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Working Paper

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Australian School of Business Research Paper No. 2014 ECON 31

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Last updated: 24/06/14 CRICOS Code: 00098G

AUCTION FORMAT AND AUCTION SEQUENCE IN MULTI-ITEM MULTI-UNIT AUCTIONS - AN EXPERIMENTAL STUDY*

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Abstract

We experimentally study the effect of auction format (sealed-bid vs. closed clock vs. open clock) and auction sequence (simultaneous vs. sequential) on bidding behaviour and auction outcomes in auctions of multiple related multi-unit items. Prominent field applications are the sale of emission permits, fishing rights, and electricity. We find that, when auctioning simultaneously, clock auctions outperform sealed-bid auctions in terms of efficiency and revenues. This advantage disappears when the items are auctioned sequentially. In addition, auctioning sequentially has positive effects on total revenues across all auction formats, resulting from fiercer competition on the item auctioned first.

* We thank Karl-Martin Ehrhart, Charles A. Holt, Axel Ockenfels, Andreas Ortmann, Hugh Saddler, Bill Shobe, participants at the ESA 2010 conference in Tucson, the ESAM 2011 in Adelaide, the ESA 2011 conference in Chicago, the ANZWEE 2011 workshop at Monash University, and the audience in seminars at Humboldt University Berlin, the University of Cologne, the University of New South Wales, and the University of Paderborn for valuable comments and suggestions. We also thank the Australian Department of Climate Change and Energy Efficiency (DCCEE) that funded the project. Data from this experiment were also reported in a technical report to the Australian Government (Betz et al., 2010a) as well as in Chapter 4 of Schweitzer's (2012) PhD thesis.
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1. Introduction

In recent decades, auctions have been established as an essential instrument for large-scale governmental sales of public resources. In many of these applications, multiple identical units of different items are auctioned. In this paper we focus on the sale of greenhouse gas emission permits for different validity periods with multiple identical units for each period. These goods are characterised by asymmetric substitutability across items and weakly decreasing marginal values across units. Other related examples for multi-item multi-unit auctions in the public or private sector are the allocation of fishing rights for different kinds of fish, the sale of different types of federal bonds, electricity markets with different delivery dates, and the famous flower auctions in the Netherlands.

Most experimental studies on emission permits and similar markets deal with multiple identical units of only one item (e.g. Cason and Plott, 1996; Burtraw et al., 2009; Mougeot et al., 2011). Auctioning multiple, heterogeneous multi-unit items raises new research questions. In this paper we address two of them: the effects of auction format (dynamic vs. sealed-bid) and auction sequence (simultaneous vs. sequential sale of the different items), as well as their interdependence. Despite the large body of research on sealed vs. open auctions (see our literature review in Section 2), even in the single-item case with only homogeneous units there is no consensus on which format is suited best for auctioning emission permits. The main arguments for open, dynamic auctions are their superior characteristics with respect to transparency, price-discovery performance, and flexibility (e.g. Betz et al., 2010b). The main counter-arguments are the potentially increased risk of collusion (e.g. Burtraw et al., 2009) and higher transaction costs (e.g. Ockenfels, 2009).

With respect to the question of auction sequence, auctioning multiple items simultaneously may allow bidders to deal with interdependencies between the items, and the existing literature therefore favours simultaneous procedures (Vickrey, 1976; McMillan, 1994). Actual applications, however, typically feature sequential auctions (e.g. Virginia NO_x, cf. Porter et al., 2009), potentially due to their lower complexity.

There is little discussion in the literature on the interaction of auction format and sequence. The conjecture of higher efficiency of simultaneous auctions hinges on the assumption that simultaneous designs facilitate bidding behaviour that reflects the interdependence of the different items. In fact, simultaneous auctions with multiple price clocks allow bidders to shift bidding quantities from one item to another which, by construction, gives simultaneous clock auctions an advantage over sequential clock auctions. In contrast, our sealed-bid auctions require bidders to submit complete bidding functions for each item and thus do not allow for deliberate switching conditional on price differences during the auction. Auctioning sequentially aligns the possibilities of interdependent bidding in so far as in all formats, bids in later auctions can be conditioned on the results of earlier auctions. Thus, for sealed-bid auctions, the sequential procedure gains compared to a simultaneous approach. In the context of emission permits, where substitutability is asymmetric (earlier vintages can be used later, but not vice versa), a sequential procedure may be sufficient to deal with the interdependencies, such that also a sealed-bid format may perform reasonably well in terms of efficiency.

We study allocative efficiency as well as prices and revenues in static sealed-bid and dynamic clock auctions under both a simultaneous and a sequential procedure in a multi-item multi-unit context. Our experimental design features a relatively large number of 14 bidders in each auction, with two related multi-unit items with weakly decreasing marginal (private) values and asymmetric substitutability. The main difference between auction formats is whether the bid function has to be specified in advance (sealed-bid) or current (and future) prices can be changed at any time during the course of the auction (clock), and whether aggregate demand is revealed at every price step (open clock) or not (closed clock). In the simultaneous auctions both items are auctioned at the same time, whereas the sequential procedure consists of two separate consecutive single-item multi-unit auctions. In all auctions we apply uniform pricing, and the mechanisms ask for quantity bids given the price of the respective item. In line with most practical applications for carbon permits or related goods, explicit combinatorial elements are not considered.

In our experiment, clock auctions outperform sealed-bid auctions in terms of efficiency when auctioning both items simultaneously. This advantage disappears (and even weakly reverses) when the two items are auctioned sequentially. We also find that auctioning sequentially has a positive effect on total revenues, consistently across all three auction formats. The source of this effect seems to be fiercer competition on the item auctioned first.[1] And finally, with our study's relatively competitive market environment, we obtain no evidence for increased demand reduction or collusion when using a clock auction (compared to a sealed-bid auction) or when revealing aggregate demand in a clock auction (compared to not revealing it).

Based on these results, we conclude that in a context with asymmetric substitutability it may suffice to auction items sequentially (beginning with the item that can substitute all other items) to cater for interdependencies. For the allocation of different emission permit vintages, where banking is allowed but borrowing is not, we therefore recommend a sequential auction, which yields the same (clock) or higher (sealed-bid) efficiency than a simultaneous procedure, is less complex, and has a positive effect on total auction revenues. Since in sequential auctions efficiency and revenues are similar across auction formats, other criteria may become decisive for the auctioneer depending on the particular environment, such as complexity, price discovery in markets with uncertain values, and susceptibility to collusion when there are only a few bidders.

The experiment reported in this paper was conducted as part of a study on the design of auctions for the allocation of greenhouse gas emission permits, advising the Australian Government (see

[1] For homogeneous items, a similar effect, known as the *declining-price anomaly* or *afternoon effect*, has been reported by Ashenfelter (1989) and McAfee and Vincent (1993). They provide examples from auctions of identical units of wine and art, where they observe lower prices for the units auctioned later. Mezzetti (2011) summarizes several explanations for the declining-price anomaly such as various forms of risk aversion.

Betz et al., 2010a).[2] While some specifics of the experimental design, like several of the 'micro rules', the relatively large number of bidders, and the asymmetric substitutability of items, are related to the design of the Australian Carbon Pricing Mechanism, we abstract away from many other particularities. We apply a neutral framing and do not model specific design elements such as international permit markets, product markets, abatement investments, compliance checks, and penalties. Rather, we assume that all these features are captured by properly induced bidder preferences. When designing a real auction for a particular purpose, however, our results provide only one source of evidence which needs to be complemented with the results obtained from other methods, such as economic theory, analysis of empirical data, field experiments, simulations, and other results of inquiry (see also Roth, 2008, for a discussion). Consistent with this approach, our report to the Australian government used the laboratory experiment reported here as one, complementary piece of evidence to derive recommendations. The subsequent draft of legislation for the Australian Auction of Carbon Units (Australian Government 2013) followed our suggestions closely.[3]

The remainder of the paper is structured as follows. Section 2 provides a brief review of the related literature. Section 3 states our hypotheses and describes the design and procedures of the experiment. Section 4 presents the experimental results with respect to aggregate auction outcomes and individual bidding behaviour. We summarize and conclude in Section 5.

2. Related Literature

There is a rich body of literature that addresses the appropriate format of permit auctions, with a particular focus on discriminatory vs. uniform pricing and sealed-bid vs. open, dynamic auctions (see Lopomo et al., 2011, for a review). With respect to the pricing rule, the theoretical and empirical literature seems to agree that permit auctions should apply uniform pricing as used in most emissions trading schemes such as the European Union Trading Scheme, the Swiss Emissions Trading Scheme, the U.S. Regional Greenhouse Gas Initiative (RGGI), the California Cap-and-Trade Program, and the U.S. NO_x schemes (see also Ockenfels, 2009, for a discussion). Some experimental laboratory studies on emission permits support this view (e.g. Cason and Plott, 1996; Porter et al. 2009) while others do not find uniform price auctions to perform superiorly (e.g. Shobe et al., 2010; Goeree et al., 2013).

Following the overall recommendation of the theoretical literature as well as major field applications, we concentrate on uniform pricing rules. The two most prominent designs of uniform price auctions are the sealed-bid and the ascending-clock auction. Clock auctions are "intuitive and easy to understand" (Betz et al. 2010b), as bidders only have to specify their

[2] In our report to the Australian Government (Betz et. al 2010a) we studied the effects of sequence and format separately. In the present paper we focus on how auction sequence and format interact, yielding more differentiated results and insights.

[3] At the time of writing, the Australian Coalition Government (elected in 2013) plans to repeal the law introduced by the previous Labor Government and replace the carbon permit trading scheme with a 'direct action' emissions reduction fund similar to the design of the 2002 UK ETS auction. Due to political uncertainties, it is still unclear whether this change in policy will take effect or not.

demand step by step at each price level, as opposed to submitting a complete demand function. Since aggregate demand can be revealed after each round, open clock auctions also provide more information during the course of the auction. According to Milgrom and Weber's (1982) linkage principle, the additional information should increase average revenues for a wide class of applications where (bidders' own) values are uncertain.[4] While the linkage principle holds in particular for unknown common value components (e.g. the costs of future CO_2-abatement technologies) and refers to revenue, governments often are more concerned with efficiency (e.g. Australian Government, 2008). Because common value components do not affect efficiency, we abstract away from them and focus on the bidders' private valuations which are driven by company specific abatement costs. Also in this case, price discovery is important, because price signals serve to guide and coordinate investments into emission abatement, especially in the beginning of permit trading schemes when secondary markets are not yet efficiently operating (Betz et al., 2010b). Cramton and Kerr (2002) as well as Mandell (2005) argue that clock auctions have superior capabilities compared to sealed-bid auctions since the open convergence of aggregate demand to supply strengthens price discovery.

A potential disadvantage of the additional information revealed in ascending clock auctions is that it may amplify demand reduction or ease collusion between bidders. Demand reduction refers to the incentives of bidders with multi-unit demand to ask for lower quantities (compared to the Walrasian benchmark) in order to lower the final auction price for their remaining demand. Experimental evidence for stronger demand reduction in clock compared to sealed-bid auctions is provided by Kagel and Levin (2001), who test the role of dropout information in a simple setting with a maximum demand of two units. Investigating collusion, Holt et al. (2007, 2008), Mougeot et al. (2011), as well as Goeree et al. (2013) provide experimental evidence of lower revenues and prices in clock auctions compared to other auction formats.[5] These experiments, though, were specifically designed to study collusion and featured not only a low number of bidders; the experimental instructions in both Holt et al. and Mougeot et al. even explicitly encouraged participants to chat about any aspect of the auction prior to each round of bidding. In most if not all actual emission permit auctions, the number of bidders is high and bid-rigging is illegal, such that the risk of collusion seems to be low (cf. also Cramton's comment to RGGI, 2007).

