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TACIT COLLUSION IN AUCTIONS AND CONDIDITON FOR ITS FACILITATION AND PREVENTION: EQUILIBRIUM SELECTION IN LABORATORY EXPERIMENTAL MARKETS

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Abstract

The paper studies bidder behavior in simultaneous, continuous, ascending price auctions. The purpose is to create (possibly extreme) conditions under which tacit collusion develops quickly, naturally and reliably; study models of its development, and then study institutional and environmental remedies that would cause it to evolve into competitive behavior. Special environments were implemented with a purpose of creating good conditions for the development of tacit collusion. The special environments were based on a type of public, symmetrically "folded" preferences together with what we call "item-aligned" preferences. Once tacit collusion developed, remedies were implemented and the success of the remedies in promoting competitive behavior was studied.

The results are as follow. (1) The environmental conditions do foster tacit collusion. (2) The tacit collusion corresponds to the unique buyer Pareto Equilibrium of a game theoretic model of the auction process. (3) Once tacit collusion developed, it proved remarkably robust to institutional changes that weakened it as an equilibrium of the game theoretic model. (4) The only remedy that was clearly successful was a non-public change in the preference of participants that destroyed the symmetrically, "folded" and "item aligned" patterns of preferences, creating head to head competition between two agents reminiscent of the concept of a "maverick".

Keywords: tacit collusion, information, auctions, game theory
JEL: L50, L94, D43

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1. INTRODUCTION

The research reported here explores both the conditions under which tacit collusion develops and the remedies that might be taken to transform tacit collusion into a competitive solution. The issue is approached from the point of view of three broad questions. Can we observe behavior in auctions that might be interpreted as successful tacit collusion (in the absence of conspiracy)? Can the behavior be understood in terms of game theoretic models? If so, can the behavior be understood in terms of equilibrium selection? The institutional setting is an auction in which game theoretic models have a natural interpretation and multiple equilibria exist in those models. In the context of the game theoretic models, the question is focused on the several equilibria of non-repeated game models and the conditions under which some equilibria are favored by the data and others are not. Specifically, one equilibrium is favorable to the buyers (labeled "tacit collusion") and another is favorable to the seller (labeled "competitive"). If the system has a tendency to go to one, under what conditions can the system be made to naturally gravitate to the other and what role can theory play in identifying the conditions?

Collusion among several (five or more) agents has never been observed in an experimental market environment in the absence of conspiracy and/or special facilitating devices. Consequently, few experimental studies have addressed the issue of how to stop tacit collusion once it has started. This paper addresses the issue in two steps. First, we identify an experimental environment in which tacit collusive-type behavior evolves naturally and quickly and does so without the aid of verbal communication and without

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the aid of side payments. Secondly, we explore the use and effectiveness of vehicles that hold a potential for disrupting or terminating collusion. Because of the complexity of the issues, the large set of potential collusion "remedies", and necessarily sparse data, we use an exploratory methodology. Institutional changes are implemented in sequences that depend upon what has been observed. The exploratory approach is frequently used under such circumstances.

Two different experimental environments were developed and explored. One environment is labeled "collusion conducive". It was designed with the purpose of creating an environment in which tacit collusion would evolve. The second environment, labeled "competitive conducive", involves changes in the first environment, implemented for the purpose of studying the stability of (tacit) collusive behavior. For convenience, from time to time we may refer to these two environments as the "collusive" environment and the "competitive" environment even though the latter will take various forms as we study how collusion can be extinguished.

Both the collusive and competitive environments have common structural elements and some common institutional elements. The common environment has "repeated game" features in that agents participated in a series of auctions. Except as otherwise noted, the number of items equaled the number of participants. Preferences of agents were additive, in the sense that no synergies existed. Each item had a value independent of other items acquired and no two items had the same value for an individual. Except under the case of special treatments that will be discussed later, the preferences over the items had two important symmetries that we thought would be supportive of (tacit) collusive behavior.

