Collusion in private value ascending price auctions

Katerina Sherstyuk*
University of Melbourne and University of Hawaii†

Abstract

We investigate the effects of bid improvement rules and bidder value asymmetry on bidder collusion in experimental ascending price auctions without communication. We find that the strict bid improvement rule and private values are not always sufficient to break collusion among well-motivated bidders. Collusion still occurs as long as bidder gains from collusion are high.

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†Department of Economics, University of Hawaii at Manoa, 2424 Maile Way, Honolulu, HI 96822. Fax: (808)-956-4347; phone: (808)-956-7851; email: katyas@hawaii.edu

1 Introduction

The issue of bidder collusion in auctions has been gaining increasing interest due to the growing use of auction mechanisms in government procurement and privatization programs in many countries. Bidder collusion, if occurs, may be detrimental for both social efficiency and governments' auction revenue. It is therefore essential to investigate the institutional features that safeguard against collusion and provide for socially efficient outcomes.

Collusion in auction markets has been studied by both economic theorists (Milgrom, 1987; Graham and Marshall, 1987; McAfee and McMillan, 1992) and experimentalists. Experimental studies indicate that while double oral auctions are not susceptible to collusion (Isaac and Plott, 1981; Clauser and Plott, 1993), conspiracies can be quite effective in posted-offer and sealed bid markets, provided that the sellers (buyers) are allowed to communicate between periods (Isaac, Ramey and Williams, 1984; Isaac and Walker, 1985; Kwasnica, 2000). The growing empirical literature presents evidence of bidder collusion in both sealed bid auctions, such as auctions for state highway construction contracts (Feinstein, Block and Nold, 1985; Porter and Zona, 1993) and school milk markets (Porter and Zona, 1999), and oral ascending bid auctions, such as forest service timber sales (Baldwin, Marshall and Richards, 1997). Collusion was of a significant concern in recent Federal Communications Commission airwaves auctions, which employed a simultaneous multi-unit ascending auction format (Cramton and Schwartz, 2000).

We study bidder collusion in experimental one-sided ascending price oral auctions where no explicit communication among bidders is allowed. Many researchers argue that ascending English-type auctions have an advantage over the sealed bid procedures in solving complex allocation problems such as allocation of airwave licenses (McAfee and McMillan, 1996). The advantage is due to a richer action space and a superior information feedback that bidders get in iterative procedures as compared to one-shot sealed-bid auctions. However, it is also well recognized that these very features of iterative procedures make such auctions more susceptible to bidder collusion (Robinson, 1985; Milgrom, 1987; Cramton and Schwartz, 2000). Fine details of institutional design may make a difference in safeguarding against or in facilitating bidder collusion.

We address two issues of interest in studying bidder collusion in ascending price auctions. First, what is the role of the strict bid improvement rule (also called the increment rule) in providing for competitive outcomes in one-sided ascending price auctions? Second, how do degree of asymmetry and bidders' expected gains from suppressing price competition affect bidder collusion? In our previous study (Sherstyuk, 1999) we show that the absence of the strict improvement rule greatly facilitates bidder collusion in common value, common information environments. If all bidders have the same value for object and are allowed to match each others' bids, and winners are chosen randomly from the set of highest bidders, then collusive outcomes prevail in ascending-price auctions. All bidders submit equal low bids, and the objects are assigned randomly; deviations can be deterred by trigger or bid matching strategies within the same auction period.[1] In contrast, sealed bid auctions conducted in the same environment without communication yield competitive outcomes.

The occurrence of collusion in a complete information environment with symmetric bidders may not be surprising given a large body of experimental evidence which indicates that, generally, symmetry and complete information help to sustain collusion (Holt, 1995). In this study, we relax the symmetric valuations, complete information assumption, and investigate the robustness of bidder collusive behavior in private values, private information environments. When all bidders have identical valuations, competitive bidding invariably leads to zero profits to all bidders; the bidders have nothing to lose by colluding. However, if objects' valuations vary across bidders and are their private information, collusion may be harder to achieve and sustain, even if expected gains from collusion are substantial to all bidders. In private value environments, high value bidders' expected payoffs in competitive equilibrium are no longer zero; the opportunity cost of following competitive strategies is reduced as compared to the symmetric valuations case.

Are symmetry of bidder valuations and complete information essential for bidder collusion, or is collusion mostly driven by bidder payoff gains and can be sustained under private values, private information environments? Is absence of the strict improvement rule critical for facilitating collusion, or bidders may collude even if bid matching is ruled out? Below we report on series of experiments that allow us to answer these questions. We investigate whether collusion is sensitive to the degree of asymmetry in bidder valu-

[1] In many discussions of antitrust policy, identical bids are interpreted as suggestive of cartel agreements, even though other forms of cartel arrangements, such as bid rotation, may prevail among colluding firms; see Comanor and Schankerman (1976). There is empirical evidence that auction rules that allow for bid matching lead to supracompetitive pricing even if the ties in bids of equal value are not broken randomly. In Cook County (Chicago), Illinois, contracts for tax lien collection are allocated in a sealed bid auction, where the ties are broken in favor of firms who have large historical market shares. Firms in this market were recently facing a class-action antitrust lawsuit, alleging anti-competitive bidding. Another example is retail online auctions "Onsale" (http://www.onsale.com) that use the "Yankee auction" format. In a Yankee auction, one or more identical items are offered for sale at the same time. When the auction closes, the highest bidders win the available merchandise at their bid price. Bids are ranked in order of price, then quantity, then time of initial bid. During the auction, the information about the current highest bidders and their bids is posted at the web site. Bidders can also post a comment together with their bid. Bid matching is very common in these auctions, and comments such as "Keep it cheap" are not unusual.

ations, payoff gains from collusion as compared to the competitive equilibrium, and the bid improvement rule adopted in the auction. We further consider how auction outcomes are affected by subjects' previous training in other experimental markets.

2 Experimental design

The experiments were designed to answer three main questions of interest. First, is a small degree of asymmetry in bidder valuations sufficient to break down the collusion that was observed in the complete information, symmetric valuations case, even if potential gains from collusion are high to all bidders? Second, how do occurrence and stability of collusion depend on bidder gains from collusion as compared to the competitive equilibrium outcome? Third, how important is the bid improvement rule for bidder collusion in private value environments?

To make a clear comparison between the complete information, symmetric valuations case studied earlier, and the private information, private values case considered here, many features of the experimental design are as in Sherstyuk (1999). There are three bidders in the market and two identical objects for sale. Each bidder demands exactly one unit in a given period. Two institutions are considered: the weekly ascending oral auction (W), where each subsequent bid submitted to the market has to be no lower than the highest outstanding bid; and the strictly ascending oral auction (S), where each subsequent bid has to be strictly above the outstanding bid.[2] Under both institutions, the soft closing rule is used to end periods: the period is closed when no new bids are incoming for 30 seconds. At the end of the period, the units are allocated to the two highest bidders, at the prices equal to their respective bids, provided that the bids are no lower than the seller's reservation price. In W auctions, ties in the bids of acceptances, if any, are broken by random choice of buyer; no ties are allowed in S auctions[3]

In the common values experiments reported earlier, all bidders had the same value of 100 experimental francs for the object, which was common information. The seller's reservation price was 5 francs and was announced at the beginning of each period. We will refer to these experiments as the benchmark common values (C) treatment. In the present study, we consider two private values, private information treatments that differ only in the support from which the bidders' private values were drawn. In the *low asymmetry* (L) treatment, the values were drawn from the uniform distribution with the support of $[90, 100]$ experimental francs; in the *high asymmetry* (H) treatment, the support was

[2]In Sherstyuk (1999), the comparison was between the weakly ascending and the sealed bid auctions.
[3]Experimental instructions are available from the author upon request.

changed to $[50, 100]$ francs. Bidder valuations and bids submitted were constrained to be integers. The seller's reservation price was 10 francs in both cases.[4] Figure 1 illustrates.