In an attempt to curb potential collusion, aggregate demand was not revealed in the sequentially conducted 2004 Virginia NO_x clock auctions. Shobe et al. (2010) experimentally compare sealed-bid auctions and clocks with and without revelation of aggregate demand in a loose-cap environment, but do not find significant differences with respect to both efficiency and revenue. Theoretically, in the *single-item* multi-unit case, a clock auction without revelation of aggregate demand is strategically equivalent to a sealed-bid uniform-price auction. This is because in a

[4] Strictly speaking, Milgrom and Weber (1982) developed the linkage principle for symmetric single-item single-unit auctions. Still, it also has been used as an argument in favour of open auctions in multi-product environments, even if the requirement of ex-ante symmetry is violated (e.g. McMillan, 1994).
[5] Holt et al.'s (2007) recommendation of a uniform-price sealed-bid auction was adopted by both RGGI and the Californian Cap-and-Trade Program (California Air Resources Board, 2014).

sealed-bid auction, bidders define their demand at each price assuming that at lower prices aggregate demand exceeds supply, which is exactly the same information that is revealed in a clock auction by the fact that the price clock ticks forward. However, in the case of *multiple simultaneously auctioned items*, the equivalence breaks: different clocks may proceed at different speeds, and bidders can react to the information implicitly revealed by a pausing clock. But even then, limiting the information revealed in a clock auction reduces the informational differences to the sealed-bid format.

Government sales of public resources often include multiple units of *multiple related items*. For example, in permit schemes several "vintages" of permits may be auctioned ahead of time, where each vintage reflects the date the permit can be first used. Reasons for advanced auctions of future vintages include the aims to reveal abatement costs, promote price discovery, and reduce transaction costs, volatility of prices and risks of bidders (Ehrhart et al., 2005; Ockenfels, 2009; Betz et al., 2010b). The different vintages are *related* because many schemes allow banking (earlier vintages can be used later) or, often to a very limited extent, borrowing (later vintages can be used in earlier years). Advanced auctions seem common in emission trading schemes, not only in the Australian context where up to four different vintages were planned to be auctioned in one event (Australian Government, 2013), but also in other schemes such as the EU ETS 2012 auctions, the RGGI system and the California Cap-and-Trade Program (Regional Greenhouse Gas Initiative 2008; California Air Resources Board 2014).

The only experimental study we are aware of which tests auctions of multiple multi-unit vintages of emission permits is Porter et al. (2009), who find that when demand is relatively elastic, uniform-price clock auctions outperform discriminatory sealed-bid auctions in terms of revenue (but not efficiency). However, the study does not separate the effects of uniform vs. discriminatory pricing from effects of sealed vs. dynamic clock bidding. Our study makes advances regarding the latter question by comparing a sealed-bid format to clock auctions with and without revelation of aggregated demand after each bidding round.

A particular issue in the multi-item case is the question of auction sequencing, i.e. whether multiple items should be sold simultaneously or in a sequence of single-item auctions. A prominent conjecture based on theoretical considerations is that simultaneous procedures outperform sequential procedures with respect to allocative efficiency whenever the values of multiple auctioned items are related, either as substitutes or complements. An early proposal to use multiple simultaneous auctions for multiple, heterogeneous items is presented by Vickrey (1976). Analysing spectrum auctions, McMillan (1994) argues strongly in favour of a simultaneous procedure by pointing out that simultaneous auctions provide flexibility in the aggregation of licenses, prevent predatory bidding, and give the opportunity to take advantage of the information revealed during the auction process. Focusing on multiple heterogeneous items in the same context, McAfee and McMillan (1996) as well as Cramton (1997) support this rationale. The latter adds that the information disadvantage of the sequential auction forces bidders to perform guesswork with respect to the prices of later items. Based on examples of electricity markets, Milgrom (2004, pp. 279ff) extends the discussion to clock auctions of multiple items and argues in line with the previous literature that interdependent items should be auctioned simultaneously. Klemperer (2010) invokes similar arguments when raising concerns that separated sequential auctions are more sensitive to market power, manipulation, and informational asymmetries.[6]

In the context of emission permits auctions there is little discussion whether to auction simultaneously or sequentially. The exception is again Porter et al. (2009), who find no differences between simultaneous and sequential clock auctions in terms of efficiency and revenues. In our experiment, we test whether the rationale in favour of simultaneous auctions in the spectrum and the electricity cases translates to the emission permits environment. On the one hand, vintages of different validity periods are interrelated as well. We study a setting where the different vintages are asymmetric substitutes in that banking (using a permit later than its vintage year) is allowed, but borrowing (using it earlier) is restricted. The advantage of the simultaneous approach with clock auctions in such a setting is that it allows bidders to shift demand from one vintage to another during the course of the auction, which may lead to more efficient outcomes. On the other hand, because the substitutability in this context is asymmetric, a sequential procedure (which allows to condition bidding in later auctions on the number of units of the substitute received earlier) may be sufficient to cater for interdependencies, in which case both clock and sealed-bid auction formats may perform reasonably well.

3. Design of the Study

3.1 Hypotheses

We investigate the dimensions sequence and format of multi-unit, multi-item auctions when the values of the auctioned items are interrelated. In line with previous studies, we evaluate the performance of the auction designs with respect to their allocative efficiency, the revenue raised, and their price discovery, and test three main hypotheses.

Hypothesis 1 relates to allocative efficiency. In a simultaneous clock auction bidders can consider valuations for bundles in their bidding and shift their demand from one to another item conditional on observed prices in the dynamic process of the auction. This is not feasible in a standard sealed-bid multi-unit auction which asks for specification of a bidding function for each item (separately) in advance. Thus, we expect that in the simultaneous environment, clock auctions outperform sealed-bid auctions in terms of allocative efficiency. For clock auctions, a sequential procedure limits the flexibility of bidding. So we hypothesise lower efficiency in that case. For sealed-bid auctions, on the other hand, the sequential procedure adds flexibility, because now the bidders may take into account the results from the first item's auction when forming their bidding function for the second item. Therefore, we expect sequential sealed-bid auctions to outperform simultaneous sealed-bid auctions.

[6] In a setting of central bank operations, Klemperer (2010) even proposes a *combinatorial* simultaneous sealed-bid auction in a multi-item multi-unit context, with uniform pricing per item. However, the complexity of combinatorial bidding procedures may preclude their use in the emissions context (e.g. Porter et al. 2009).

Hypothesis 2 refers to revenues raised by the auction and bidder surplus. Open clock auctions might facilitate collusion and ease unilateral demand reduction. If that is the case, we should expect lower prices and revenues in clock auctions when aggregate demand is revealed after each price step. Finally, Hypothesis 3 is related to information efficiency. By revealing aggregate demand during the course of the auction, clock auctions provide more information regarding the convergence of aggregate demand to supply, and might therefore have superior price discovery capabilities as compared to sealed-bid auctions. The three hypotheses can be summarised as follows:

1. *Allocative efficiency:*	1A:	Simultaneous clock auctions result in higher social surplus than simultaneous sealed-bid auctions.
	1B:	Simultaneous clock auctions result in higher social surplus than sequential clock auctions.
	1C:	Sequential sealed-bid auctions result in higher social surplus than simultaneous sealed-bid auctions.
2. *Auction revenue:*		Sealed-bid auctions lead to higher prices and revenues than closed clock auctions, which in turn yield higher prices than open clock auctions.
3. *Information efficiency:*		Open clock auctions exhibit better price discovery than closed clock auctions, which in turn exhibit better price discovery than sealed-bid auctions.

To evaluate the hypotheses we use as a benchmark the Walrasian equilibrium, in which bidders are assumed to be price takers. The competitive Walrasian price structure is defined as the set of prices at which the market is cleared (there is no excess supply or demand at these prices) and units are allocated efficiently.[7] We measure *allocative efficiency* as the fraction of the realised social surplus over the maximum surplus according to the Walrasian benchmark, *revenue* as auction revenues relative to the Walrasian benchmark, and *information efficiency* as the closeness of prices generated by the auction relative to the competitive prices in the Walrasian benchmark, and their variances across auctions within the same demand structure.

3.2 Experimental Design and Procedures

We employed a 3x2 factorial experimental design with the two dimensions auction format (sealed-bid vs. ascending-clock with and without demand revelation) and auction sequence (simultaneous vs. sequential). For each of our six treatments we conducted six sessions, with fourteen bidders each,[8] from January to March 2010 at the University of New South Wales

[7] Units valued exactly at competitive prices may be rationed. For any demand structure created for our experiment, a unique *efficient set of prices* for Items A and B exists, which, however, usually allows for multiple *efficient allocations* among bidders. Given the efficient set of prices, all related efficient allocations result in the same total welfare, revenues, and bidder surpluses.

[8] We are not aware of any other experimental study involving such a large number of bidders per auction. Most experiments on emission markets have had six or fewer bidders per auction. In practice, the number of (potential)

(UNSW) and Karlsruhe Institute of Technology (KIT). Twelve sessions (two sessions per treatment, 168 participants) were run at UNSW, and twenty-four sessions (four sessions per treatment, 336 participants) at KIT.[9] Participants were university students recruited from the ASBLab subject pool at UNSW using the online recruitment system ORSEE (Greiner, 2004), and from a respective subject pool at KIT. Sessions at UNSW were conducted in English, sessions at KIT in German. No communication with other participants was allowed during the experiment. At the beginning of each session, instructions were distributed in written form and were also repeated orally.[10] Then, participants had to answer a short computerized comprehension test.

We employed a stationary replication of a one-shot design. All fourteen participants of a session participated in six auctions (two for training and four according to treatment) in which 100 units of Item A and 80 units of Item B were sold. No bidder was allowed to bid for more than 15 units of Item A and 10 units of Item B. In each auction, individual heterogeneous demand functions were induced with the help of individual redemption values for each possible bundle of A and B that could be purchased. The same set of fourteen individual demand functions was used in all six auctions of a session, but individual functions were rotated after each auction, such that no bidder received the same demand function more than once while the overall market demand structure was kept constant.[11] To prevent bidders from focusing on the price of the previous auction and to further explore the robustness of the auction mechanisms, we added constant exogenous demand function shocks in each auction, shifting aggregate demand up- or downwards.[12] In Walrasian equilibrium, these constant shocks should only shift the individual demand by the same amount, and (after controlling for the shock) should not affect market prices, seller revenues, or bidder profits.

The sets of demand functions (demand structures) differed between the sessions within a treatment, but the same six different session demand structures were implemented in each experimental treatment. To create each of the six demand structures, we first generated fourteen individual marginal value functions for Item A by randomly drawing heights and lengths of steps.[13] The marginal values for Item B were either defined as being the same as for Item A, or

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bidders will be even larger. E.g., around 350 entities were liable under the Carbon Pricing Mechanism in Australia in January 2013.

[9] Our analysis does not indicate any cultural effect, and our results are robust against including session fixed effects which capture a potential effect of country/language.

[10] English sample instructions and screenshots of the software can be found in Appendices A and B, respectively. Written instructions, instruction videos (see below), and value tables (see below) are available online at http://ben.orsee.org/supplements/. The German versions of all materials are available on request from the authors.

[11] After each auction, all value schedules were shifted by three laboratory seats. The specific role rotation mechanism was not known to the subjects.

[12] The sequence of shocks was 3, 1, 5, 0, 8, and 6 monetary units, respectively. This sequence was determined in advance and used consistently in all sessions in all treatments.

[13] Details are explained in Online Appendix D. In a carbon permit context, an individual demand function corresponds to a firm's marginal abatement cost curve. The height of the steps represents the costs of a particular abatement measure, and the length of a step represents the amount of emissions which can be avoided using that measure at these costs. The complete function shall represent the size, sector, and production and abatement technologies of a firm.

