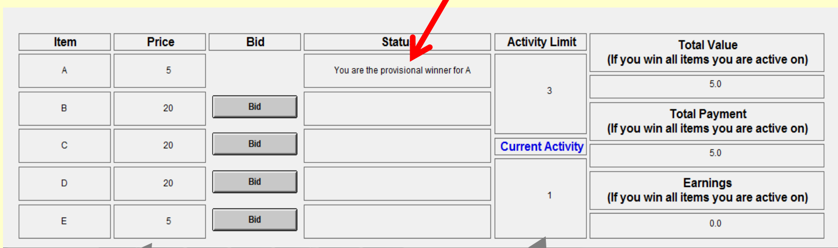
When the auction ends, you will be informed about the items you win.

Your payment will equal the sum of the prices at which you won each item.

Your activity limit will be reset to 3 when a new auction starts.

Bidding

Provisional winner ≠ Final winner



Prices are increased by 15 points every round

If you do not use all your available activity in a given round, your activity limit is reduced in the next round.

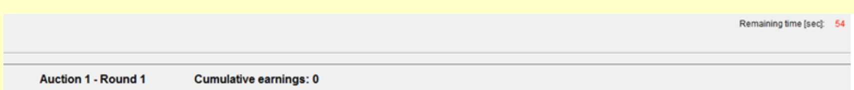
Rounds and Timer

Each auction consists of **multiple rounds. Round 1** will last for **at most 60 seconds**. Any further round will last for **at most 30 seconds**.

If you don't need the full 30 or 60 seconds then you can speed up the auction: select the items you want to bid for and click "**Done**". If you do not use this option the software will automatically move to the next round after 30 or 60 seconds with whatever items you have selected at that point. **Your next-round activity limit will be reduced** if you did not use all available activity.

If you don't have spare activity left and cannot bid on new items then you will automatically be moved on to the next stage after **10 seconds**.

On the decision screen, you will see the timer counting down (top right corner) as well as the auction, round and the cumulative earnings.



Earnings

Your earnings from each auction equal the value of the items you win minus your payment.

Your Earnings = Your Value – Your Payment

NOTE: if your Total Payment exceeds your Value for the items you won then your earnings will be negative and will be subtracted from your cumulative earnings so far. If you finish the experiment with negative earnings you will only be paid the show-up fee.

Results

Item	Final Price	Winner
A	35	Bidder 1
B	35	**You**
C	5	Bidder 3
D	0	
E	0	

Total Value	Auction Earnings
10.0	-25.0
Total Payment	**Cumulative Earnings**
35.0	-25.0

OK

Final Prices

Final Winner

Earnings are negative when total payment exceeds total value

Summary

The experiment consists of a series of **15 auctions** preceded by 1 **practice auction** that does not affect earnings.

You will be either a **type X** or a **type Y** bidder. Your type will remain the same throughout the experiment. Your type and that of others in your group will be shown on your screen.

In each auction, each bidder receives a **new** random number **R** that determines the values for winning 1, 2, or 3 items.

The value of winning **consecutive** items is **higher** than the sum of individual item values.

Each auction consists of multiple rounds:

- Your activity (items you are provisional winner for and items you bid for) cannot exceed your activity limit.
- Your current activity will be your next round's activity limit.
- Prices increase by **15** every round.

Your earnings are equal to the value of the items you win minus your payment.

Concluding Remarks

The exchange rate used in the experiment is **1 dollar for every 4 points**.

You also receive a **$10 participation fee**.

You will be paid at the end of the experiment the total amount you have earned in all of the periods. You need not tell any other participant how much you earned.

Welcome to the UTS Behavioural Laboratory

Welcome and thank you for participating in today's experiment.

Place all of your personal belongings away, so we can have your complete attention. In particular, please turn off your phone and put it away.

Please sit at the computer you have been assigned to and log on using your usual UTS username and password. Click once on the grey screen and await further instructions.

The Experiment

The experiment you will be participating in today will involve a series of auctions. At the end of the experiment you will be paid in cash for your participation. Each of you may earn different amounts. The amount you earn depends on your decisions, chance, and on the decisions of others.

You will be using the computer for the entire experiment, and all interaction between you and others will be through computer terminals. Please DO NOT socialize or talk during the experiment.

If you have any questions, raise your hand and your question will be answered so everyone can hear.

The Auction

The experiment consists of a series of **15 periods.** In each period, there will be an auction.

In the auction, you will be in a group of **3 bidders** (you and 2 other bidders). You will remain in the same group for all 15 periods.

In each auction, there will be **5 items** for sale, labeled A through E.

Each bidder can win a **maximum of 3 items.**

We will explain the details of the auction later. We first explain the items' values to you.

Bidder Values

Each bidder has values for winning a single item, two items or three items. These values depend on the following:

- Whether item A is among the items you won. Item A has a lower value than the other items.
- In each period, each bidder will get their own values, and the values will likely differ from bidder to bidder. Also, each bidder will get new values when a new period starts, so your values will likely differ from period to period.

Bidder Values

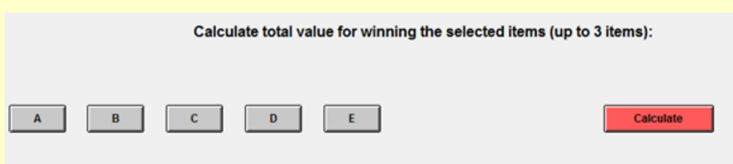
In each period, you will be shown a table with your values like the one shown below. The numbers used in the experiment will be quite different from the ones below, which are shown for illustrative purposes only.

You will not know the values of the other bidders.

# of items	Value **WITH** item A	Value **WITHOUT** item A
1 item	1	2
2 items	4	7
3 items	8	9

Example of values

A calculator is available on your screen to calculate the value of any possible combination of items you can win.



Bidding

In each auction, you are asked to submit bids for different quantities of items **WITH** or **WITHOUT** **Item A**.

# of Items	value WITH Item A	value WITHOUT Item A
1 Item		
2 Items		
3 Items		

You place 6 bids in total: for 1, 2, and 3 items with or without item A.

But **at most one** of these bids can be winning. The computer assigns the 5 items such that the sum of the winners' payments is maximized.

If one of your bids is winning then you pay that bid (you pay nothing if none of your bids are winning).

Earnings

Your earnings from each auction equal the value of the items you win minus your payment.

Your Earnings = Your Value – Your Payment

NOTE: if your Payment exceeds your Value for the items you won then your earnings will be negative and will be subtracted from your cumulative earnings so far. If you finish the experiment with negative earnings you will only be paid the show-up fee.

Summary

The experiment consists of a series of **15 auctions** preceded by 1 **practice auction** that does not affect earnings.

In each auction, each bidder receives **new** values for winning 1, 2, or 3 items **with** or **without item A**

You will know your values but not the ones of other bidders

Item A has a **lower** value than the other items.

You bid for the number of items you want to win **with** or **without item A**

Your earnings are equal to the value of the items you win **minus** your payment.

Concluding Remarks

The exchange rate used in the experiment is **1 dollar for every 4 points**.

You also receive a **$10 participation fee**.

You will be paid at the end of the experiment the total amount you have earned in all of the periods. You need not tell any other participant how much you earned.