FIGURE 1 ABOUT HERE

The distributions of values and the seller's reservation price were chosen so that expected payoff gains from collusion relative to the competitive equilibrium were substantial in all cases. This was achieved by keeping the minimal (seller reserve) price substantially below the lower support of bidder valuations.[5] Further, even though the supports of bidder values differed across treatments, the current design effectively constrained bidder action spaces to the same maximal range of $[0, 100]$ francs. Thus, bidders had comparable across treatments opportunities to coordinate their actions within a given auction period.[6]

For a given degree of values asymmetry, weakly ascending (W) auctions were compared with strictly ascending (S) auctions to evaluate the importance of the strict bid improvement rule.

The low asymmetry [90,100] L treatment was introduced to assess whether a small degree of asymmetry would be sufficient to break down the collusion which was observed in the benchmark common values C treatment. The high asymmetry [50,100]H treatment in comparison with the [90,100] L treatment was used to study how the degree of values asymmetry and gains from collusion affect bidder collusive behavior. Observe that the gains from collusion were higher, and the expected payoffs in the competitive equilibrium were lower in the L treatment than in the H treatment. Theoretically, with 3 bidders and 2 objects, the competitive equilibrium price is equal to the lowest value drawn among the three bidders. If the values are drawn from the uniform distribution with the support

[4]The reserve price of 10, instead of 5 experimental francs, was announced by mistake in the first experimental session, and was then replicated in each session. The difference between 5 and 10 experimental francs was negligible.

[5]If the seller is well informed about the distribution of bidder valuation, he or she has no reason to set the reserve price below the bidder value support. Several recent studies demonstrate, however, that an asymmetric information setting may be more appropriate in modeling procurement auctions. Feinstein, Block, and Nold (1985) argue that colluding firms have a strategic interest in keeping the purchaser misinformed, and support their theory with the highway construction auctions data; Hendricks and Porter (1988) show that better informed bidders are the ones who coordinate on their bidding decisions in federal auctions for offshore drainage oil leases. Baldwin, Marshall and Richard (1997) note that the reserve price of the Forest Service timber auctions is always very low. Alternatively, as suggested by McAfee and McMillan (1992), the minimal (reserve) price may represent bidders' shared perception of how low a bid they may get away with, without either causing a seller to refuse to sell or arousing the suspicion of the antitrust authorities.

[6]The common reserve price and the common upper bound on valuations also ensured a comparable market duration across treatments. This was an important design consideration, given the soft closing rule used in the auctions.

$[\underline{v}, \bar{v}]$, then, in the competitive equilibrium, the expected payoff of bidder i who has a value v_i is:

$$EP^{CE}(v_i) = \frac{(v_i - \underline{v})^2}{(\bar{v} - \underline{v})^2}(\bar{v} - v_i/3 - 2\underline{v}/3) \tag{1}$$

In a W auction, if all bidders collude and submit bids equal to the seller's reservation price $\underline{p}$, then each bidder has a two thirds chance of buying the unit at the minimal price. The expected payoff from collusion, given a value of v_i, is:

$$EP^{Coll}(v_i) = 2(v_i - \underline{p})/3 \tag{2}$$

The same expected payoff can be obtained by bidders in an S auction if bidders rotate their bids across periods, i.e., take turns in buying the objects at the reserve price.

Define the absolute expected gains from collusion as the difference between expected payoffs at the collusive and the competitive equilibrium outcomes:

$$AG(v_i) = EP^{Coll}(v_i) - EP^{CE}(v_i) \tag{3}$$

We may expect the absolute gains to be important for collusion if bidders, in deciding what strategy to follow in the ascending auction, seek to achieve a payoff maximizing outcome. We may further conjecture that the magnitude of payoffs at the competitive equilibrium by itself is important for bidder collusion. Suppose, for example, that bidders are short-sighted and seek the opportunities to collude only if they find that their payoffs at the competitive equilibrium are "too low". Such boundedly rational bidders may stay at the competitive equilibrium even if the absolute gains from collusion as compared to the competitive equilibrium are high. We account for a possible effect of the payoff magnitude at the competitive equilibrium by measuring relative expected gains from collusion, which indicate the percentage gain from collusion relative to the competitive equilibrium payoff:

$$RG(v_i) = \frac{AG(v_i)}{EP^{CE}(v_i)} \cdot 100\% \tag{4}$$

It is straightforward to show that as long as the seller's reservation price is no higher than the lower bound of the support of bidders' valuations, the relative gains from collusion are non-negative for all bidder types, but are strictly decreasing in bidder valuations. A bidder who draws the value of $\underline{v}$ is certain to gain nothing in the competitive outcome, and therefore may have strong incentives to collude. On the contrary, a bidder who draws $\bar{v}$ expects a positive gain from the competitive outcome; his incentives to collude, as measured by either absolute or relative gains from collusion, are minimal among all bidder types. Thus, we can compare the different treatments on the basis of gains from collusion to the bidder with the highest value. Table 1 presents such a comparison.

TABLE 1 ABOUT HERE

Table 1 indicates that both absolute and relative gains from collusion are higher under the L than under the H treatment, provided that a common exchange rate is used to convert experimental francs into dollars. Thus, under a common exchange rate, we may expect the L treatment to result in more collusive outcomes as compared to the H treatment due to the absolute and (or) relative gains increase. Further observe that by manipulating exchange rates, we can create the high and low asymmetry designs that have identical absolute gains from collusion in dollar terms and differ only in relative gains, and thus investigate the effect of relative gains alone.[7] This will allow us to investigate whether *absolute* or *relative* payoff gains are more important for collusion occurrence.

We also consider how bidder collusion in our experiments depends on subjects' previous training in other experimental markets. We used two subject pools in the experiments: Melbourne University students (Australia) and Caltech students (USA). Most Melbourne university students had no prior experiences with experimental markets. Most Caltech students have previously participated in a number market experiments. Both weakly ascending (W) and strictly ascending (S) auctions were conducted at Melbourne University; experiments at Caltech involved W auctions only. The low and high asymmetry treatments with a common dollar exchange rate were tested in the W auctions at Melbourne. The design that isolated the effect of relative gains from collusion, keeping the absolute gains constant, was implemented in the S auctions at Melbourne, and in the W auctions at Caltech.

The features of experimental design are summarized in table 2.[8]

TABLE 2 ABOUT HERE

Procedures The total of twenty four experimental sessions were conducted: sixteen sessions at Melbourne university, with eight W auctions and eight S auctions, and eight

[7] Such design variation also isolates the effect of "asymmetry" as such, i.e., the spread of bidder values, from the effect of absolute payoff gains, on bidder collusion.