Seat No.	X				Bundle Values				Auction	X	
Value (E$)	Quantity Item B										
Quantity Item A	0	1	2	3	4	5	6	7	8	9	10
0	0	22	44	66	88	107	126	145	164	183	201
1	27	49	71	93	115	134	153	172	191	210	228
2	54	76	98	120	142	161	180	199	218	237	255
3	81	103	125	147	169	188	207	226	245	264	282
4	108	130	152	174	196	215	234	253	272	291	309
5	132	154	176	198	220	239	258	277	296	315	333
6	156	178	200	222	244	263	282	301	320	339	357
7	180	202	224	246	268	287	306	325	344	363	381
8	204	226	248	270	292	311	330	349	368	387	405
9	228	250	272	294	316	335	354	373	392	411	429
10	250	272	294	316	338	357	376	395	414	433	451
11	272	294	316	338	360	379	398	417	436	455	473
12	294	316	338	360	382	401	420	439	458	477	495
13	316	338	360	382	401	420	439	458	477	495	513
14	338	360	382	401	420	439	458	477	495	513	531
15	360	382	401	420	439	458	477	495	513	531	548

Figure 1. *Example total bundle valuation table handed out to participants*

were proportionally discounted by a factor of 0.8.[14] To derive valuations over A-B-bundles we modelled asymmetric substitutability on top of the separate marginal value functions. In particular, we specified that Item A units (current vintage) can be used for purpose B (cover next year's emissions), but Item B units (next year's vintage) cannot be used for purpose A (cover this year's emissions). As a result, the marginal bundle value of one more unit of Item A was always at least as high as the marginal bundle value of one more unit of Item B. Further, the items and units had weakly decreasing marginal values, i.e. the sum of the values of two disjunctive subsets of items and units was always at least as high as the value for the combined set.

Participant received values for A-B-bundles in the form of two tables: a table displaying total bundle values (see Figure 1) and a table displaying, for each possible bundle, the marginal values of one additional unit of Item A or one additional unit of Item B. In addition, the participants received the following information: "The more units of an item you purchase, the more the bundle is worth. If you purchase more units of the item, additional units may decrease in value. Item A is more valuable than Item B, i.e. for each bundle, the value of an additional unit of A is at least as high as an additional unit of B."

Bidding in all auctions was restricted to prices between E$1 and E$30 (the maximum marginal value including demand shocks, E$ = Experiment-Dollars). If at the price of E$1 aggregate

[14] In a carbon permit context, Item B can be interpreted as a future vintage. The discount factor between Item A and Item B represents technology improvements or simple discounting of future profits. The sequence of discount factors implemented was 0.8, 1, 0.8, 1, 1, 0.8 for Auctions 1 to 6, respectively. This sequence was determined randomly under the condition that three auctions employ a factor of 1 and three auctions a factor of 0.8, and was used in all sessions in all treatments.

demand were already lower than the supply, the auction would be considered to have failed. Thus, the E$1 can be thought of as the reserve price. However, all of our experimental auctions closed at higher prices, and in none of our auctions the price reached E$30.

In each session (bidder group), the first two of the six auctions were implemented as simple clock auctions. This allowed bidders to learn about the functioning of the auction mechanism and ensured that in all treatments the bidders received the same training before the start of their particular treatment. The auction started at a price of E$1 and asked for quantity bids at this price. If the group demand over all bidders at this price was higher than the number of units offered, the price was increased by E$1, and new quantity bids were elicited. Each price step lasted 30 seconds (except the first and second step which lasted 60 and 45 seconds, respectively). If no new quantity bid was submitted within this time, the previous bid was automatically repeated (the maximum bidding quantities of 15 and 10 for Item A and B, respectively, were set as the default bids in the first price step). This procedure continued until, at a given price, the aggregated demand for an item was equal to or lower than the respective supply. Then the price clock stopped. If aggregate demand increased again (which was possible in the simultaneous auctions due to switching of demand from one item to the other), the price clock started to tick forward again. Once both clocks stopped at the same time, the auction was over.[15] Auction history tables for each item showed the personal bidding history over previous price steps. In the treatments where aggregate demand was revealed, the total demand over all bidders was also displayed for all previous price steps.[16]

In auctions three to six of each session, the actual auction format according to the experimental treatment was implemented. The treatments featured either a sealed-bid auction (SB), or a clock auction with (open clock, OC) or without (closed clock, CC) revelation of aggregate demand. In treatment SB, the simple change with respect to the introductory clock auction format was that now a complete and binding bidding plan had to be submitted before the auction started. The visual display of the auction history table now included sliders that allowed bidders to select their demand for each price, i.e. a bidding plan for the upcoming auction. The change in the software interface was explained to the subjects with the help of a short video.[17] Bidders had 5 minutes to decide on a bidding plan. Then the auction ran automatically according to the submitted bid function, with no possibility of interventions by participants.

Differently to the two training auctions, our implementation of the ascending clock auction in treatments OC and CC allowed for proxy bidding.[18] That is, similar to the sealed-bid mechanism,

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[15] In the sequential treatments, which basically employed two consecutive single-vintage auctions, each auction was over once aggregate demand for the respective item dropped to or below supply.

[16] For a screenshot of the computer screen in these auctions see Figure B.1 in Online Appendix B.

[17] Schweitzer (2012) discusses the methodology of instruction videos in economic experiments in detail.

[18] Proxy-bidding has become a very popular auction feature in the Internet. It creates hybrid auction formats by allowing bidders to decide whether they would like to participate in a sealed-bid or in an English auction. If nobody made use of the proxy feature, eBay's auction, for example, could be classified as an open English auction, while it would be characterized as a sealed-bid second-price auction if all bidders used the proxy feature (see also Roth and Ockenfels, 2002; Seifert, 2006). Advantages of proxy-bidding are that it reduces transaction costs and increases the number of bidders by allowing participation by bidders who may not have been able to be present at the live auction. In a dynamic market design context, a proxy-bidding option might also smooth a

the change between the training auctions and the treatment auctions was that bidders now could use sliders and submit a bidding plan for all upcoming clock prices.[19] This plan, however, was not binding as in the sealed-bid format. Rather, it could be revised at any time during the auction for the current and all future prices. Each price step now lasted 30 seconds (180 seconds for the first step).

At the end of the experiment session, one of the six auctions was randomly selected for payoff. Participants were paid privately in cash and left the laboratory. During the experiment we used E$ (experiment dollars) as the currency. For the randomly selected auction, participants were paid their profits/losses from the auction, plus a lump sum of E$150 to cover potential losses. The E$ were converted at a publicly known exchange rate of AUD 0.15 / E$ at UNSW and EUR 0.10 / E$ at KIT. On average, sessions lasted about 2 hours, and participants earned AUD 30.53 at UNSW and EUR 21.02 at KIT, including a show-up fee AUD 5 / EUR 5.

Some specifics of our experimental design, like the relatively large number of bidders and the asymmetric substitutability of items, are related to the discussions on the Australian emissions trading scheme. In addition to our main parameters of interest, auction sequence and general auction format, we had to define a number of micro rules, some of which are still a matter of scholarly and practical debate. For example, in our study, the price was determined by the lowest accepted bid; excess demand at the final price was proportionally served, with non-integer fractions of supply being rounded according to the largest remainder method; in sealed-bid auctions, bids were sorted such that the auction would not result in a price reversal; and in the sequential auctions, we auctioned the more valuable Item A first. For reasons of space restrictions and readability, we discuss the details and reasons for these specific design choices in Online Appendix D.

4. Results

4.1 Overview

In our analysis, we first normalized the data from all auctions by subtracting the respective demand shocks. We restrict our attention to the four auctions in each session which were run according to the respective treatment. Table 1 displays treatment averages of relative efficiency, auction revenues, and bidder surpluses, as well as average relative prices for our six treatments.[20]

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migration from a clock auction format to a sealed-bid format, as the sealed-bid element is already implemented and only the possibility of updating during the auction would be "switched off". A potential drawback is a higher complexity of the bidding process. From an experimental design perspective, the proxy option also allowed us to use the same user interface in both sealed-bid and clock auctions, which eliminates artefacts that only stem from the user interface.

[19] See Figure B.2 in Online Appendix B for a screenshot of the computer screen.

[20] Tables C.1 and C.2 in Online Appendix C display the averages of these measures at the independent session level. While we only report the results from regression analysis in the paper, we also conducted non-parametric tests based on session averages. The results from these tests do not yield different conclusions.

Table 1

Treatment averages for relative allocative efficiency, auction revenues, bidder surpluses, and prices

	SB	CC	OC
Relative allocative efficiency			
Simultaneous	85.8%	88.3%	88.7%
Sequential	89.4%	88.3%	88.7%
Relative auction revenues			
Simultaneous	80.8%	88.0%	84.0%
Sequential	93.8%	89.9%	91.9%
Relative bidder surplus			
Simultaneous	110.1%	90.7%	110.0%
Sequential	71.7%	82.6%	78.7%
Relative price A			
Simultaneous	0.871	0.911	0.890
Sequential	0.997	1.007	0.994
Relative price B			
Simultaneous	0.724	0.838	0.772
Sequential	0.857	0.754	0.818

Allocative efficiencies in all our treatments are relatively high. In particular in the clock auctions they are very close to each other, while the sealed-bid format yields lower efficiency in the simultaneous environment and slightly higher efficiency in the sequential environment, compared to the clock auctions. A consistent effect on the bidders' surplus, revenues, and prices is observed with respect to the auction sequence. Revenues and prices, are generally higher in the sequential auction treatments compared to the simultaneous treatments (except for the Item B price in CC), while bidder surpluses are lower. Section 4.2 provides statistical analyses of aggregate auction outcomes that explore the direct effects of sequence and formats as well as their interactions. Section 4.3 investigates individual bidding behaviour, replicating the aggregate effects, but also indicating that less demand shading in the Item A auctions under the sequential procedure is the source of the effects on revenues and bidder profits.

4.2 Aggregate Results

For the analysis of treatment effects and controls, we run Ordinary Least Square (OLS) regressions on aggregate auction outcomes. In all regressions, we cluster standard errors robustly at the independent session level, thereby accommodating for the potential relatedness of auctions within a session. Additionally, all regressions control for fixed effects of demand structures. We include the following explanatory treatment dummies: *isClock* being 1 in clock treatments and 0 in sealed-bid auctions; *isClock.isOpen* being 1 in clock treatments where the aggregate demand was revealed, and 0 otherwise; *isSequential* taking the value 1 in auctions where the two items were auctioned sequentially, and 0 in the simultaneous case; *isSequential.isClock* being 1 in sequential clock treatments, and 0 otherwise; and *isSequential.isClock.isOpen* being 1 in sequential clock treatments where the aggregate demand was revealed. Thus, the baseline case is the sealed-bid format with both vintages auctioned simultaneously. Further controls comprise the variable *DemandShock* which equals the demand shock in the individual auction, and the dummy variable *RelVintValueScheme*, with a value of 1 indicating an Item B/Item A value relation of 1, and 0 denoting a relation of 0.8. The results of our regressions are reported in Table 3.[21] In addition to the coefficient estimates, the table also reports results from post-estimation F-tests which assess combined effects directly. Table 2 lists the Null hypotheses of these post-estimation tests and what they assess.