The first property of preferences we will call "strong ordinal symmetry" – if agent i had the mth highest value for item X and agent j had the nth highest value item X then agent i had the nth highest value on the item for which individual j had the mth highest value. As will be discussed, this pattern of symmetry has a type of "folded" property in that it has the potential for simultaneously placing any two individuals in two, exactly opposite conflicts. This pattern of relationships holds the possibility that competition can "unfold" into tacit collusion as pairs are able to find a mutually beneficial equilibrium. If i and j do not compete then both face a "next in line" with a similar conflict. The

sequential resolution of these conflicts can theoretically result in an "unfolding" from one equilibrium to a completely different one.

The second feature of preferences we will call "item-aligned" preferences. For any item that an individual preferred the most, that individual also had the highest value among all agents. That is, each had his or her "own item" in the sense that it was clear that in any bidding contest an individual would always "win" the item that the individual preferred the most. In that sense, we can label an item as "individual i's item" as if it is clear who would get it. Thus, except in the special cases discussed later each agent had the highest value among all agents for one item and that was the item that was most valuable to the individual agent.

The issue is how the institutions might interact with these basic structural features to determine equilibrium. Institutional issues aside, how the two structural features might work together suggests why they might be supportive of collusion. Suppose agent i's item is A. If j has the second highest value then i has the second highest value on B. If they compete then i will pay j's value for A and j will pay i's value for B. If they do not compete then they are faced by competition from agents whose values are third from the top, and if competition can be removed at that level through the same mechanism then competition is encountered at still a lower level. This "unfolding" of competition is what the environment was designed to facilitate. The issue is how the unfolding might be facilitated by institutions and more importantly, what institutions might "reverse" the process if a (tacit) collusive equilibrium evolved. Thus, partial success would be the creation of an environment in which collusion would naturally evolve.

The basic institutional framework studied is the simultaneous, continuous, ascending price auction. The collusive conducive environment operated under conditions of full information. All preferences, payoffs, and bids and the identification numbers of bidders were public information. By contrast, the competitive conducive environment operated with less public information and with slightly different rules that operated within the auction.

The primary objective was to learn if the collusive conducive environment could facilitate the (tacit) collusive equilibrium for without it, the second issue could not be addressed. As mentioned in the introductory paragraph, the creation of the tacit collusive

outcome was definitely not a foregone conclusion because collusion with a large number of agents had never before been observed. Early experiments had demonstrated that symmetry is an important feature in moving solutions away from simple competitive outcomes toward more cooperative ones (Plott, 1982) and more recent research by Sherstyuk and her co-authors successfully produced tacit collusion in auctions with no more than three bidders, but more complex environments prices almost always converge to near the competitive equilibrium.[3]

The first basic results are that within the collusive conductive environment the system equilibrated quickly to the (tacit) collusive equilibrium. Several measures and characteristics of this process are chronicled in the results section of the paper. The process does not seem to have the sequential property as suggested by the unfolding property but instead is discontinuous, with an almost "jump" toward the equilibrium. Thus, the first part of the study was very successful. Collusive equilibria emerged and did so reliably under collusive conducive conditions.

The second result is that collusive equilibria, once established, are stable in the sense that removal of central properties of the collusive conducive environment did not force the auction away from the collusive equilibrium. Public information about preferences and about bidder identification did not change the equilibrium. Several changes in auction rules had no effect. Disruptions of the strong, ordinal symmetry by removing some of the items did not disrupt the equilibrium. Only when a "maverick" preference was introduced under conditions of lack of public information about preferences, the collusive equilibrium was quickly disrupted and the system evolved to the competitive solution. The "maverick" was an agent who had the same most preferred item as one of the other agents.

The paper is outlined as follows. In Section 2, the background experimental work is discussed. Our experiments build on that literature. Section 3 contains the details of the experimental environments. The details of the preferences and institutions are found there. Section 4 is the experimental design that explains the number of experiments and the conditions that were in place for each experiment. Section 5 discusses models and

[3] The posted price effect discovered by Plott and Smith (2004) shows that a "sealed-bid" like institution can have the effect to improve the payoff of the side of the market tendering the bid.

theory. The correspondence between the game theoretic solutions and the experimental procedures in the auctions are discussed in detail. Section 6 contains the results, which are divided into two sections. The first section of the results explains the nature of the collusive equilibrium and how it is reached. The second section of the results explains the changes in the environment that we implemented as attempts to make the collusive equilibrium switch itself to the competitive equilibrium. Section 7 is a summary of conclusions.