[8] Table 2 shows that the dollar exchange rates in W auctions at Caltech were higher than in W auctions at Melbourne for both L and H treatments. Thus, one could argue that incentives to collude in W auctions were higher at Caltech than at Melbourne. This argument is complicated by possible differences in subjects' opportunity costs and in purchasing power of Australian and US dollar in respective domestic markets. As will be discussed in the next section, the differences in the exchange rates between Melbourne and Caltech experiments do not prevent us from answering the research questions of interest.

sessions at Caltech, all with W auctions. For each subject pool, half of the sessions were conducted under the low asymmetry L treatment, $v_i \in [90, 100]$, and half sessions under the high asymmetry H treatment, $v_i \in [50, 100]$. All experimental procedures in W auctions, other than the private value draws, were identical to the benchmark common values experiments conducted earlier at Melbourne. All experimental procedures, up to the differences induced by bid improvement rules, were identical between W and S auctions. Most Melbourne university subjects were undergraduate students in economics and commerce, all recruited through posted flyers or class announcements. All Caltech subjects were recruited through a web recruitment program; there were both undergraduate and graduate students among the subjects. Each session involved three subjects. The sessions were conducted as non-computerized experiments; the subjects were seated in a classroom, behind each other, and two rows away from each other, to guarantee that they could not see each other's faces. No communication was allowed. Each session consisted of 15 identical periods, preceded by one practice period. At the beginning of each period, each bidder's private value was drawn from a big envelope by the experimenter. The subjects were explained that the envelope contained around 1000 numbers, and there was an equal number of each value between the lowest one (either 50 or 90) and 100 in the envelope. In each auction period, all bids together with bidder ID numbers were recorded on the overhead. In W auctions, ties in the bids of acceptance were resolved in front of the subjects by an assistant or by one of the subjects, using cards marked with bidders' ID numbers. At the end of each session, subjects were paid their earnings in private, plus $5 participation fee (Australian and US dollars, respectively).

3 Results

The results on auctions' overall performance, pooled by treatment and subject pool, are summarized in figure 2 and table 3. Since the competitive equilibrium price in a given period depends on specific realization of bidder values, we cannot use the observed auction prices to compare the auction outcomes within a treatment and across treatments. We use the following measure of auction competitiveness. Let v^1, v^2 and v^3 denote bidder valuations in a given period, ranked from the highest to the lowest. Let b^1, b^2 and b^3 denote the bidders' final bids, also ranked from the highest to the lowest. According to the competitive equilibrium prediction, $b^1 = b^2 = v^3$; according to the collusive prediction, $b^1 = b^2 = \underline{p}$. The percentage of market competitiveness is given by:

$$Comp = \frac{b^1 + b^2 - 2\underline{p}}{2(v^3 - \underline{p})} \cdot 100\% \quad (5)$$

The market competitiveness is at 0% in the collusive equilibrium, and is at 100% in the competitive equilibrium. It will exceed 100% if the units are traded at prices above the competitive equilibrium prediction v^3.[9]

FIGURE 2 ABOUT HERE

The dynamics of average market competitiveness in private value auctions pooled by treatment is illustrated in figure 2; the data from the benchmark common values C treatment is also added for comparison. Figures 3-5 in the appendix graph the dynamics of market competitiveness in each of the private value treatments, by session. The figures also report, for each session, the average market competitiveness and, for W auctions, the percentages of collusive-type matches in the end-of period bids (to be discussed in detail in section 3.2 below). Descriptive statistics on market competitiveness by treatment are summarized in table 3. To trace possible effects of subjects' experience, we divided all observations into two time intervals: the early periods (periods 1-8), and the late periods (periods 9-16).[10]

TABLE 3 ABOUT HERE

We first consider overall performance of the auctions and the effects of private values, and then turn to the role of bid improvement rules in achieving and sustaining collusion.

3.1 Effects of private values and gains from collusion

Result 1 *Private values and asymmetry alone were not sufficient to break down the collusion in the oral auctions where gains from collusion were high. Collusive tendencies were present and persisted under the low asymmetry treatments in Melbourne experiments, and both high and low asymmetry treatments in Caltech experiments.*

Support: Figures 2-5, table 3. The average across sessions value of market competitiveness under the low asymmetry treatments was 56.27% (LW auctions, Melbourne), 58.62%

[9]This measure is closely related to the index of monopoly effectiveness used to evaluate the performance of market insitutions (e.g., Davis and Holt, 1993, p. 134). We employ the market competitiveness measure since under our design, it closely traces, both graphically and numerically, the dynamics of auction trading prices.

[10]Period 1 was the practice period. We include it in the data analysis since it may contain valuable information about the subjects' initial perceptions of the game.

(LS auctions, Melbourne), and 30.52% (LW auctions, Caltech); it was 45.23% under the high asymmetry HW treatment at Caltech. With the exception of the LS treatment at Melbourne, these values are below the competitive equilibrium prediction of 100% at the 5% level of significance according to the t-test (one-tailed).[11] Moreover, the mean competitiveness decreased from the early periods to the late periods in all of these treatments. □

Result 2 *The incidence and stability of bidder collusion was sensitive to payoff gains from collusion; lower payoff gains resulted in less or no collusion.*

Support: Figures 2-5, table 3. In Melbourne W auctions, where the LW and LH treatment were clearly ranked by both absolute and relative gains from collusion, the mean market competitiveness increased from 56.27% under the LW treatment to 103.43% under the HW treatment;[12] according to the permutation test (Siegel and Castellan, 1988, pp. 151-155) the difference between the HW and the LW treatments is significant at 1.4% level (one-tailed). Similarly, in Melbourne S auctions, where the L and H treatments differed by relative gains, the mean market competitiveness increased from 58.62% (LS treatment) to 102.33% (HS treatment); the difference between the treatments is significant at 2.8% level. In both high asymmetry treatments at Melbourne, the market competitiveness exceeded the competitive equilibrium prediction of 100%. For Caltech experiments, where the absolute gains from collusion were the same under the LW and HW treatments (even though the relative gains differed), the hypothesis of no difference in market competitiveness between these treatments is sustained with the p-value of 30.0% (one-tailed). □

Result 3 *In Caltech experiments, the absolute gains from collusion were decisive for collusion occurrence and sustainability; the amount of bidder collusion was not significantly different between the LW and HW treatments. Collusion in Melbourne experiments was largely determined by the relative gains and the degree of bidder value asymmetry.*

Support: See support for result 2. Remarkably, in three out of four sessions under the HW treatment at Caltech, the payoff-dominant collusive outcomes were sustained in the late periods: the market competitiveness was close to 0% (table 3, figure 5). No collusion was observed in any of the high asymmetry sessions at Melbourne. □

[11] In the t-tests, mean per experiment values were taken as units of observation.

[12] The mean competitiveness observed earlier in the common values C experiments was 21.03%.