Table 2
Null hypotheses of post-estimation F-tests

Assessed question	Null Hypothesis
In Sim: OC vs. SB	isClock + isClock×isOpen = 0
Seq effect for CC	isSeq + isSeq×isClock = 0
Seq effect for OC	isSeq + isSeq×isClock + isSeq×isOpen = 0
In Seq: OC vs. CC	isClock×isO + isSeq×isClock×isOpen = 0
In Seq: CC vs. SB	isClock + isSeq×isClock = 0
In Seq: OC vs. SB	isClock + isClock×isOpen + isSeq×isClock + isSeq×isClock×isOpen = 0

Notes. SB, CC, and OC refer to sealed-bid, closed clock and open clock auction format, respectively. Sim and Seq refer to simultaneous and sequential auctions.

With respect to auction efficiency, we do not find differences between a closed clock and an open clock auction, neither when auctioning simultaneously nor when auctioning sequentially. As expected, the clock formats outperform the sealed-bid format in the simultaneous auctions, increasing efficiency by about 2.5 per cent. This can be attributed to the fact that during a clock auction, individual demands can be switched from one item to another based on observed prices and aggregate demand, a feature not available in sealed-bid auctions. However, auctioning sequentially has a strong positive 3.6 per cent efficiency effect for sealed-bid auctions, while no such effect can be observed for clock auctions. As a result, when auctioning sequentially the sealed-bid auction leads to weakly more efficient allocations than the clock auctions.

With respect to prices for Item A (the higher-value item which is auctioned first when auctioning in a sequence), we do not find significant differences between auction formats. However, for all formats, the sequential auction yields significant higher prices for Item A than the simultaneous auction, about 13 per cent in the sealed-bid format and 10% in the clock formats, bringing them closer to the Walrasian benchmark prices. The effects on Item B prices show a more complex

[21] In addition to the models reported in Table 3, we ran regressions replacing the independents *DemandShock* and *RelVintValueScheme* with auction fixed effects for each of the 4 auctions per session. All of our results and conclusions are robust with respect to these model variations. Including auction fixed effects generally does not increase the explanatory power of the regression model, indicating that *DemandShock* and *RelVintValueScheme* are sufficient statistics of an auction within a session.

Table 3

Results from OLS regressions
of auction outcomes on treatment parameters and controls

Independent	Efficiency	Price A	Price B	Revenue	BidderSurplus
Constant	0.7425***	0.9047***	0.7773***	0.8525***	0.3608***
	[0.0102]	[0.0312]	[0.0357]	[0.0316]	[0.1333]
Treatment Parameters					
isClock	0.0251**	0.0403	0.1143***	0.0723*	-0.1944
	[0.0104]	[0.0407]	[0.0387]	[0.0388]	[0.1682]
isClock × isOpen	0.0031	-0.0207	-0.0658**	-0.0402	0.1930
	[0.0096]	[0.0438]	[0.0313]	[0.0362]	[0.1478]
isSequential	0.0358***	0.1269***	0.1331***	0.1302***	-0.3840**
	[0.0080]	[0.0340]	[0.0382]	[0.0344]	[0.1510]
isSequential × isClock	-0.0366***	-0.0313	-0.2176***	-0.1117**	0.3027
	[0.0122]	[0.0545]	[0.0555]	[0.052]	[0.2358]
isSequential × isClock	0.0014	0.0078	0.1303**	0.0601	-0.2321
× isOpen	[0.0110]	[0.0547]	[0.0499]	[0.0488]	[0.2094]
Controls					
DemandShock	-0.0006	-0.0094***	-0.0079***	-0.0088***	0.0314***
	[0.0010]	[0.0029]	[0.0029]	[0.0026]	[0.0103]
RelVintValueScheme	0.0014	0.0389***	0.0086	0.0202*	-0.0978*
	[0.0057]	[0.0133]	[0.0192]	[0.0119]	[0.0565]
Obs	144	144	144	144	144
R-squared	0.8619	0.3629	0.2479	0.3209	0.5804
Post-estimation F-tests, p-values					
In Sim: OC vs. SB	0.000***	0.626	0.276	0.423	0.993
Seq effect for CC	0.930	0.031**	0.043**	0.639	0.656
Seq effect for OC	0.930	0.005***	0.130	0.011**	0.005***
In Seq: OC vs. CC	0.418	0.696	0.106	0.545	0.794
In Seq: CC vs. SB	0.078*	0.806	0.014**	0.264	0.517
In Seq: OC vs. SB	0.324	0.886	0.065*	0.376	0.496

Notes. *, **, and *** denote significance at the 10%, 5%, and 1%-level, respectively. Regressions are based on Auctions 3 to 6 from all sessions. All regressions include fixed effects for demand structures. Robust standard errors are clustered at the independent session level and are given in brackets.

pattern. In the simultaneous case, the closed clock format yields higher Item B prices than the open clock or the sealed-bid auction. The sequential procedure has a positive effect on Item B prices with the sealed-bid format, a negative effect in the closed clock, and no significant effect with the open clock. As a result, in the sequential case the sealed-bid auction yields higher Item B prices than the two clock formats.

Revenues follow the combined effect of these price effects. With simultaneous auctions, the closed clock format outperforms the sealed-bid format (because of higher Item B prices in the former), while the open clock format is statistically indistinguishable from both. The positive effect of sequence on Item A prices drive revenues up in all auctions, in sealed-bid auctions reinforced by the positive Item B price effect, but in closed clock auctions mitigated to statistical insignificance by the negative Item B price effect. As a result, in the sequential environment the closed clock format falls behind the other two in terms of revenues.

Finally, bidder profits seem not to be affected by the choice of auction format, neither in the simultaneous nor in the sequential environment. However, we detect some negative impact of auctioning sequentially for sealed-bid and open clock auctions.

Demand shocks turn out to matter for normalised relative prices, auction revenues, and bidder surpluses. In particular, the higher the shock, the lower are the relative prices for Items A and B. If bidders bid according to the Walrasian benchmark, a shock on the demand structure would just shift the price upwards by the same absolute amount, and after deducting the shock from the realized prices (as we did in preparing our data for analysis), no effect should remain. The observed effect, however, implies that rather than increasing their bids by the same absolute amount as the item values are increased, bidders discount the demand shock in their bidding. These effects are mirrored in auction revenues, which do not increase by the full amount that would be predicted by a positive demand shock. As a result, bidder surpluses increase in response to positive demand shocks.

Since all auctions in a session of our experiment relied on the same market structure and auction format, the variance of prices over the auctions of a session might serve as a measure of the quality and speed of price discovery. We analyse this indicator using OLS regressions to estimate the effect of treatment parameters on the price variances of Items A and B in our N=36 sessions. We find that price variance in sealed-bid auctions is decreased when auctioning sequentially, but not in clock auctions. However, the two models yield insignificant F-statistics, indicating that they do not explain much of the variance in price variances across sessions. Thus, we interpret these results cautiously, and only conclude that we do not find evidence that using clock auctions or revealing the aggregate demand in a clock auction yield a smoother price formation process (in the sense of lower variances of final auction prices for the same basic demand structure).

4.3 Individual Bidding Behaviour

In order to explain our findings we assess the bidders' behaviour at the individual level. We consider only bids in the last round of an auction and compare them to the profit-maximizing quantities a bidder should have requested at the final prices. The analysis of individual behaviour is complicated by two facts. First, the profit-maximizing bid quantities are not necessarily unique; at a given set of prices for Item A and Item B, multiple quantity combinations of A- and B-items can yield the same profit. Second, different information was available to the bidders in different treatments. At any point in the simultaneous auctions, bidders in clock auctions (but not in sealed-bid auctions) knew the current prices of both items. In all formats in the sequential auctions, bidders could only guess about the outcome of the auction for the second item when

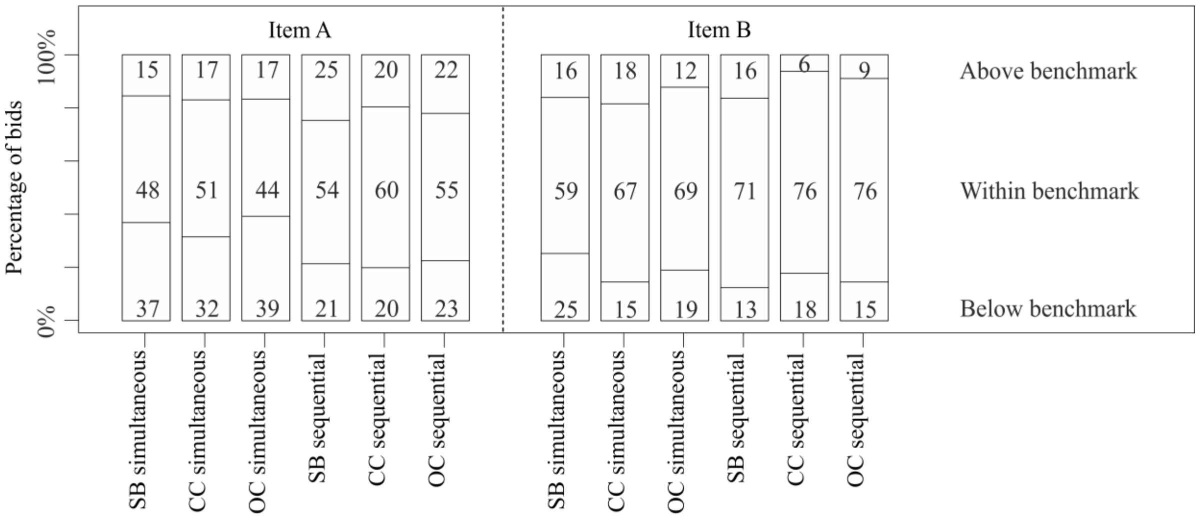

Figure 2. *Percentage of "truthful" bids across treatments*

Notes. The lower part of the bars indicates bids for fewer units than defined by the benchmark range as truthful bidding. The middle part and the upper part of the bars indicate bids for a number of units within and above the benchmark range. The figure includes data from Auctions 3 to 6 of all sessions.

bidding on the first item, but when bidding on the second item, they knew the outcome of the first auction.

In order to deal with these specifics and facilitate a comparison between conditions, we consider each item and bidder separately and calculate an individual "benchmark range" for "truthful" bidding. In doing so, we make minimal assumptions about bidders' beliefs. The upper limit of the benchmark range is the highest number of units of an item a bidder should have demanded if she expected to obtain *no* units of the other item. Similarly, the lower limit of the range equals the number of units the bidder should have purchased if she expected to obtain the *full* amount of the other item (limited by the quantity cap). Bids within this range we consider "truthful".[22] The typical width of the range is about three units.

Figure 2 depicts the percentage of bids for Items A and B that are below, within, and above the benchmark range of truthful bidding. Table 4 reports results from multinomial logit regressions on the effects of auction format and auction sequence on the classification of final bids with respect to the benchmark range. For Item A, across all three auction types we observe a shift from bids below the benchmark range to within and above the benchmark range when auctions are sequential rather than simultaneous. In particular, the fraction of bids *within* the benchmark range exceed the respective fractions in the simultaneous counterparts by 6 to 11 percentage points, the share of bids *above* the benchmark range is between 3 and 10 per cent higher in the sequential environment. As a result, while in the simultaneous treatments more than twice as many bids are below than above the benchmark, these numbers are almost balanced in the sequential treatments.

[22] The assumptions are minimal in the sense that bids outside the range are not in line with truthful bidding under any belief (irrespective of the particular information setting). Any bid within the range, however, could in all treatments be rational given a respective course of events (which might be different from what actually had happened before or will happen later in the respective auction). We also investigated more restrictive benchmarks (for example assuming perfect foresight of the other item's price and allocation); these variations did not yield qualitatively different conclusions.