2. BACKGROUND EXPERIMENTAL WORK

There are very few empirical examples of collusion in auctions in the absence of conspiracy or without the aid of facilitating devices. Hendricks and Porters (1988) studied the bidding of drainage leases on the Outer Continental Shelf. Their findings suggest that there were coordination in bids among firms that own tracts adjacent to the lease for sale. Cramton and Schwarz (2000) reported what appear to be attempts to collude in FCC spectrum auction but have no evidence of actual, price influencing collusion. In particular, they pointed out how bidders used the last several digits of the bids to signal their intent.

Of course, since bidder values are typically unknown in the field, collusion is hard to document. This difficulty can be easily overcome by laboratory experiments, since values of the bidders can be designed by the experimenters. Isaac and Plott (1981) were the first to study conspiracy experimentally. Isaac and Walker (1985) allowed explicit communications among bidders in auctions, and they observed conspiracies in seven out of twelve auction series. Tacit collusion in auctions with standard procedure, however, was rarely observed in earlier experimental studies. Even when it was observed, tacit collusion was unstable and the prices easily converged back to competitive levels. (See Burns (1985) and Clauser and Plott (1993)). In a related industrial organization context, Isaac and Smith (1985) searched for predatory behavior in constraint of competition and failed to find any. Kagel (1995) offered a survey on earlier experiments on collusions in auctions.

A sequence of recent experiments successfully observed robust tacit collusion in special auction institutions. Sherstyuk (1999) studied ascending auctions under common

values. In her experiments, there were in each auction two units of items and three bidders, who demanded one unit of item only. She introduced in the auction a particular bid improvement rule: bidders are allowed to submit a bid that *equals* the highest outstanding bid. If there are multiple highest bidders on the items, a lottery will be run to decide the winner. With this bid improvement rule, Sherstyuk reported persistent and stable tacit collusions: bidders match each other's low bids in most of the auctions. Sherstyuk (2001) obtained similar results under private values.

Robust tacit collusion in auctions with "standard institutions and procedures" was first observed by Kwasnica and Sherstyuk (2003). In their environment, there were two items for sale in an ascending auction with either two or five bidders, who demand both items. The experimental environment conformed to the theoretical conditions of Brusco and Lopomo's (2002), and the auction results mirrored patterns suggested by theory. When there were two bidders only, they often tacitly colluded through splitting the two items. No collusion was found in auctions with five bidders. Kwasnica and Sherstyuk (2003) also examined the role of complementarity in collusions. They found that complementarity between items reduced collusion. However, with moderate level of complementarity, collusion still occurred with bidders taking turns to win the auction. A survey of recent results on collusion in auction can be found in Sherstyuk (forthcoming).

3. COLLUSION-CONDUCTIVE ENVIRONMENTS

Each experiment started with a collusion-conductive environment. In this environment, each auction consists of eight subjects and eight items. The basic market architecture has all items offered in simultaneously functioning, continuous, ascending first-price auctions. Within that basic structure, the experimental environments have three major parts. The central feature, the "folded" and "item-aligned" properties of valuations pattern will be discussed below in the subsection (3.1) of Items and Preferences. The details of the auction architecture will be in the institution environment subsection, (3.2). The information structure is discussed in a separate subsection, (3.3).

Once perfect tacit collusion[4] emerged and had persisted, the experimental environment then transitioned into a competition-conductive environment through various treatments. These treatments were exploratory in nature and occasionally differed in experiments. We document these treatments in details in the experimental procedure and design section.

3.1 Items and Preferences:

In every experiment, there were eight subjects. Each of them was given an ID number from 101-108 anonymously. In the collusion-conductive environments, there were eight items for sale, which were numbered from one to eight. The subjects' valuations for the items ranged from 50-900 francs, where one franc can be exchanged after the experiment for1 cent. There were no complementarities between items, so a subject's valuation of a group of items was the sum of his valuations of each item in the group. These valuations were identical across experiments to facilitate comparisons. Within an experiment, the valuations differed round by round and was designed to facilitate tacit collusion in earlier rounds. In the first six rounds, on each item, there were two subjects whose valuations were significantly higher than the rest. This is illustrated in Figure I below, which is the actual valuation sheet we used in round 1 of all the experiments.