Result 4 *Previous training in market experiments together with higher monetary incentives increased bidder collusion: Overall, bidder collusion was higher in Caltech experiments than in Melbourne experiments.*

Support: Figure 2, table 3. The permutation test shows that the average per experiment market competitiveness under the LW treatment was lower for Caltech than for Melbourne with the p-value of 7.1% (one-tailed). The average market competitiveness under the HW treatment was lower for Caltech than for Melbourne with the p-value of 1.4% (one-tailed). □

To summarize, we find that under the auction rules which allow for implicit coordination of bidder strategies, the incidence of bidder collusion strongly depends on bidders' incentives to collude, measured by payoff gains from collusion. Interesting differences in behavior are observed between a relatively inexperienced and a well-trained subject pools (Melbourne and Caltech subjects, respectively). The dynamics of Melbourne experiments suggests that, most often, collusion emerged only after the subjects experienced low payoffs at the competitive equilibrium; consider the market dynamics in the early periods under the LW treatment (figure 3).[13] Under the HW and HS treatments, where the competitive equilibrium payoffs were non-negligible, collusive tendencies never emerged (figures 3-4). This evidence suggests that for inexperienced subjects, collusion is driven by relative, rather than absolute, payoff gains. In contrast, Caltech experiments demonstrate that more experienced subjects pursue absolute payoff gains. As it is evident from the HW treatment at Caltech, private values, high value asymmetry and non-negligible competitive equilibrium payoffs were not sufficient for the auctions to result in competitive outcomes

3.2 The role of bid improvement rules

Result 5 *The strict bid improvement rule was not sufficient to eliminate bidder collusion in all cases. However, there were fewer incidents of collusion in the S auctions than in the W auctions.*

Support: Figures 2-4, table 3. Although the LW and LS treatments at Melbourne are close in average market competitiveness (56.27% and 58.62%, respectively), the variance in competitiveness across sessions is significantly higher for the LS treatment than for

[13] The obvious exceptions are sessions LS-3 and LS-4 at Melbourne, where collusion emerged in the early periods (figure 4). Most of the subjects in these sessions were third year students in economics who were familiar with game theory and had previously participated in other experiments.

the LW treatment. According to the t-test, the hypothesis of no differences between the average per session market competitiveness and the competitive equilibrium prediction of 100% is sustained at 10% level for the LS treatment; it is rejected at 5% level for the LW treatment (both one-tailed). From figures 3 and 4, it is evident that collusion was attempted in all four sessions of the LW treatment, but only in 2 out of 4 sessions in the LS treatment.[14] □

To take a closer look at the effect of bid improvement rules on bidder collusion, we classify all auction outcomes into the following categories. We will call an outcome *collusive* if the highest closing bid in the market is below the lower bound of the private values support: $b^1 < \underline{v}$. As discussed in section 2, in such an outcome a bidder with any value (including the highest value of 100 francs) is at least as well off as in the competitive equilibrium, provided that he has a two thirds chance of winning the unit. We will call all other outcomes *competitive*.[15] Further observe that in W auctions, collusive outcomes may be of two types: (i) *Collusive bid matching* outcomes, where all three bidders have a positive chance of winning a unit within the same period (these involve three-way symmetric matches in the highest bids, $b^1 = b^2 = b^3$, or two-way asymmetric matches in the lower bids, $b^1 > b^2 = b^3$); or (ii) *Bid rotation* outcomes, where one of the bidders stays (or prematurely drops) out of the competitive bidding process (hence, $b^1 \geq b^2 > b^3$). Only bid rotation outcomes are attainable in the S auctions.[16]

Table 4 displays the percentages of auction outcomes by type, pooled by treatment. The percentages of collusive type matches in the end-of-period bids (irrespective of auction outcomes) for individual sessions of W auctions are reported in figures 3, 5. We conclude the following.

TABLE 4 ABOUT HERE

Result 6 *Bid matching was the most frequently used collusive scheme in Melbourne W auctions. In Melbourne S auctions, where bid matching possibilities were absent, collusive*

[14] Also observe that collusion prevailed in the HW treatment at Caltech but never emerged in the HS treatment at Melbourne, although both absolute and relative gains from collusion were equal between these two treatments (figures 4-5).

[15] In the results reported below, we classified outcomes as collusive if $b^1 \leq (\underline{v} - 5)$, not if $b^1 < \underline{v}$. Under such a classification, colluisve outcomes guaranteed minimal positive gains for bidders of any type, and were therefore qualitatively different from competitive outcomes.

[16] The empirical literature distinguishes between bid rotation schemes (colluding firms take turns in participating in auctions) and bid rigging schemes (several colluding firms participate in most auctions, but all but one submit non-competitive "phantom" bids); see Porter in Zona (1993). We pool bid rotation and bid rigging schemes into one category, since they both rely on repeated play. In contrast, bid matching schemes can be sustained as Nash equilibria within one auction period; see Sherstyuk, 1999.

bid rotation was successfully adopted in two out of four markets. Both bid rotation and bid matching schemes were used to sustain collusion in Caltech experiments.

Support: Table 4, figures 3-5. Table 4 shows that bid matching was the dominant collusive scheme in LW auctions at both Melbourne and Caltech; 50% or more of all outcomes in the late periods involved collusive bid matches. In LS auctions at Melbourne, where bid matching was ruled out, 54.7% of all outcomes were of collusive bid rotation type. In Caltech HW experiments, 29.2% of all outcomes were collusive bid rotation outcomes, as compared to 24.6% collusive bid matching outcomes; in the late periods, the percentage of bid rotation outcomes increased to 45.5%. □

From results 5 and 6, we conclude that the absence of the strict improvement rule served as an important collusion-facilitating device in the oral auctions. In the W auctions, bid matching was widely used to achieve collusion; in the S auctions, where bid matching was not available, collusion occurred less often. Arguably, in a W auction where explicit communication is not allowed, bidders may be able to tacitly communicate their intention to collude through matching each others' bids. This intention may be more difficult to communicate in an S auction, where bid matching possibilities are absent. It is then not surprising that Melbourne subjects in W auctions overwhelmingly adopted bid matching schemes when they were available; what is fascinating is the ability of Melbourne subjects in the S auctions and of Caltech subjects in W auctions to adopt bid rotation schemes in some cases. From bidders' perspective, bid rotation may have various advantages over bid matching. (Empirical studies of bidder collusion discuss advantages of bid rotation and bid rigging over bid matching schemes in repeated procurement auctions; see Comanor and Schankerman, 1976; Porter and Zona, 1993 and 1999.) Bid rotation eliminates uncertainty; if bidders take turns in staying out, then each bidder is guaranteed to get the object in two thirds of the auctions in a session. Further, if bidders pursue efficiency and are somehow able to communicate a likely ranking of their private valuations, then bid rotation can achieve higher market efficiency than bid matching. The market efficiency is defined as the percentage of the maximal social surplus realized in the market:

$$Eff = \frac{\sum_{i=1}^{3}(v_i - \underline{p})x_i}{v^1 + v^2 - 2\underline{p}} \cdot 100\%, \tag{6}$$

where v_i and x_i denote the object valuation and the assignment coefficient of bidder i ($x_i = 1$ if bidder i wins the object, and $x_i = 0$ otherwise), and v^j denotes the j-th highest value drawn among the bidders. Under the competitive equilibrium prediction, the market efficiency is 100%; under collusion, efficiency losses occur unless the bidders find a way to allocate the objects to the bidders with the two highest values.

Consider whether, in fact, collusion resulted in efficiency losses in our experiments, and whether bid rotation outcomes were any different from bid matching outcomes in terms of their efficiency. Table 5 displays the theoretically predicted and experimentally observed market efficiencies by treatment and by type of outcome.[17] Interestingly, we find that efficiency losses under collusion were minimal and below the theoretical predictions.