Table 4

Determinants of bidding within, above or below the benchmark range, multinomial logit estimates of marginal effects (dy/dx) for discrete changes of dummy variables

Item	Item A			Item B		
Outcome	Below	Within	Above	Below	Within	Above
Pr(outcome)	0.28	0.53	0.19	0.17	0.70	0.12
isClock	-0.05	0.03	-0.02	-0.10***	0.09***	0.02
	[0.06]	[0.03]	[0.05]	[0.03]	[0.03]	[0.02]
isClock x isOpen	0.07	-0.07	0.00	0.04	0.01	-0.05***
	[0.06]	[0.06]	[0.05]	[0.04]	[0.04]	[0.01]
isSequential	-0.15***	0.06	0.09**	-0.12***	0.12***	0.00
	[0.05]	[0.04]	[0.04]	[0.03]	[0.05]	[0.03]
isSequential x isClock	0.03	0.03	-0.06	0.18**	-0.06	-0.12***
	[0.07]	[0.05]	[0.05]	[0.07]	[0.07]	[0.02]
isSequential x isClock	-0.04	0.02	0.02	-0.07*	-0.04	0.12***
x isOpen	[0.06]	[0.06]	[0.07]	[0.04]	[0.05]	[0.03]
N		2016			2016	
Log Pseudolikelihood		-2014.2			-1624.9	

Notes. *, **, and *** denote significance at the 10%, 5%, and 1%-level, respectively. Regressions are based on categorized final bids in Auctions 3 to 6 from all sessions. Robust standard errors are clustered at the independent session level and are given in brackets. Significance and size of all reported effects are robust against inclusion of shock and discount controls and demand structure fixed effects.

The regression results on bidding behaviour correspond well to our findings of treatment effects on Item A and Item B prices at the aggregate auction level. For Item A, we observe significant underbidding on Item A (with respect to our conservatively defined range of truthful bidding) in the simultaneous auctions, but not in the sequential auctions. For bids on Item B, similar to our findings for Item B prices, treatment effects are more ambiguous across our treatment dimensions.[23]

As a last step in our analysis of individual bidding behaviour, we consider pairs of bids that an individual bidder submits for the Items A and B within one auction and investigate the correlation of the respective deviations from truthful bidding. We find that these deviations are positively correlated across the two items. In all 36 independent sessions there are more deviations into the same rather than into opposing directions.

Categorical classification of bids on Items A and B of a bidder in an auction is significantly positively correlated (Cohen's w=0.5319, Pearson-χ^2=570.26, p<0.001), as is the classification of bidders into types according to their bidding behaviour (Cohen's w=0.4242, Pearson-χ^2=90.68,

[23] In a complementary analysis, in which we classified all individual bidders as generally underbidding, within-range, overbidding, and inconsistent across the four auctions they participated in, we find qualitatively the same pattern as reported for individual bids.

$p<0.001$).[24] The positive correlation suggests that bidders who deviate from the Walrasian benchmark (under all possible beliefs) on one item tend to be of over- or underbidding types across both items.

5. Discussion and Conclusions

Regarding allocative efficiency, we find support for Hypotheses 1A and 1C. The clock formats outperform the sealed-bid format in the simultaneous auctions, and auctioning sequentially has a pronounced positive effect for sealed-bid auctions. We do not find evidence for Hypothesis 1B as simultaneous and sequential clock auctions perform similarly well.

With respect to Hypothesis 2, we do not find evidence that (open) clock auctions lead to lower prices due to increased demand reduction or collusion.[25] This stands in contrast to a related set of experiments on permit auctions (Holt et al. 2008; Burtraw et al. 2009 and Mougeot et al. 2011). These experiments, though, featured a low number of bidders, communication opportunities, and high gains from colluding. Our design builds on a relatively large number of fourteen bidders and excludes communication. We conjecture that in applications of large governmental auctions with several hundred bidders collusion is not a major issue. We do find, however, that auctioning sequentially yields higher total revenues. This effect is most pronounced in the sealed-bid auctions and seems to result from fiercer competition for the item auctioned first. Deviations from truthful bidding on the individual bidder's level point in the same direction for both items.

We do not find support for Hypothesis 3, since we do not observe reduced volatility of prices across the auctions within the same demand structure if an open clock auction format is used rather than a closed clock or a sealed-bid format. However, our experiment did not involve uncertainty about the bidders' own valuations. In real-world applications, including carbon permit markets, bidders may not know their exact valuation of goods. In contrast to sealed-bid auctions, clock auctions might be able to better deal with these uncertainties. Therefore, and given no opposite evidence, we would still expect clock auctions to perform (weakly) better than sealed-bid auctions in terms of price discovery if traders faced uncertainties regarding the value of the permits.

In sum, our recommendation for an auction scheme to allocate permits with asymmetric substitutability and weakly decreasing marginal values is to use a sequential procedure which yields higher efficiency with sealed-bid and about the same efficiency with clock auctions. Moreover, sequential auctions are less complex and have a positive effect on revenue. The choice between a sealed-bid and a clock format may then depend on the particular application. If there

[24] These test statistics do not account for the potential relatedness of data within an independent session. To control for this we ran, for each bid type and bidder type, probit regressions with the type under Item B as the dependent and the type under Item A as the independent, with robust standard errors clustered at the independent session level. These alternative tests confirm the strong positive correlations, with all *p*-values smaller than 0.01 (except for bidder type *Generally Overbidding*, a category with only 16 bidders for Item B).

[25] We do not find a trend of decreasing revenues over time in the open clock auctions, and therefore no evidence that bidders would learn to collude over the sequence of auctions.

are concerns about demand reduction and collusion due to a small number of bidders, a sealed-bid auction may be preferred. If, in contrast, complexity or smooth price discovery is an issue, then a clock auction might be favoured. With our relatively large number of bidders, this format demonstrated a solid performance in all treatments. Even though we did not find evidence for better price discovery in our setting with private values, this format might still have advantages if uncertainty is high or unknown value components exist.

The experiments reported in this paper were part of a study conducted to inform policy makers in Australia on the design of emission permit auctions. Our results, though, are applicable in a broader context and relate to multi-item multi-unit auctions in other domains as well. The arguments and experimental evidence on interaction effects between auction format and sequence have practical implications for market designers. A fruitful object of further research is how our findings with respect to auction sequence and format extend to other auction environments that are characterised by complementary or uncertain value components.

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ONLINE APPENDIX

A. Sample Experimental Instructions

The instructions below were handed out in written to the participants at the start of the experiment. They refer to all treatments with simultaneous auctions. After the first two auctions which were conducted as straight-forward open clock auctions without proxy-bidding a video was shown which explained the details of the particular treatment's auction rules, i.e. proxy-bidding in the clock auctions, the revelation of demand, and the sealed-bid procedure. The instructions of all treatments can be found at http://ben.orsee.org/supplements/.

Instructions

Introduction
Welcome to this experiment. In this experiment you can earn money. The monetary unit in this experiment is E$ (experimental dollars), where 1 E$ is worth 0.15 AUS$. How much money you earn depends on your decisions and on the decisions of the other participants. Each participant makes her/his decisions by her-/himself at a computer terminal. Communication between participants is not allowed. Please use the computer only for entering your decisions. Please only use the decision forms provided, do not start or end any programs, and do not change any settings.

Situation
In the experiment you are a bidder in a sequence of six auctions. In each of those auctions you are one of altogether 14 bidders in your group. The composition of this group does not change throughout the experiment.
At the end of the experiment one of those auctions will be randomly selected for payoff. Additionally, you receive a lump sum of E$150 for your participation in the experiment. If you made a loss in the auction selected for payoff, i.e. if the price you pay for the goods you purchased is higher than your value for these goods, then your loss will be deducted from this lump sum. However, your payoff will be at least E$33, or AUS$ 5 (i.e your “show-up fee“). Thus, you cannot lose money in this experiment.
In the auctions several units of two different items A and B will be auctioned off. In particular, in each auction 100 units of item A and 80 units of item B are auctioned to the 14 bidders in your group. Both items will be auctioned *simultaneously*.
Before the start of each auction you will be informed of how much the items are worth to you. For each auction you will receive a table that looks like the one below. For each “bundle” of units of A and B, the table states the value of this bundle for you. The values are given in E$.

Please note that the numbers in the table are just an example. In the experiment you will receive a different table for each of the six auctions. Tables also differ between the participants.

All tables have the following properties:

- The more units of an item you purchase, the more the bundle is worth.
- If you purchase more units of an item, additional units may decrease in value.
- Item A is more valuable than item B, i.e. for each bundle, the value of an additional unit of A is at least as high as an additional unit of B.

Your profit in each auction is the value of the units of A and B you purchase (i.e. the value stated in the table), *minus* the price you have to pay for these units (i.e. the price per unit of A times the quantity you buy of A plus the price per unit of B times the quantity you buy of B).

Seat No.	X	Bundle Values									Auction	X
Value (E$)		Quantity Item B										
		0	1	2	3	4	5	6	7	8	9	10
Quantity Item A	0	0	22	44	66	88	107	126	145	164	183	201
	1	27	49	71	93	115	134	153	172	191	210	228
	2	54	76	98	120	142	161	180	199	218	237	255
	3	81	103	125	147	169	188	207	226	245	264	282
	4	108	130	152	174	196	215	234	253	272	291	309
	5	132	154	176	198	220	239	258	277	296	315	333
	6	156	178	200	222	244	263	282	301	320	339	357
	7	180	202	224	246	268	287	306	325	344	363	381
	8	204	226	248	270	292	311	330	349	368	387	405
	9	228	250	272	294	316	335	354	373	392	411	429
	10	250	272	294	316	338	357	376	395	414	433	451
	11	272	294	316	338	360	379	398	417	436	455	473
	12	294	316	338	360	382	401	420	439	458	477	495
	13	316	338	360	382	401	420	439	458	477	495	513
	14	338	360	382	401	420	439	458	477	495	513	531
	15	360	382	401	420	439	458	477	495	513	531	548

Example
Assume, in an auction you purchase 2 units of A and 3 units of B. The prices are E$22 for each unit of A and E$20 for each unit of B. Thus, you pay 2 x E$22 + 3 x E$20 = E$104 for this bundle. According to the table above, the value for this bundle is given in row "2" (Quantity of item A) and column "3" (Quantity of item B), and is equal to E$120. Consequently, your profit from this auction is E$120 – E$104 = E$16. If this auction is randomly selected for payoff, you will receive E$16 x 0.15 AUS$/E$ = AUS$ 2.40. Additionally you receive E$150 (AUS$ 22.50) as a lump sum, such that your total payoff will be AUS$ 24.90.

For your convenience, you will also receive a second table, which, for each bundle of A and B, shows your value of an *additional* unit of A or B, respectively. These values represent the difference between two neighbouring fields in the first table (the one with the total bundle values).
Let us illustrate the use of this second table using the same example as before. According to the first table, a bundle of 2 units of item A and 3 units of item B is worth E$120. The "Additional value" table now tells you how much worth one more unit of item A or one more unit of item B would be. For example, a bundle of 2 units of item A and 4 units of item B, i.e. a bundle with one more unit of item B, is worth E$142. Thus, the value of the fourth unit of item B is E$22. This value can be found in row 2 and column 3 of the "Additional value" table, in the upper right corner. Analogously, the value in the lower left corner of row 2, column 3 of the "Additional value" table tells you the value of the third unit of item A (E$27), if you purchase 3 units of item B.

Value (E$)	Quantity Item B: 0	1	2	3	4	5
Quantity Item A: 0	0	22	44	66	88	107
1	27	49	71	93	115	134
2	54	76	98	120	142	161
3	81	103	125	147	169	188
4	108	130	152	174	196	215
5	132	154	176	198	220	239

Value of additional units (E$)	Quantity Item B: 0	1	2	3	4
Quantity Item A: 0	22 / 27	22 / 27	22 / 27	22 / 27	19 / 27
1	22 / 27	22 / 27	22 / 27	22 / 27	19 / 27
2	22 / 27	22 / 27	22 / 27	22 / 27	19 / 27
3	22 / 27	22 / 27	22 / 27	22 / 27	19 / 27
4	22 / 24	22 / 24	22 / 24	22 / 24	19 / 24

Auction procedure

Each auction runs over several bidding rounds. Each auction starts in the first bidding round with a price of E$1 for each unit of item A and E$1 for each unit of item B. During the auction these prices increase in price steps of E$1 per unit.