On item 1 and 3 in Figure I, subject 101 and 102 had valuations higher than 700 francs, while the rest had valuations below 350. Similar pattern holds for 103 and 104 on item 5 and 7, 105 and 106 on item 2 and 6, and 107 and 108 on item 4 and 8. These valuations suggest that if 101 and 102 could "split" item 1 and 3, then each could win one of items at a low price, and similarly for others.

The symmetry of valuations runs deep into the preference. For convenience, we call a subject n-th on an item if he has the n-th highest valuations on the item.[5] We design the valuations such that, if subject i is m-th and subject j is n-th highest on an item, then j is m-th on the item where i is n-th. In Figure 1, 101 is 7th and 105 is 3rd on item 4. Then on item 7, on which 105 is 7th, 101 is 3rd. For the purpose of collusion, it is enough

[4] We define an auction outcome as perfect tacit collusion if all items are sold at their reservation price efficiently.
[5] There are no ties in valuations.

to note that for any subject i and j, if j is n-th on an item i is 1st, then i is n-th on the item where j is 1st.

The general ordinal structure of folded preference remained throughout the collusion-conductive experiment, but the valuations of subjects changed from round to round. Consequently, the pairs of subjects who shared higher valuations on the same items in one round were typically not "paired together" in the next round. In Figure I which corresponds to the real round 1, subject 101 was paired with 102 and had high valuations in item 1 and 3. In round 2, 101 had high valuations on item 3 and 7, and 102 had high valuations on item 1 and 8. (Detailed valuations of subjects in round 2 is not reported here.)

Other than strong ordinal symmetry, another crucial feature in the design of preference is "item-alignedness." This says that for any bidder, the item on which he has the highest valuation among the bidders also happens to be the one he values most. The general property of "item-aligned" feature is also clear from Figure I: subject 103 had the highest valuations among all subjects for item 7. Consequently, 103 by design valued item 7 most among all items. This "item-aligned" feature suggests that 103 would be a natural winner of item 7. Therefore, we denote item 7 as "103's item." More generally, we denote the item on which subject i has the highest valuation as subject i's item.

[Figure I]

The total payoff of any subject in the experiments is calculated by summing his payoffs from all the items he won. In particular, a subject's payoff on each of his winning item is the difference between his valuation of the item and the price he pays. If a subject's winning price exceeds his valuation, then the subject incurs a loss on the item he wins. A subject's payoff in a given round is the sum of the payoffs of each item he wins. A subject's total payoff in the experiment is the sum of his payoffs in all rounds, excluding a practice round, which will be discussed later.

3.2 Institutional Environment:

The basic institutional environment is a computerized simultaneous ascending auction (SAA). SAA is an auction in which all the items are open for sale simultaneously using an English-Auction like format until some ending criteria is reached. Subjects place

their bids through computers. Each bid specifies an item to be bid on and the associated bid price, while satisfying two restrictions. First, the smallest bid that can be entered is 100 francs, the *reservation price* of all items. Second, the *minimal bid increment* is 10 francs. This means that a new bid on an item is required to be at least 10 francs higher than its current highest bid. For example, if the current highest bid for an item is 680, then the lowest possible new bid on it is 680+10=690. The auction ends only when no new bid is entered for any item for a consecutive 30 seconds. That is, all auctions are open until they all close. The highest bidder of an item wins it and pays his bidding price. It is possible for a subject to win multiple items.

3.3 Information Structure:

In the collusion conductive stage of the environment, the subjects have almost complete information of the auctions: they know the valuation of all subjects through a valuation sheet passed out by the experimenter at the beginning of each auction; they can also observe from the computer screen who (given by the ID number) had bid what price on which item. The only information missing is that ID numbers are assigned anonymously, so the subjects do not know the IDs of other subjects. Furthermore, the subjects do not know the total number of rounds, except in two experiments where the experimenters announced immediately before the final round that it was the final round. When the experiment transitioned into the competition-conductive phase, various treatments were applied to reduce information. We discuss the details in next section.