TABLE 5 ABOUT HERE

Result 7 *Overall, there were no efficiency losses due to collusion in either Melbourne or Caltech experiments. The average market efficiency under collusive outcomes was no different, and in some cases even higher, than under competitive outcomes. The efficiency of collusive outcomes under the HW treatment at Caltech was higher than theoretically predicted. The differences in efficiencies between the bid matching and bid rotation outcomes were minimal.*

Support: Table 5. In the LW treatments at both Melbourne and Caltech, the average market efficiencies under competitive outcomes were no higher than under either collusive bid matching or bid rotation outcomes. In the LS markets at Melbourne, the mean efficiency was higher under collusive than under competitive outcomes (98.4% and 89.58%, respectively).[18] In the HW experiments at Caltech, the average market efficiencies under collusive bid matching and bid rotation outcomes were 94.57% and 96.57%, respectively, as compared to 96.94% for competitive outcomes, and the theoretical prediction of 91.32% for collusive outcomes. □

Apparently, in cases when collusion succeeded, bidders were able, in many instances, to allocate the objects efficiently. From observation, a bidder drawing a low value in a given period often stayed out of the market, or submitted a bid below the seller reserve price, thus signalling his or her willingness to pass on the object. Bidders with high value draws were more persistent in keeping up with the highest winning bid. The bidders were

[17] The theoretical predictions for bid rotation outcomes given in table 5 were obtained assuming that the objects are allocated to bidders in turn and independently of their private valuations. The predicted efficiencies are therefore identical for the bid rotation and bid matching collusive outcomes. The estimates of the efficiencies of collusive outcomes were obtained through computer simulations.

[18] In a "non-collusive" session LS-1, one of the bidders got frustrated with his unsuccessful attempts to establish collusion in the first few periods, and started to bid at his resale values just to get out of the session early. As a result, one of two units remained unsold in a number of periods, which led to a low efficiency of 84.0% in this session.

obviously able to use the rich strategy space in the ascending oral auctions to signal and coordinate their actions to maximize bidder gains. While in many cases bid matching, when available, was the key to achieving successful collusion, it is also apparent that the bidders relied on repeated nature of the auction to improve on collusive efficiency.

4 Discussion

The above results provide interesting insights into the nature and stability of bidder collusion in oral auctions with a small number of bidders. We conclude that it is not the complete information and symmetry as such that are necessary for the emergence and sustainability of collusion. Rather, it is the bidders' common knowledge of potentially high gains from collusion. Under the private value treatments where the gains from collusion were high, collusive tendencies did emerge and increase with bidders' experience, as it is evident from LW and LS experiments at Melbourne and both LW and HW experiments at Caltech. On the other hand, we observe that decreasing gains from collusion and increasing bidder value asymmetry may contribute to the breakdown of collusive tendencies. In HW and HS experiments at Melbourne, where bidder payoff gains in competitive equilibrium were non-negligible, we observed no incidence of collusion.

We have obtained experimental evidence that the absence of the strict improvement rule in ascending price oral auctions can be very favorable for bidder collusion and equally detrimental for auctioneer's revenue. Bid matching was a widely used collusive method that was easily adopted by both inexperienced and well-trained subjects in the weakly ascending auctions. Thus, we provide experimental support for interpretation of identical bidding as suggestive of collusion. However, the absence of the strict improvement rule was not critical for bidder collusion. In the auctions where the strict bid improvement rule was imposed, the bidders were able, in some cases, to find alternative (bid rotation) schemes to attain collusive outcomes.

We found that the subjects' ability to achieve and sustain collusion increased with their previous training in other experimental markets. Caltech experiments resulted in higher bidder collusion than Melbourne experiments, and more experienced Caltech subjects were able to adopt a broader variety of collusive schemes than less experienced Melbourne subjects. Bidder collusion did not affect the market efficiency in our experiments to the extent predicted by the theory. These findings match well the existing empirical evidence, which documents that, depending on specific features of the market, bidders adopt different collusive schemes, including identical bidding, bid rotation, bid rigging, and splitting markets. Efficiency and stability of collusive methods, as well as their detectability, affects the choice of collusive scheme in each particular case (Comanor and Schankerman, 1976; Porter and Zona, 1993 and 1999; Baldwin et al., 1997; Cramton and Schwartz, 2000).

Sustainable collusion in our experimental markets should be attributed, at least partially, to the repeated nature of the auction. It is then a question whether collusion would be possible in a non-repeated ascending price auction format. The empirical evidence from the airwaves auctions suggests that repetition is not a necessary condition for collusion if bidders are able to coordinate their actions in the process of bidding. Besides, many procurement auctions, such as government auctions for highway construction contracts, are in fact repeated in nature. Cases of collusion were detected there even under the sealed bid auction format (Porter and Zona, 1993).

The above demonstrates that although the absence of the bid improvement rule and repeated nature of the market significantly facilitate bidder collusion, one should expect well-trained highly motivated bidders to engage in tacit collusion even under less "favorable" institutional arrangements. The strict bid improvement rule, asymmetry of bidder values, and private information are not an obstacle for experienced bidders in achieving collusion. Further research is necessary to investigate other institutional features that help to safeguard against bidder collusion in auction markets.

Appendix

FIGURES 3-5 HERE

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	Expected payoff		Collusive gains	
	Compet.Eq.	Collusive	Absolute	Relative
	$EP^{CE}(100)$	$EP^{Coll}(100)$	$AG(100)$	$RG(100)$
Common values (C), $v_i = 100$	0.00	60.00	60.00	∞
Private values, low asymmetry (L)				
$v_i \in [90, 100]$	6.66	60.00	53.34	800.9%
Private values, high asymmetry (H)				
$v_i \in [50, 100]$	33.33	60.00	26.67	79.98%

Table 1: Absolute and relative gains from collusion for the highest type bidder with $v_i = 100$, given the reserve price $\underline{p} = 10$. Payoffs and absolute gains are in experimental francs; relative gains are in percent.

Treatment	Number of sessions	Exchange rate	Collusive gains absolute (cents)	Collusive gains relative (percent)
Melbourne, low asymmetry, weak (LW)	4	1	53.34	800.9%
Melbourne, low asymmetry, strict (LS)	4	1.5	80.01	800.9%
Caltech, low asymmetry, weak (LW)	4	1.5	80.01	800.9%
Melbourne, high asymmetry, weak (HW)	4	1	26.66	79.98%
Melbourne, high asymmetry, strict (HS)	4	3	80.01	79.98%
Caltech, high asymmetry, weak (HW)	4	3	80.01	79.98%

Table 2: Features of experimental design. Exchange rates show the worth of one experimental franc in cents (Australian and US cents, respectively).

Mean (Stddv)	Comp. Eq	Collu-sive	Total	Early periods	Late periods
Low asymmetry, weak – LW, Melbourne	100	0	56.27 (45.64)	77.05 (35.81)	35.48 (45.38)
Low asymmetry, strict – LS, Melbourne	100	0	58.62 (44.41)	63.59 (39.89)	53.65 (48.70)
Low asymmetry, weak – LW, Caltech	100	0	30.52 (42.42)	36.31 (41.09)	24.89 (43.55)
High asymmetry, weak – HW, Melbourne	100	0	103.43 (6.95)	103.00 (6.98)	103.9 (7.00)
High asymmetry, strict – HS, Melbourne	100	0	102.33 (11.02)	102.17 (14.24)	102.48 (6.62)
High asymmetry, weak – HW, Caltech	100	0	45.23 (47.16)	66.23 (43.64)	24.23 (41.29)

Table 3: Market competitiveness under private value treatments, pooled data, percent.