In each bidding round you submit bids in which you state how many units of both items you would like to purchase at the prices of the current bidding round. Thus, a bid consists of two quantities: the number of item A units and the number of item B units which you demand at the current prices.

The following rules apply for submitting quantity bids:

- You can demand a maximum of 15 units of item A and 10 units of item B.
- Starting with the second bidding round you can at most demand as many units of A and B together (i.e. the sum of A and B units) as you demanded in the previous bidding round. This "current total bidding limit" will be displayed at the top of your bidding screen.
- Given those limitations, you can freely distribute your "current total bidding limit" between bids for item A and bids for item B.
- Your "current total bidding limit" will be reduced automatically if in a bidding round you demand less units than in the previous bidding round. Thus, your "current total bidding limit" will decrease over the course of the auction, but will never increase.

At the end of a bidding round the system checks the quantities demanded for both items by all bidders in your group.

- If the group demand for an item is larger than the number of units offered (100 units for item A and 80 units for item B, respectively), then the price for the item is increased by E$1 in the next bidding round.
- If the group demand for one item is smaller than or equal to the number of units offered, then the price of that item does not change in the next bidding round.
- If the group demand for each of the two items is smaller than or equal to the number of units offered, then the auction ends.

These rules imply that from one bidding round to the next either the prices for both items increase by E$1, or the price of one item increases by E$1. The auction ends if none of the two prices increase. In that case, the group demand for items A and B at their current prices is smaller than or equal to the number of units offered (100 or 80 units, respectively). The units of both items will be allocated according to the following rules:

- If for an item the group demand at the last price is exactly equal to the number of units offered, then each bidder receives the number of units he or she asked for at the last price, and pays the last price for each unit.
- If for an item the group demand at the last price is smaller than the number of units offered, then each bidder first receives the number of units he or she asked for at the last price. The remaining number of units (the "excess supply") will be allocated proportionally to the unfulfilled demands at the last price at which the group demand was still higher than the number of units offered (second-to-last price). Thus, if you reduced your demand for an item between the second-to-last bidding round and the last bidding round, then you might be allocated a number of units between your demand in the last round and your demand in

the second-to-last round. However, the price for each unit of the item will be the price of the second-to-last round.

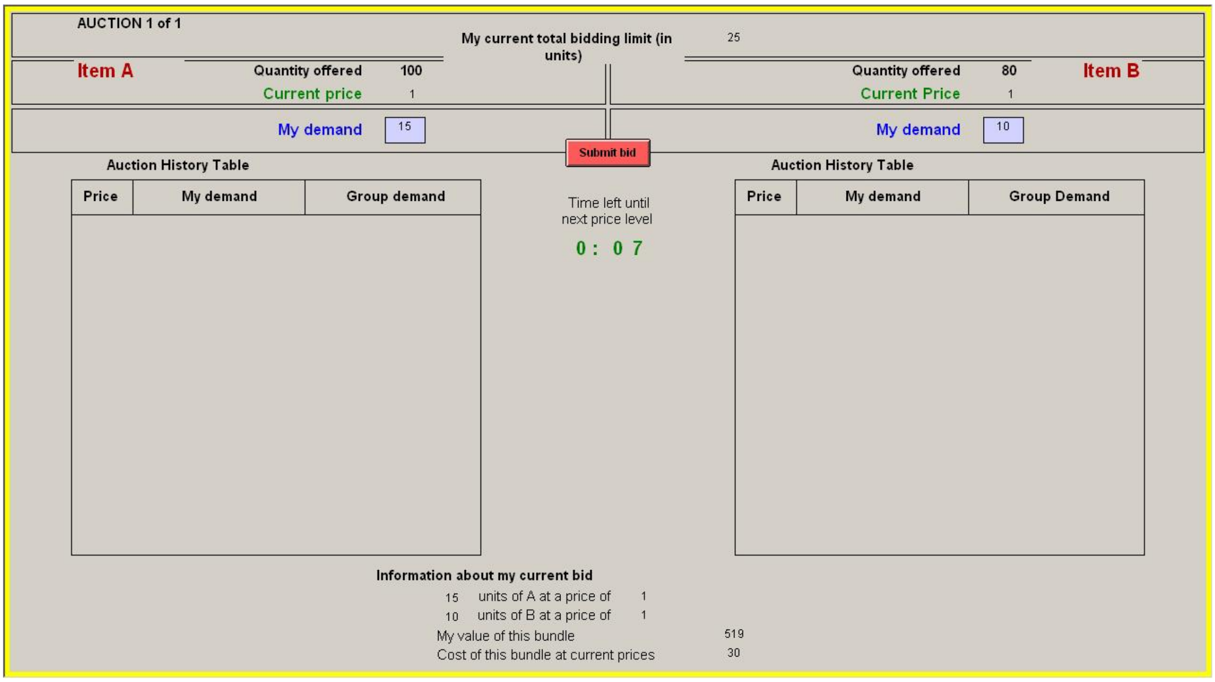
- Additionally, the software will make sure that you are not allocated more units in total than your current total bidding limit. If you shift your demand between items such that you would be allocated more units in total than your current total bidding limit allows, the software will only partially execute this shift. If this happens, the software will inform you that your shift could only be partially executed.

Please note, that if already at the start price of E$1 the group demand for an item is smaller than the number of units offered, then the auction is determined to have failed for that item, and no bidder will be allocated any units of that item.

Examples
In the following examples we assume that the current price for item A is E$9, and the current price of item B is E$7. As in all auctions in this experiment, 100 units of item A and 80 units of item B are offered.

- *If at those prices the group demand for item A equals 110 units, and the group demand for item B equals 92 units, then the auction continues, and the prices for both items will increase by E$1. Thus, the prices in the next bidding round will be E$10 for item A and E$8 for item B.*
- *If, instead, the group demand for item A equals 110 units as before, but the group demand for item B is only 75 units, then only the price for item A increases by E$1. The auction continues, and the prices in the next bidding round will be E$10 for item A and E$7 for item B.*
- *If the current group demand is exactly 100 units for item A and 80 units for item B, i.e. if the group demand exactly equals the number of units offered, then the auction ends in this bidding round. Each bidder receives the number of units he asked for, and pays a price of E$9 for each unit of item A, and a price of E$7 for each unit of item B.*
- *Assume that the group demand for item A equals 100 units as before, but the group demand for item B is only 75 units. Thus, for item A the group demand exactly equals the number of units offered, but the group demand for item B is lower than the supply. The auction ends in this bidding round, and each bidder receives exactly as many units of item A as he or she asked for, and pays a price of E$9 for each of those units. As the group demand for item B is lower than 80 units offered, the price for each unit of B will be the price of the second-to-last bidding round, E$6. Bidders will receive first the number of units they demanded at a price of E$7 (but pay for them only the price of E$6). The remaining 5 units of item B (the excess supply) will be allocated proportionally to the (yet unfulfilled) demands of the bidders in the second-to-last bidding round, at the same price of E$6.*

The screen shot below shows the screen of the bidding software. In the upper part of the screen you see some information about the current state of the auction. In particular, your current total bidding limit and the current prices of both items are displayed. In the row below you see two input fields. Here you enter your demand for both items at the current prices. You must confirm your input by clicking the “Submit bid” button. Your bid will then be displayed in the lower part of the screen. In that part you also see the value of the bundle you are currently bidding on, and the total cost for that bundle if you would purchase it at the current prices. You can correct/update your bid by submitting new bidding quantities until the time of the bidding round runs out.



Please note: In the first bidding round you have 1 minute to submit your bid, in the second round 45 seconds, and in the third and all following rounds 30 seconds. If you do not submit a bid within this time, the program will submit a bid on your behalf. In the first bidding round the program would ask for 15 units of item A and 10 units of item B, in all following rounds the program will just repeat the bid from the previous bidding round. Thus, it is important that you submit your bid in time, in order to avoid the program bidding on your behalf for quantities larger than you would want to purchase. The remaining time of a bidding round is displayed in the middle of the screen, below the button “Submit bid”.

The main part of the screen is divided into two tables, one each for item A and B. Those tables display, for all previous bidding rounds, the price, your own demand at this price, and the group demand at that price.

Altered bid submission in auctions 3 to 6

The first two auctions in this experiment will proceed as described above. In the auctions 3 to 6 there will be a change of procedures that does not affect the auction itself, but only the way in which you enter your quantity bids. Before the third auctions starts we will show you a short movie in which the change in bid submission will be explained. After auction 2 we will ask you to put on the audio headset in order to be able to listen to the audio of the movie.

Concluding remarks

After the last auction has finished, please remain seated and do not communicate with other participants. For paying you, we will call you individually by your seat number. After you have been paid, please leave the room. Please return all instructions and other handouts to the experimenter at the payoff counter.

Before the experiment starts, we will ask a number of comprehension questions on the computer screen. Please enter your answers. The actual experiment will start immediately thereafter.

Video Instructions

After the first two auctions, a video running in the experiment software explained the proxy-bidding interface to the participants. An example of a video's script, referring to the simultaneous clock auctions is given below. All videos including the scripts can be found at http://ben.orsee.org/supplements/.

In the previous two auctions, you submitted a quantity bid for both items in each bidding round. In the following auctions 3 to 6 you will be able to plan all your bids right from the beginning of the auction. The auction then runs automatically according to your plan, such that you do not have to submit bids in each bidding round, and can instead observe how the auction unfolds.

Your bidding screen is very similar to the one you used before. What’s new, is that the two tables in the middle do not only contain the results of the previous bidding rounds, but also your plan for all following bidding rounds. Using the sliders you can instruct the computer how many items it should demand on your behalf at each price.

Consider the following example: We first set the slider of item A at E$8 to 12 units. The computer then automatically reduces all sliders at higher prices to 12 units. This way the computer makes sure that you do not ask for fewer units at lower prices, and that you do not ask for more units at higher prices. Now if you additionally set the slider at price E$14 to 9 units, then the computer will automatically reduce all sliders at higher prices to 9 units, too. Similarly, the computer will automatically increase the sliders at the prices of E$8 and E$9 if you increase the slider at E$10 to 13 units.
In this example we also set the slider at price E$18 to 7 units, and the slider at E$22, and thereby for all higher prices as well, to 0 units. We also adjust our quantity bid plan for item B.

You will have 3 minutes to enter your bidding plan before the start of the auction. All following bidding rounds will last 30 seconds.

You may now observe how the auction proceeds. In our example, the auction continued and the current prices are now E$8 for item A and E$7 for item B.
While the auction proceeds you may always change your bidding plan for the current and all future bidding rounds. This can be done using the respective sliders. In our example you may change your bidding plan for item A for all prices higher than or equal to E$8, and your bidding plan for item B for all prices higher than or equal to E$7.
If, for example, you wish to change your bidding plan and reduce your demand for item A at a price of E$8 from 14 to 13 units, then just change the corresponding slider. A warning message appears in red, noting that by reducing your total demand in this bidding round you will reduce your total bidding limit for future bidding rounds. If you don’t like that, you may avoid a reduction of your total bidding limit by either moving the slider back to its original position, or by increasing the slider of item B by 1 unit. Through this combined change – a reduction of one unit for item A and an increase of one unit for item B – you are shifting your demand from item A to item B without decreasing your future total bidding limit.
For shifting demand at the current price between the two items you may also use the two “Shift demand” buttons. A click on one of these buttons shifts your demand from A to B or vice versa by one unit. Please note that these buttons do not only move the slider at the current price, but simultaneously move all sliders of both items at prices higher than the current price. Also note that you can only shift your demand from one item to the other if your demand for that item is still below 15, if it is item A, or 10, if it is item B, as you cannot ask for more than 15 units of item A or 10 units of item B.