4. EXPERIMENTAL PRODCEDURES AND DESIGN

4.1 Experimental Procedures:

The subjects in the experiments were mostly Caltech undergraduates, with a few graduate students in non-economics departments in some experiments. All the experiments lasted between one and a half to two and a half hours and took place in the Laboratory of Experimental Economics and Political Science. Upon entry into the experimental laboratory, subjects were randomly assigned an ID number and a seat. They also received an instruction sheet, a sample valuation sheet, and were asked to read them

carefully. Several minutes after all subjects had arrived, the experimenter read the instruction sheet out loud in the laboratory. To make sure all subjects understood the rules, the experimenter then invited the subjects to raise their hands and ask questions about the experiment. The experimenter answered the questions in public until no more questions were asked. All subjects then went through a practice round, which was identical to a real round except its outcome is not counted in the total payoffs. Subjects were again encouraged to ask questions after the practice round, and the experimenter answered them in public. The first real round started only when no further questions were asked.

In the first several rounds of the experiments until perfect tacit collusion had emerged and persisted, i.e. in the collusion-conductive stage of the experiment, all subjects received a valuation sheet from the experimenter at the beginning of each round. The sheet contained information about the valuation of all subjects on every item in that round. The subjects were asked to read the valuation sheet carefully and raised their hands once they were ready. The experimenter waited for all of the subjects to raise their hands before starting the auction. The auction was conducted in the format described in section 3.2. Once the auction ended, the subjects were asked to record their earnings on the sheet at the end of their instruction sheet. The experimenter typically waited for one to two minutes for the subjects to record their earnings before starting another round by passing out new valuation sheets. Once the experiment transitioned to the competition-conductive phase, the experimenters stopped passing out valuation sheets under conditions to be discussed later, and the subjects obtained their own valuation through computer screen. In some experiments, the experiment also announced before the final round that it was the final round. Once all auctions are finished, subjects received their payoffs from the experimenter. This concluded the experiment.

4.2. Experimental Design

A total of six experiments were conducted. With the exception of institutional and informational changes that will be described below, all experiments were conducted in the same way. In addition, three pilot experiments were conducted as part of the process of developing procedures and debugging instructions and software.

The design calls for all experiments to begin within the collusion-conducive environment. The collusion-conductive stage of the experiment starts from Round 1 and lasts until the subjects reached two consecutive rounds of perfect collusion. The experiment then transitioned to the competition-conductive stage. In this environment, the experimenter started to remove information and applied various treatments sequentially to assess the effectiveness of a procedure to break the collusion. Of course, this design was unknown to the subjects. The number of rounds in an experiment depended on the bidding behavior of subjects.

The treatments were motivated by the six experimental design features, which were particularly conductive to tacit collusion. We discuss these features in the Model Section. For each of the feature, we design one treatment to eliminate it. These treatments include (i) removing public displays of the subject's ID associated with the bids; (ii) removing public information of valuations by not passing out the valuation sheet; (iii) changing the ending rule of the auction to fixed duration, (iv) removing several items for sale so some agents would necessarily win nothing; (v) destroying expectations of subjects by unexpectedly changing the structure of the preferences to eliminate the folding and item-alignedness properties; and finally (vi) announcing the final round.

These treatments were applied in roughly the same order as above in most experiments, where occasional differences in orders came from the exploratory nature of the treatments. We followed the general rule that a new treatment was implemented if the previous treatment failed to sustain a competitive outcome, and tacit collusion returned. When applying the new treatment, we retained all the previous treatments. In this way, we examined the combined effects of the treatments. Since the speed to reach perfect tacit collusion after each treatment varied in different experiments, the number of rounds in each experiment differed significantly. Table I below documents the details of these treatments.