%	# of obs.	Competitive outcome	Collusive bid match	Collusive bid rotation	All
LW – Melbourne, all	64	53.1	34.4	12.5	100
-early periods	32	71.9	15.6	12.5	100
-late periods	32	34.4	53.1	12.5	100
LS – Melbourne, all	64	45.3	—	54.7	100
-early periods	32	40.6	—	59.4	100
-late periods	32	50.0	—	50.0	100
LW – Caltech, all	64	28.1	40.6	31.2	100
-early periods	32	31.2	31.2	37.5	100
-late periods	32	25.0	50.0	25.0	100
HW – Melbourne, all	64	100.0	—	—	100
-early periods	32	100.0	—	—	100
-late periods	32	100.0	—	—	100
HS – Melbourne, all	64	100.0	—	—	100
-early periods	32	100.0	—	—	100
-late periods	32	100.0	—	—	100
HW – Caltech, all	65	46.2	24.6	29.2	100
-early periods	32	68.8	18.8	12.5	100
-late periods	33	24.2	30.3	45.5	100

Table 4: Frequencies of auction outcomes by type, %

Mean, % (Stddv)	Competitive outcome	Collusive bid match	Collusive bid rotation	All
L – predicted	100	98.56	98.56	—
	(0)	(1.53)	(1.53)	
– LW, Melbourne	97.93	98.38	97.98	98.10
	(9.46)	(1.56)	(1.92)	(6.94)
– LS, Melbourne	89.58	—	98.40	94.40
	(20.24)		(1.64)	(14.25)
– LW, Caltech	96.53	98.21	97.96	97.66
	(0.13)	(1.90)	(2.03)	(7.08)
H – predicted	100	91.32	91.32	—
	(0)	(9.00)	(9.00)	
– HW, Melbourne	99.63	—	—	99.63
	(1.47)			(1.47)
– HS, Melbourne	99.85	—	—	99.85
	(0.92)			(0.92)
– HW, Caltech	96.94	94.57	96.57	96.25
	(0.10)	(9.08)	(6.15)	(8.98)

Table 5: Market efficiencies of auction outcomes by type, %

List of figures

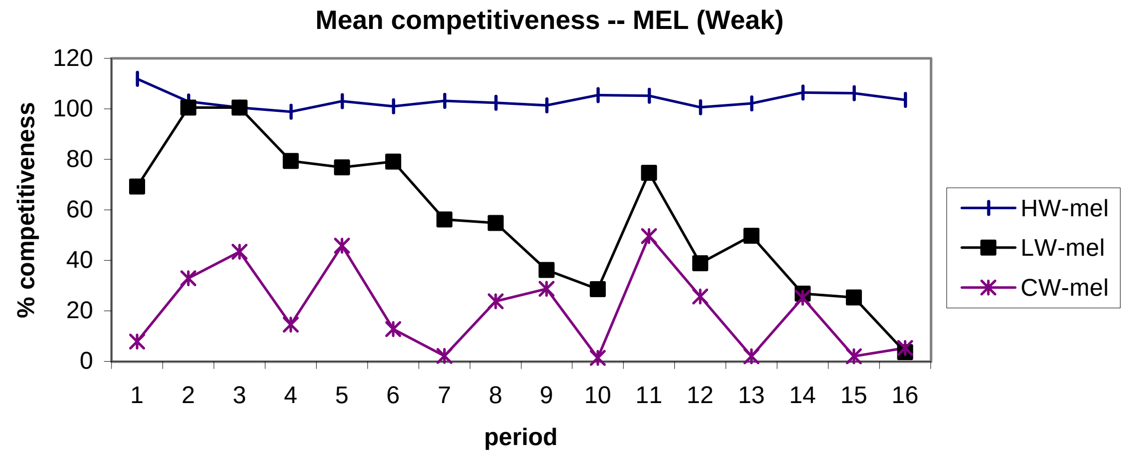
Figure 1 Supply and demand schedule.

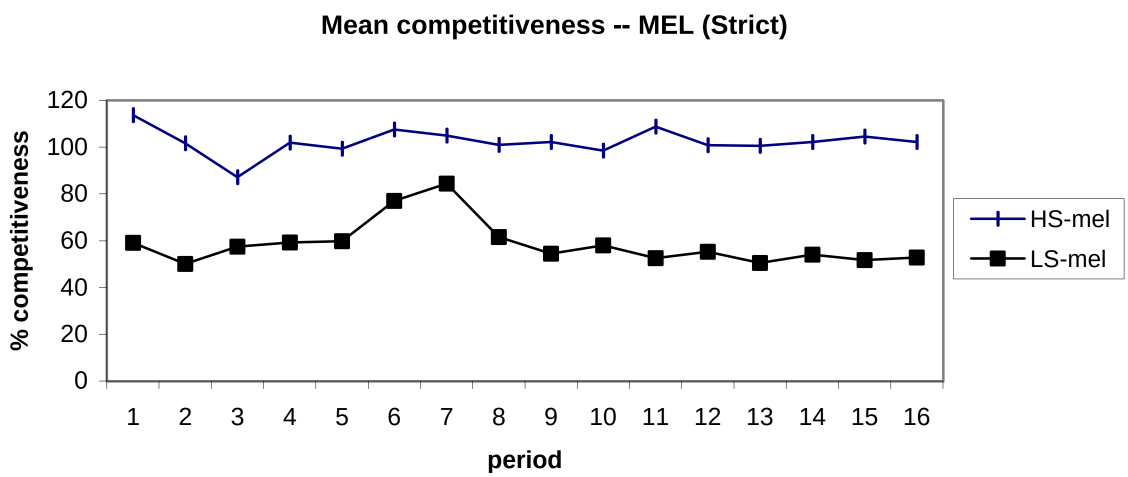
Figure 2 The dynamics of mean per period market competitiveness, by treatment. Above: W auctions, Melbourne (the data from the benchmark C treatment is added for comparison). Middle: S auctions, Melbourne. Below: W auctions, Caltech.

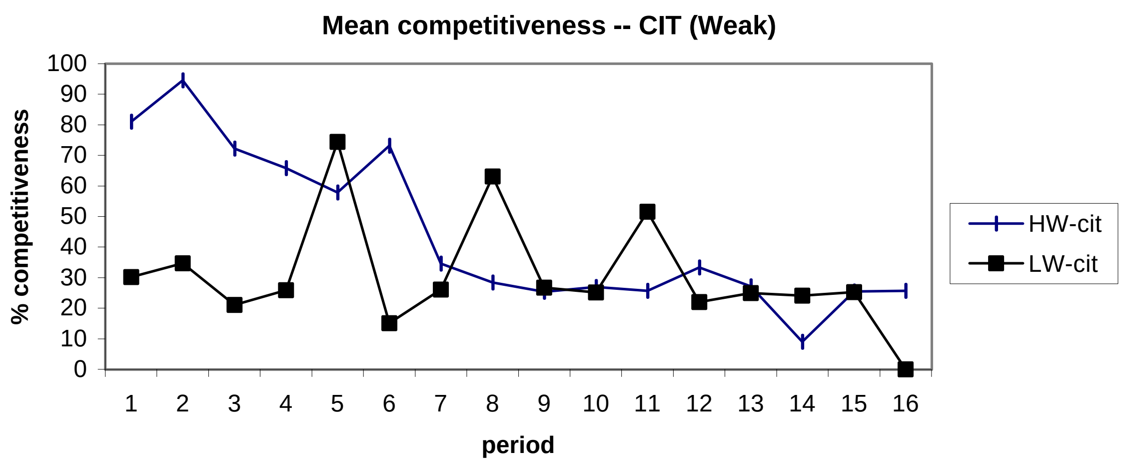
Figure 3 The dynamics of market competitiveness in the weakly ascending auctions, Melbourne. Left column: low asymmetry; right column: high asymmetry. Comp: average market competitiveness; Match: percentage of collusive-type matches in the end-of-period bids.