B. Screenshots

Figure B.1: Bidding screen in auctions 1 and 2

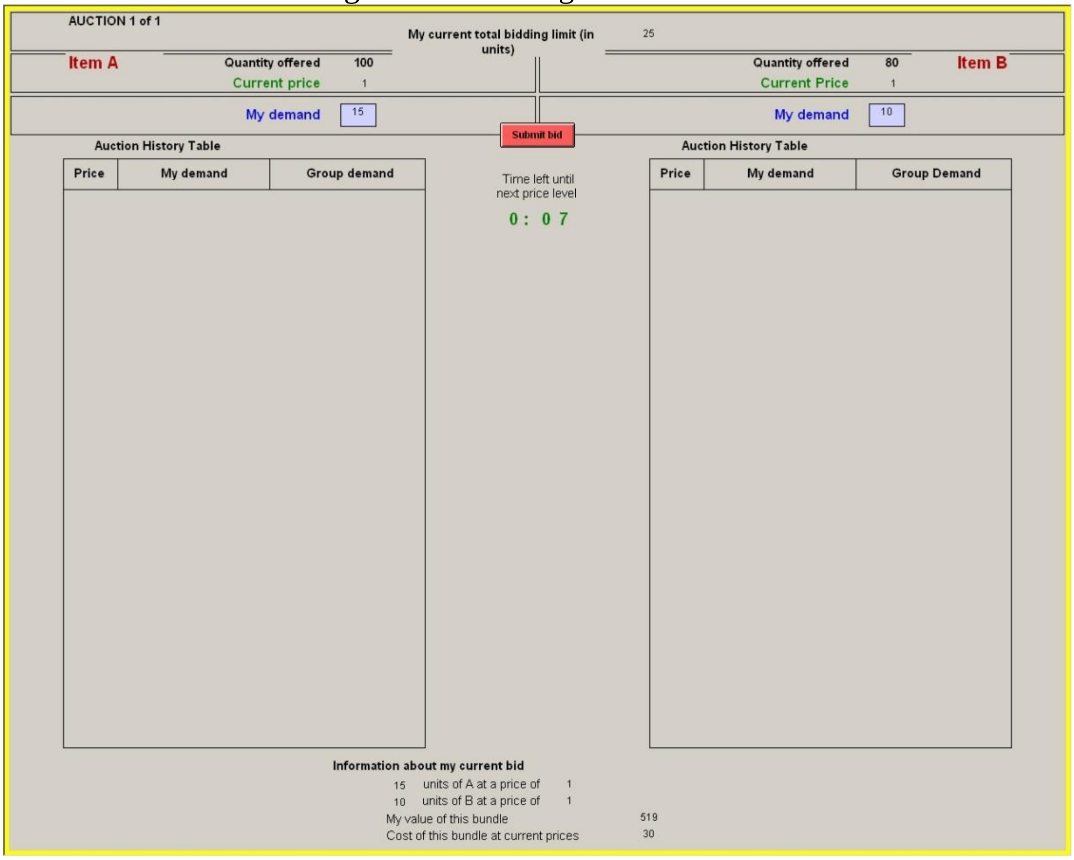
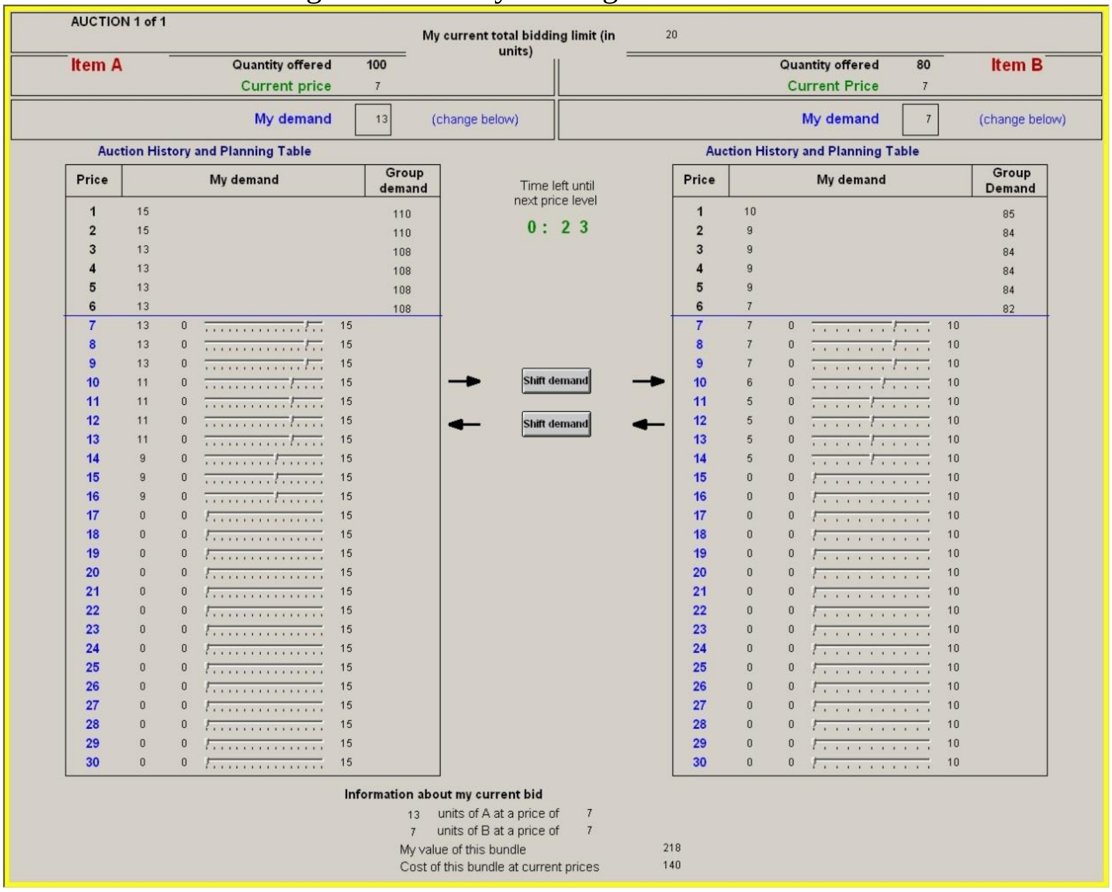


Figure B.2: Proxy-bidding screen in auctions 3 to 6



C. Additional Tables

Table C.1: Average relative efficiency, auction revenue and bidder surplus in all experimental sessions

	Treatment					
	Sealed-bid		Clock, closed		Clock, open	
	Sim	Seq	Sim	Seq	Sim	Seq
Relative auction efficiency						
Session 1	89.8%	92.3%	94.6%	93.9%	94.1%	94.2%
Session 2	91.1%	97.2%	96.8%	95.6%	93.6%	96.8%
Session 3	91.7%	97.3%	96.7%	95.5%	96.5%	94.1%
Session 4	86.0%	87.2%	88.9%	87.0%	87.8%	87.0%
Session 5	81.3%	83.7%	78.5%	82.6%	83.0%	82.2%
Session 6	75.1%	78.8%	74.6%	75.0%	76.9%	78.0%
Relative auction revenue						
Session 1	76.7%	94.5%	77.1%	90.9%	91.1%	96.7%
Session 2	76.5%	99.6%	94.9%	95.8%	79.8%	93.0%
Session 3	85.5%	88.7%	88.5%	77.5%	86.3%	90.4%
Session 4	71.0%	93.8%	82.7%	98.2%	79.3%	83.3%
Session 5	94.9%	88.7%	97.2%	89.7%	77.1%	94.4%
Session 6	80.1%	97.6%	87.7%	87.0%	90.5%	93.3%
Relative bidder surplus						
Session 1	136.8%	86.0%	156.2%	105.6%	105.5%	86.2%
Session 2	156.0%	89.5%	105.2%	94.9%	152.8%	114.3%
Session 3	117.7%	133.7%	131.7%	174.0%	140.3%	109.0%
Session 4	159.7%	51.3%	120.0%	33.5%	130.3%	105.5%
Session 5	32.8%	65.2%	9.7%	57.4%	104.7%	37.8%
Session 6	57.9%	4.9%	21.3%	30.1%	26.3%	19.1%

Table C.2: Average relative prices for items A and B and variances of relative prices, in all experimental sessions

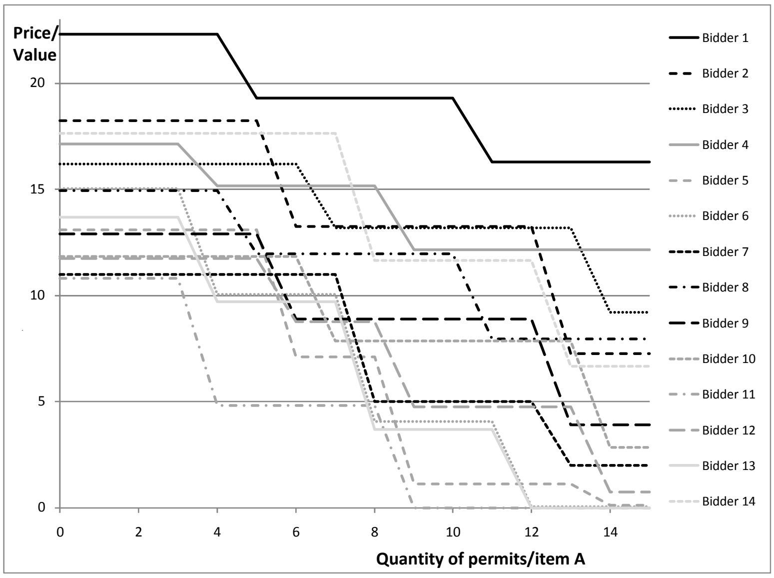
	Treatment					
	Sealed-bid		Clock, closed		Clock, open	
	Sim	Seq	Sim	Seq	Sim	Seq
Relative price of Item A						
Session 1	0.83	1.04	0.77	0.98	1.00	1.06
Session 2	0.82	1.05	0.98	1.07	0.80	0.96
Session 3	0.92	0.94	0.92	0.92	0.90	1.00
Session 4	0.78	1.00	0.87	1.09	0.83	0.91
Session 5	1.00	0.94	1.02	1.02	0.85	1.02
Session 6	0.87	1.02	0.91	0.96	0.96	1.00
Relative price of Item B						
Session 1	0.68	0.80	0.77	0.81	0.79	0.83
Session 2	0.69	0.92	0.90	0.80	0.79	0.88
Session 3	0.78	0.82	0.84	0.58	0.81	0.78
Session 4	0.62	0.86	0.77	0.84	0.75	0.73
Session 5	0.88	0.82	0.90	0.73	0.66	0.85
Session 6	0.71	0.92	0.84	0.75	0.83	0.84
Variance of relative price of Item A within session						
Session 1	0.023	0.012	0.011	0.020	0.009	0.002
Session 2	0.029	0.015	0.005	0.003	0.015	0.005
Session 3	0.005	0.002	0.005	0.023	0.002	0.005
Session 4	0.014	0.005	0.003	0.006	0.005	0.005
Session 5	0.019	0.002	0.002	0.006	0.011	0.006
Session 6	0.001	0.001	0.023	0.002	0.002	0.004
Variance of relative price of Item B within session						
Session 1	0.012	0.044	0.013	0.017	0.017	0.016
Session 2	0.019	0.014	0.006	0.012	0.005	0.002
Session 3	0.005	0.004	0.006	0.021	0.008	0.010
Session 4	0.008	0.005	0.003	0.002	0.020	0.001
Session 5	0.010	0.004	0.007	0.013	0.012	0.014
Session 6	0.010	0.000	0.009	0.007	0.016	0.003

D. Discussion of Details of the Experimental Auction Design

Generation of demand structures

To create the six demand structures, we first generated marginal value functions for Item A. We randomly and independently drew intercept (uniformly distributed on {14, 15, …, 24}) and slope (uniformly distributed on [-0.4, -1.6]) of a linear, decreasing function. We then mapped this linear function to a step function with randomly drawn step-lengths (uniformly distributed on {3, 4, … , 7}), with the value of each step equalling the value of the linear function at its left end, rounded to the next integer. As an example, Figure D.1 shows the resulting marginal value functions for Item A for each of the 14 bidders in our experimental demand structure 3.