[Table 1]

Four of the experimental treatments are straightforward, including blanking the ID, taking away valuation sheets, changing the ending rule to fixed duration, and announcing the final rounds. Removing the items for sale and destroying expectations are more complicated. While removing the items for sale, we used the same structure of

valuations and then took away several columns, which corresponded to the removed items. While destroying expectations, we typically switched the valuations of two items for some subjects in order to have multiple subjects with valuations above 800 on some items. In this way, all subjects with valuations above 800 on an item might want to bid for it, and this could lead to a bidding war. Details on how items were removed and how valuations of items were switched are documented in detail in Section 6.2, and can be found in Table X and Table XI.

5. MODELS

As is well known, game theory lacks precision when the environment applied has multiple *Nash Equilibria* (N.E.). In some situations, the prediction can be so broad that almost any pattern of outcomes can be described as a N.E. The challenge, of course, is to supplement the theory with additional principles to yield more precise predictions. Auction theory is a good example in this regard. Since Robinson (1985), many papers have demonstrated the theoretical existence of low price N.E. Recently, Brusco and Lopomo (2002) showed that as long as there are not too many more bidders than the number of objects sold, there is a *Perfect Bayesian Equilibrium* resulting in low prices even under incomplete information.

While our environment has complete information, similar reasoning from Brusco and Lopomo can be applied, and it can be shown that every price between the reservation price and the second-highest valuations can be supported as a *Subgame Perfect Equilibrium(SPE)*. In terms of predicting outcomes, there are two equilibria that deserve special attention.

The first equilibrium corresponds to competitive bidding. The behaviors of the subjects that reach this equilibrium can be characterized by two principles. The first is the *principle of surplus maximization*, which says that when choosing a bid, individual bidders will place their bids on the item that maximizes their surplus given the current prices in the auction. The second is a *minimum bid principle* that says that the individuals

choose the minimal possible price allowed by the system when choosing an amount to bid.[6]

In the environments studied here, it can be seen that if everyone else is following the strategy implied by the two principles, the best response of an individual is to follow the same strategy as well. Consequently, these strategy forms a S.P.E. and the prices of all items will ascend to the second-highest valuations, at which price the individual with the second highest value stops bidding.

The second equilibrium is called perfect tacit collusion. If we treat all buyers as a group, perfect tacit collusion occurs when the buyers maximize their own total surplus, defined as the sum of profits across all buyers. In a perfect tacit collusion, each item goes to the bidder with the highest valuation while the prices of all items equal the minimum prices set by the auction (the auction reservation price). To describe intermediate levels of tacit collusion, we define $c(TotalProfit) = \frac{MaximumSurplus - TotalProfit}{MaximumSurplus - CompetitiveProfit}$ as a measure of the competitiveness of the market. In this definition, *Maximum Surplus* is the largest possible sum of profits of the buyers, which is obtained only if all items are sold to the buyer of the highest valuations at the reservation price. *Competitive Profit* is the sum of the profits obtained by the buyers when each item is sold to the highest-valued buyer at the price of the second-highest valuation. A higher *c* reflects a greater competitiveness of the market. In particular, $c=1$ indicates the market is perfectly competitive and $c=0$ corresponds to perfect tacit collusion.

An alternative definition of tacit collusion applies to bidding behavior as opposed to the prices and allocations. Under this definition, a subject is classified as a tacit colluder if he only bids on items that satisfied one of the following three criteria:

1) the item is the subject's own item.

2) the item remains at the reservation price for more than 60 seconds.[7]

3) the item "belongs" to a bidder who has previously bid on the subject's item.

[6] These two principles were first described and tested in Brewer and Plott (1996) and later were combined and termed "straightforward bidding" by Milgrom (2000). The principles were tested again in Plott and Salmon (2004).

[7] The "at least one bid in the 60 seconds" is to require that the subjects are not "negligent". We pick 60 seconds arbitrarily: any change from 30 to 100 seconds will not make any difference in our definition of tacit colluders.

Otherwise, the subject is considered a non-colluder. We say "an item belongs to a subject" if the subject has the highest valuation on the item.