Figure 4 The dynamics of market competitiveness in the strictly ascending auctions, Melbourne. Left column: low asymmetry; right column: high asymmetry. Comp: average market competitiveness.

Figure 5 The dynamics of market competitiveness in the weakly ascending auctions, Caltech. Left column: low asymmetry; right column: high asymmetry. Comp: average market competitiveness; Match: percentage of collusive-type matches in the end-of-period bids.


Mean competitiveness -- MEL (Weak)
% competitiveness
120
100
80
60
40
20
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
period
HW-mel
LW-mel
CW-mel


Mean competitiveness -- MEL (Strict)
% competitiveness
120
100
80
60
40
20
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
period
HS-mel
LS-mel


Mean competitiveness -- CIT (Weak)
% competitiveness
100
90
80
70
60
50
40
30
20
10
0
1
2
3
4
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7
8
9
10
11
12
13
14
15
16
period
HW-cit
LW-cit

Figure 2

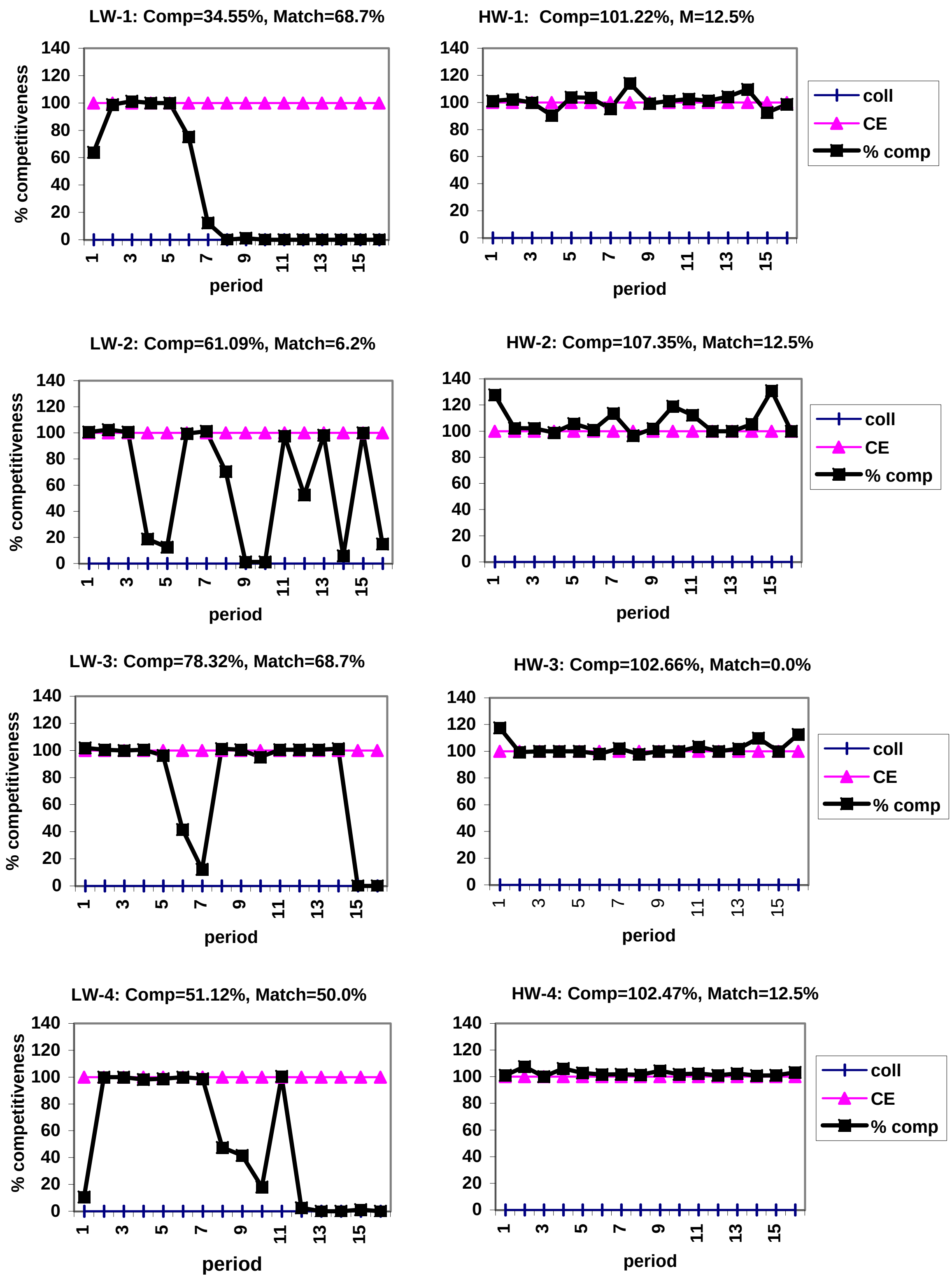
LW-1: Comp=34.55%, Match=68.7%
HW-1: Comp=101.22%, M=12.5%
LW-2: Comp=61.09%, Match=6.2%
HW-2: Comp=107.35%, Match=12.5%
LW-3: Comp=78.32%, Match=68.7%
HW-3: Comp=102.66%, Match=0.0%
LW-4: Comp=51.12%, Match=50.0%
HW-4: Comp=102.47%, Match=12.5%
% competitiveness
period
0
20
40
60
80
100
120
140
1
3
5
7
9
11
13
15
coll
CE
% comp