Figure D.1: Individual demand curves induced in demand structure 3



Then, we derived the marginal values for Item B units by multiplying the Item A step function with a discount factor of either 1.0 or 0.8. To compose valuations over A-B-bundles, we modelled asymmetric substitutability of the two items, in that a unit of Item A can substitute a unit of Item B unit but not vice versa. As a result, given any bundle, the marginal value of one more unit of Item A was always at least as high as the marginal value of one more unit of Item B.

Uniform pricing rule

Under uniform pricing, different pricing rules may be applied. The two most prominent rules are the "lowest accepted bid" rule (LAB), stating that the lowest price of all winning bids determines the price which all winning bidders have to pay, and the "highest rejected bid" rule (HRB), under which the final price of the auction is given by the highest price of all losing bids. Sujarittanonta and Cramton (forthcoming) argue that in environments with unit-demand, from a theoretical perspective, HRB outperforms LAB in particular in terms of efficiency. For a large number of losing bidders, Mezzetti and Tsetlin (2008) show that the bidding functions for HRB and LAB converge. With respect to a smaller number of bidders, the authors point out that the HRB rule yields a continuum of undominated asymmetric equilibria, and that it provides incentives for collusive agreements which do not exist under LAB. Due to these properties LAB may be preferable in practical applications. Indeed, Cramton et al. (2009) find in an experiment with two bidders that LAB yields higher revenues, and conclude that this might be a reason for the frequent use of this rule in central bank auctions, spectrum auctions as well as consumer auctions on the Internet.

With multi-unit demand, however, the two rules will only yield different prices if at the end of the auction demand exactly equals supply. Otherwise demand must be rationed (see below for the rationing rules we apply in this case), and both LAB and HRB yield the same final price. This case is even more likely the more units are auctioned and the more bidders participate. The latter also reduces the probability that a bidder will impact the closing price, such that the strategic differences between the two rules diminish. In our experimental design, we follow the predominant practice and use the LAB rule. This means that when all clocks stopped, the final price for each vintage is the price at which demand exactly equals supply, and the second-to-last price step if demand is lower than supply. (The HRB rule would specify the second-to-last price in both cases.)

Activity requirements

Activity rules control the pace of an auction by requiring minimum levels of bidding activity (Cramton, 1997). Milgrom (2004) argues in his assessment of the simultaneous ascending auction format used in the first radio spectrum auctions in the U.S. in 1994 that activity rules are important to restrict wait-and-see strategies which may lower revenues if auctions end (too) early. Typically, an activity rule requires that the total demand of a bidder may not increase from round to round as prices are increasing. In a strict implementation, bidders lose “bidding rights” if they do not fully utilize their bidding eligibility. Many actual auctions, however, apply weaker versions which require activity levels below 100% (e.g. FCC spectrum auctions or German 4G spectrum auction). This is particularly the case if the different items are difficult to compare. This heterogeneity does not hold for emissions permits intended to be used in a particular time period. Thus, in the experiment we apply a straightforward activity rule which does not allow bidders to increase their total demand (the sum of demanded quantities over all vintages) from one price step to the next. In the OC and CC treatments, this still allows for shifting demand between the items. In the SB treatment switching between items is not possible because the bidding language does not allow for conditional or package bids, such that the demand schedule must be monotonically decreasing for both vintages individually.

Bid rationing

If price steps are discrete and the number of auctioned items is large, then aggregate demand at the closing price of the auction will typically not exactly equal supply. One way to deal with this is to allow for intraround bids (Ausubel and Cramton 2004). Another (less involved) solution is to set the final price to the last step at which demand still exceeded supply (i.e. the second-to-last price step), and to use a tie-breaking rule to determine which of the bids at the final price are fully served and which are rationed. In order to maximize allocative efficiency, particularly those bids must be served where the bidders' values for the items are higher than the closing price. Thus, a first allocation is made according to demand at the last price step. The remaining supply may be distributed proportionally, randomly, or according to bid timing. Note, however, that 1) with uniform pricing different allocation rules will not result in different auction revenues, and 2) if bids are close to the bidders' (marginal) valuations, the allocation rule does not (strongly) affect efficiency or the bidders' surplus as the rationed bidders are approximately indifferent with respect to acquiring the units at the final price or not.

In our experiment we allocate the remaining supply (after demand at the last price step has been fulfilled) proportionally to the remaining demand at the final price. This procedure is common in financial markets (e.g. IPOs) or central bank auctions (e.g. Term Auctions of the U.S. Federal Reserve). A further, rather technical issue in proportional allocation is the rounding of fractions smaller than the unit size. Again, any rounding rule is feasible. In the experiment we use the largest remainder method (also known as the Hare-Niemeyer rule and commonly applied in proportional representation voting).

Switching demand in clock auctions

The principle idea of simultaneous clock auctions is to give bidders the flexibility to switch between vintages. Generous switching, however, is not without pitfalls. Any switching rule must obey two basic conditions: First, aggregate demand must never fall below total supply if at any time during the auction aggregate demand was at least as high as supply (efficiency requirement), and second, a bidder may never obtain in total more items than the activity rule allows (eligibility requirement). A natural approach which stems from the analogy of simultaneous ascending auctions is to announce "temporarily assigned quantities" (similar to "standing high bids").[26] This rule has been applied in numerous spectrum auctions around the world. So it seems applicable in permit auctions as well.

The focus of this experiment, however, is on the comparison of different auction types. In order to not distort observations by differences in the user interface, very similar interfaces with the same visual appearance were used in all auction designs. A switching rule based on temporarily assigned quantities had required major changes on the software interface. Thus, in the experiment we employed a different approach which allowed (ex-ante) unrestricted switching (within the limits of the bidders' respective activity rule constraints). If demand for an item dropped below supply solely due to switching, the respective switches were (ex-post) proportionally reduced

[26] According to a "temporarily assigned quantities"-rule, only the remaining (not temporarily assigned) demand of a bidder would be considered as free bidding rights, and a bidder would be free to decide on the vintage for which she would like to use these rights. Thus, a bidder would be (ex-ante) restrained to switch not more than an amount equal to his free bidding rights. Obviously, the rule obeys both the efficiency and the eligibility requirement.

such that both the efficiency and the eligibility requirement were met. This ex-post adjustment allowed maximum flexibility for bidders and ensured that the activity rule was obeyed.

Bid sorting in sealed-bid auctions

In an emission trading scheme permits can typically be transferred forward into future periods without restrictions, but the reverse does not hold. Holt et al. (2008) discuss the possibility of price inversions when two or more vintages are sold in separate simultaneous sealed-bid auctions. In this case, the price of the later vintage may exceed the price of the earlier one, which is inconsistent with the fact that an earlier vintage can substitute the later, and hence, is at least as valuable. This is not a problem in clock auctions where bidders are able to shift demand during the course of the auction, thereby being able to avoid price reversals.

To fix the problem, Holt et al. (2008) suggest "automated sorting of bids in combined vintage auctions". They propose an algorithm which considers a consolidated list of the bids for all items. The algorithm allocates the items starting with the highest bid and then continues down the list. As long as the items are available that the bidder has bid on, the bidder receives a unit of that item. If, however, a bid of a later vintage is supposed to be served, but only units of earlier items are available, then the bid is automatically served with a unit of the more valuable item.

While the algorithm by Holt et al. (2008) prevents inverted prices, it may allocate more valuable items for higher prices to lower bids.[27] In our experiment, we apply bid sorting, but improve Holt et al. (2008)'s algorithm in order to maintain a monotone bid-value relation. In particular, we consider the sealed bids as proxy bids of a clock auction. If in one round only the clock of the later vintage would tick forward and thereby show a higher price than the clock of the earlier vintage, the algorithm automatically shifts demand from the later to the earlier vintage such that either both clocks stop and the auction ends or the aggregated demand for the earlier vintage is exactly one unit larger than supply, so that at least this clock ticks forward. [28] Again, the amount of the shifted demand is allotted proportionally on all bids and fractions of a unit are dispensed according to the Hare-Niemeyer rule.

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[27] Consider Example 1 in Holt et al. (2008, p. 10). In the example, permits of two vintages, 2009 and 2012, are auctioned. Without bid sorting the 2009-permit would sell for $1 and the 2012-permit would sell for $4. Moreover, a bid of $4 for the 2012-permit would be rejected (note that Holt et al. use HRB in their example), so the allocation likely is inefficient. With bid sorting the afore rejected $4 bid for 2012 is allocated a 2009 permit which can be used in 2012. Given the numbers in Holt et al.'s example, the price for a 2009-permit increases to $3 and the 2012 price drops to $2, so price inversion is avoided. Note, however, that in the example there is another bid of $5 for a 2012-permit. The respective bidder obtains a 2012-permit at $2. So the lower bid of $4 receives a more valuable and more expensive good.

[28] Strictly speaking, in order to prevent inverted prices automatic demand shifting is also necessary if in one round the demand for the earlier vintage drops below supply and demand for the later vintage exactly equals supply. Due to our use of the LAB pricing rule one special case must be considered: If aggregated demand is smaller than aggregated supply, then demand must be shifted such that the resulting demand for the later vintage is one unit smaller than its supply. Otherwise the price for the later vintage would be set to the last price step of the clock and the earlier vintage would sell at the second-to-last price step, i.e. the earlier vintage would still sell for a lower price.

Order of vintages in sequential auctions

When selling two or more vintages sequentially, one has to decide on their order. Bernhardt and Scoones (1994) discuss such issues using a model with private (partly unknown) values, and show that auctioning the good with the more dispersed buyer valuations first yields higher revenues for the seller. In a permit trading context, valuations of the earlier vintage are likely more dispersed as short-term abatement costs depend on the actual (possibly heterogeneous) situations of the companies whereas longer-term abatement costs depend more on the available technologies as well as overall market developments such as (relative) primary energy prices (e.g. prices for coal vs. prices for gas which hold for the whole industry) or the price of the permit in the secondary market. Another aspect regarding the sequence of auctions is that empirically declining prices are persistently observed in sequential auctions, a phenomenon commonly referred to as declining price anomaly or afternoon effect (Ashenfelter, 1989). Even though this effect refers to homogeneous goods, it is also of relevance for permit vintages because of their (asymmetric) substitutability, with the earlier vintage being somewhat more flexible with respect to its use and, thus, more valuable. According to McAfee and Vincent (1993), the declining price anomaly results in inefficient outcomes with positive probability. We conjecture that inefficiency will be even higher if more valuable items (earlier vintages) were auctioned later than less valuable items (later vintages) as the price anomaly might invert the theoretical price structure. Thus, in our experiment we auction Item A (i.e. the earlier vintage) first. This also seems to be best practice: both in RGGI and the Virginia NOx scheme, earlier vintages are auctioned first.

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