Although this definition does not contain the full complexities of bidding strategies, which will be discussed further in the Results Section, it does capture the key characteristics of the collusive behaviors. The definition reflects the idea that a tacit collusive bidder is one who mostly bids only on his own item. The tacit colluder bids on other subject's item if and only if either 1) the item has not been bid at all for a long time, or 2) the item belongs to a non-collusive subject who has bid on his item. In the first case, the tacit colluder tries to exploit the possible negligence of some bidder. In the second case, some subjects bid on the tacit colluder's item. The tacit colluder punishes the other subject and perhaps tries to push the subject away from competitive bidding. Using this definition, we obtain perfect tacit collusion if every subject is a tacit colluder.

Other than perfect collusion and the competitive equilibrium, there is also a continuum of equilibrium in between. In fact, any efficient allocation with a price vector between the reservation price and the second-highest valuations can be supported as a SPE. To see this, we construct an easy strategy as follows. In the first bid, we require each subject to bid on "his own" item of the final equilibrium price. If any subject deviates, all the subjects then revert to the strategy given by the *Principle of Surplus Maximization and Minimum Bid Principle*. The strategy constructed above can be checked as a SPE. In other words, all intermediate equilibrium can be thought of as a combination of the competitive strategy and the collusive strategy.

The discussions above suggest that if we simply look for N.E. or even S.P.E. in our collusion-conductive environment, little can be said about the final outcome. Without further equilibrium refinement, any price vector between the reservation price and the second highest-valuations of the items is a possible outcome consistent with a S.P.E. However, since the collusive and competitive equilibria corresponds to clear bidding behaviors and the rest equilibria are combinations of the two, it is natural to conjecture that the bidding outcome is likely to converge to one of the these two polar equilibria. One might think the competitive equilibrium is the natural outcome because the collusive equilibrium requires a huge amount of coordination among subjects. The competitive equilibrium can be supported by natural and simple bidding strategies, and it has been

observed in various experimental studies on auctions. However, the profits of the subjects under the competitive equilibrium are very low compared to that under perfect tacit collusion. Moreover, the difficulties to obtain a collusive equilibrium, which requires a grand collusion among all subjects, are reduced in our environment. Our symmetrical and "item aligned" feature of the preferences helps reduce a grand collusion with many subjects into a sequence of smaller collusions with two subjects.

In summary, there are six key features of the collusion-conductive environment of this auction that support the tacit collusion model as an equilibrium. We focus on these because their removal or perturbation could eliminate important support for the collusive equilibrium and thus lead to the identification of tools for the shaping and enforcing of the competitive outcome. The first two features relates to the information structure of the auction. (1) There is common knowledge of valuations for all items: before each auction, a valuation sheet with every subject's valuations is passed to all subjects. This facilitates perfect tacit collusion by helping the subjects coordinate on the allocation of the items. (2) The bidding behavior of subjects can be identified: all subjects know the ID number associated with each bid. In other words, they know who has entered which bid. This makes perfect tacit collusion easier to implement because it makes easy the necessary punishments to enforce the collusive equilibrium. For example, if subject i enters a bid on subject j's item, j knows for sure i has made the bid and won't be mistaken at his target of punishment. Increasing the punishment power of j helps discourage i from bidding on j's item.

(3) Every bid can be followed by a reaction of other bidders: The ending rule in this experiment states that the auction ends if and only if no new bids are entered for a consecutive 30 seconds. This gives a quasi-repeated structure to each single round of the auctions in the sense that it can be viewed as a game with possibly infinitely many stages. Each stage ends if a) someone enters a bid or b) no subject enters the bid for a consecutive 30 seconds. If b) occurs, the game ends. In contrast to auctions with fixed ending times, this rule deters "last second deviation" and in turn prevents competitive bidding in fear of "last second deviation." Related discussions on ending rules are in, for example, Ockenfels and Roth (forthcoming).