Figure 3

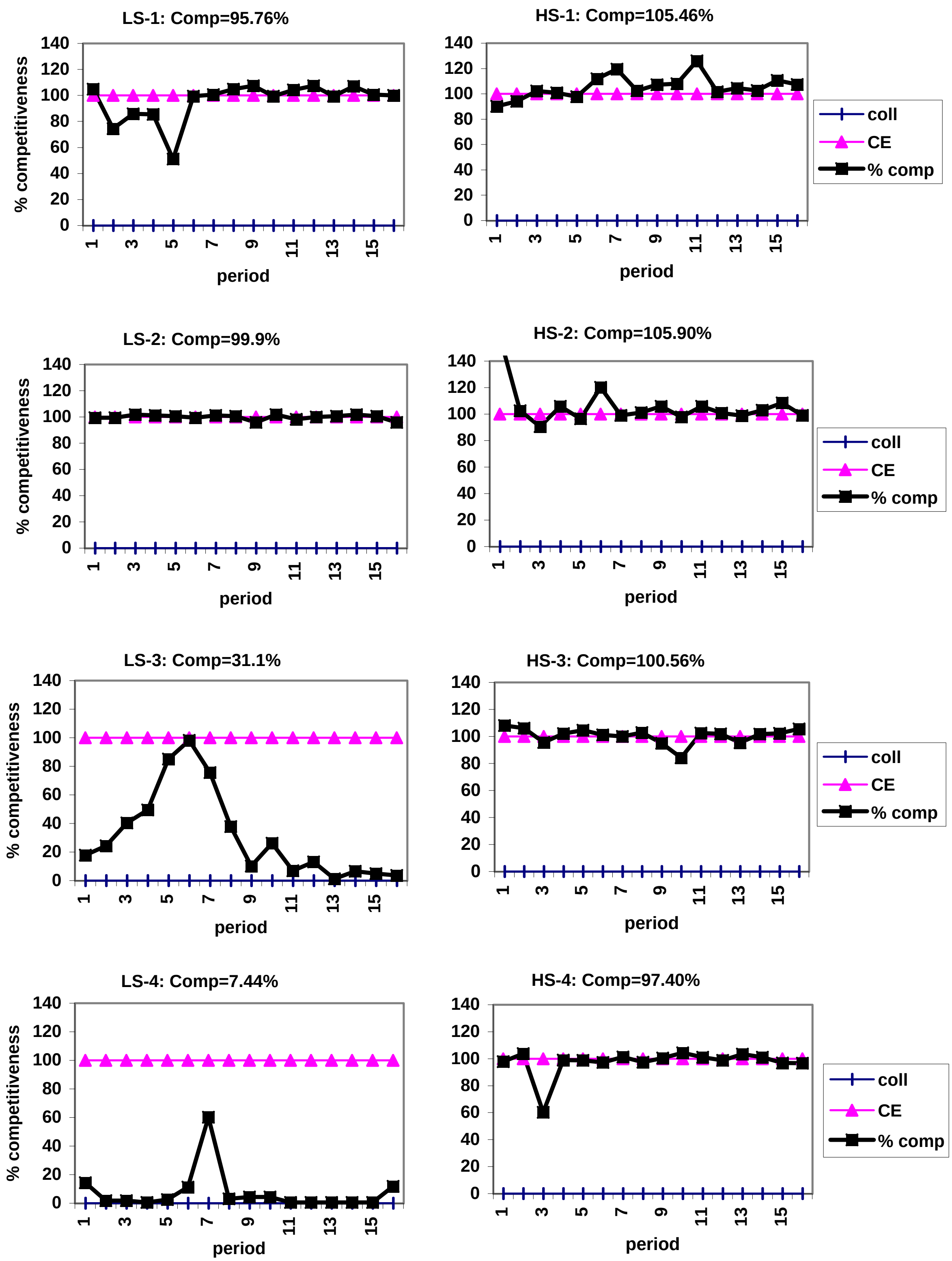
LS-1: Comp=95.76%
HS-1: Comp=105.46%
LS-2: Comp=99.9%
HS-2: Comp=105.90%
LS-3: Comp=31.1%
HS-3: Comp=100.56%
LS-4: Comp=7.44%
HS-4: Comp=97.40%
% competitiveness
period
coll
CE
% comp

Figure 4

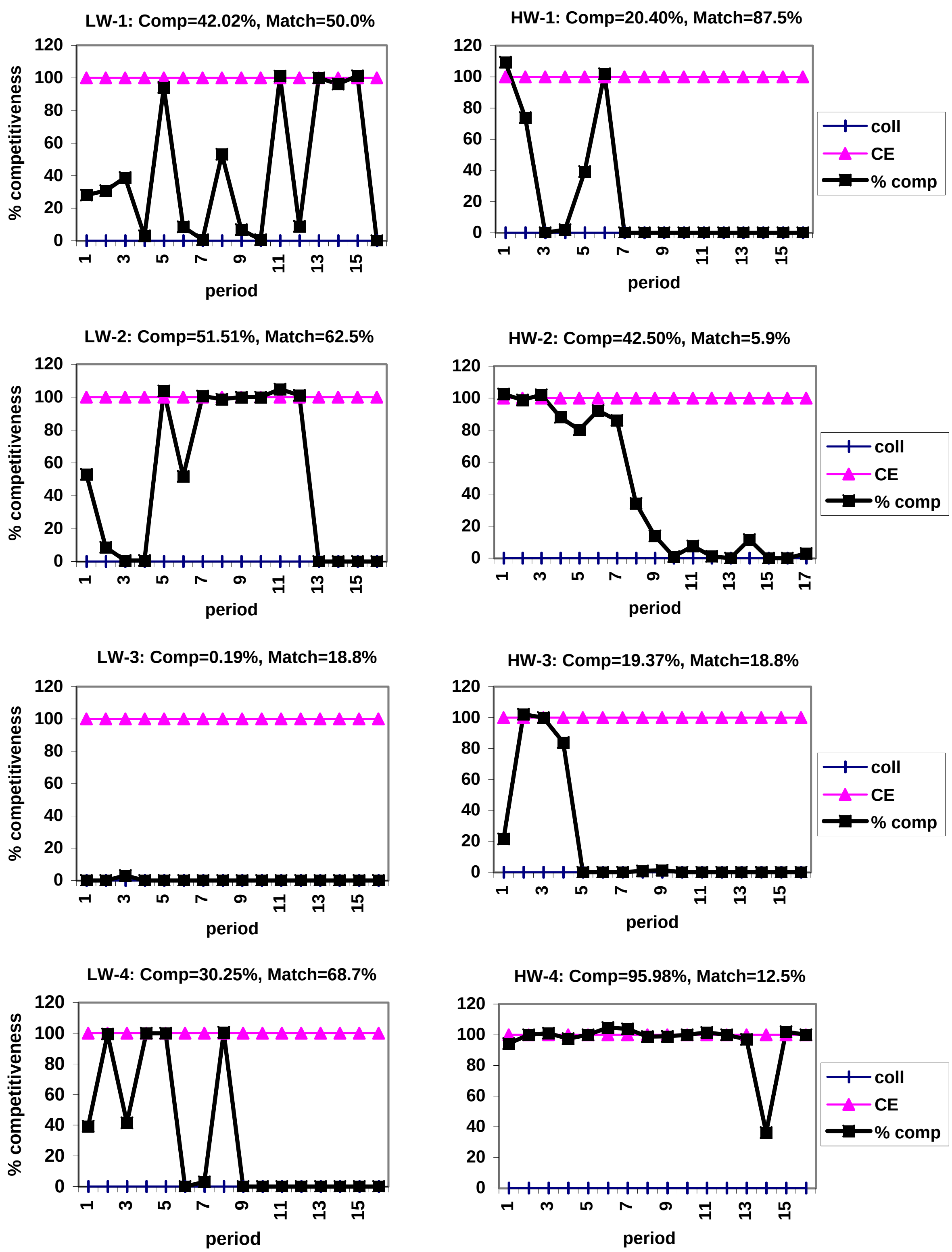
LW-1: Comp=42.02%, Match=50.0%
HW-1: Comp=20.40%, Match=87.5%
LW-2: Comp=51.51%, Match=62.5%
HW-2: Comp=42.50%, Match=5.9%
LW-3: Comp=0.19%, Match=18.8%
HW-3: Comp=19.37%, Match=18.8%
LW-4: Comp=30.25%, Match=68.7%
HW-4: Comp=95.98%, Match=12.5%
% competitiveness
period
coll
CE
% comp

Figure 5