(4) The environment is characterized by strong ordinal symmetry. Symmetry of the valuations is known to increase the likelihood of collusive outcomes. Exactly why this occurs is still unknown. It could be related to the ease with which a subject can identify and understand the behavior of others. Alternatively, it could be related to a focal point argument. The fact that each item has a distinct highest valued subject makes focal the tacit collusive equilibrium in which every subject bids reservation price on the item he has the highest valuation. Moreover, the symmetry implies in this tacit equilibrium the division of profits for the buyers is natural: each subject wins his own item. Without this property, a tacit collusion can be sustained only through some "repeated game" arguments: bidders who don't win any item in one hundred have to be compensated in the future. The symmetry allows for tacit collusion an equilibrium without invoking complicated repeated game strategies.

(5) The valuations of the bidders satisfy the item aligned property. In other words, the subject who has the highest valuation on an item also prefers the item most. As with symmetry, this greatly facilitates the division of profits among the subjects. With item alignedness, what is best for the group is also best for all individual subjects. In contrast, if we destroy this property by having several subjects prefer the same item most, there will be several Pareto collusive equilibria. Since each subject prefers the equilibrium that gives him the highest profit, this conflict in equilibrium preference might push the subjects to the competitive equilibrium.

The above observations make clear a central theoretical property of the situation. With item alignedness property, together with symmetry, there is a unique a Pareto Optimal Subgame Perfect Equilibrium from the point of view of the buyers. The following proposition states the property formally.

Proposition 1: Consider a simultaneous ascending auction with n bidders and n items. If each bidder has the highest valuation on exactly one item, which also is his most valued item, then the unique buyer Pareto Optimal Subgame Perfect Equilibrium with undominated strategy is that each bidder wins his item (the item he has the highest valuation) at the reservation price.

Proof: See Appendix.

(6) Finally, the theory of repeated games can be applied to the experiment. The repeated nature of the auctions in the experiment makes the tacit collusion more likely to occur. As mentioned in (4), perfect tacit collusion cannot be supported as a SPE if there are more buyers than the items and the buyers play undominated strategy. However, if we allow for repeated auctions, perfect tacit collusion will be enforceable as an equilibrium with sufficiently high discount rates of the subjects. This brings extra instruments to sustain the tacit collusion outcome. One possible strategy that supports the perfect tacit collusion is that if any subject ever bids on another subject's item, then all of the subjects revert back to competitive biddings immediately in all future rounds.

Together these six features in our experimental design create a presumption in favor of the perfect tacit collusion as opposed to other outcomes. Even if perfect tacit collusion happens in this setting, however, it is unclear which feature or the combinations of them foster the occurrence of perfect tacit collusion. Since each of the six features can be associated with the institutional features above, we apply treatments designed to remove one of the features at a time to develop insights about how it interacted with other features to promote the collusive or the competitive outcome.

6. RESULTS

The results are divided into two sections. The first section summarizes the patterns of behavior during the collusion development process. The second section focuses on treatments that examine the robustness of collusion and the institutional perturbations that hold a potential for mitigating or stopping collusion once it has evolved.

6.1 Collusion and Features of the Collusion Formation Process

Result 1: In these environments perfect tacit collusion is reached.

Support: We use the competitiveness of the market to measure the degree of tacit collusion. Recall that $c(TotalProfit) = \frac{MaximumSurplus - TotalProfit}{MaximumSurplus - CompetitiveProfit}$ is a

normalized measure such that when items are sold on average at a price that equals the second highest valuation and the auction market is perfectly competitive, we have c=1. When c=0, every item is sold to the highest-valued bidder at its reservation price. In this case, we say perfect tacit collusion is reached. Figure II below shows the evolution of *c* in all six experiments.

[Figure II]

Perfect collusions were reached in all six experiments. Furthermore, the speed they were reached is remarkable. By round 4, the competitiveness has fallen below 0.1 in all but two experiments. By round 7, all six experiments have reached perfect tacit collusion. It is also worthwhile to note that once subjects have perfectly tacitly colluded, they continued to do so before any treatments were applied to the experimental environment.

Result 2: Tacit collusion develops over time and is indicated by (i) falling average prices, (ii) decreasing number of bids, and (iii) decreasing duration of the auction.
Support: The support for the result is divided into three separate sections. Each addresses a separate feature of the process.
(i). *Prices fall.*

[Figure III]

All six experiments displayed solid decreases in prices and convergence toward perfect tacit collusion. The average prices in all but four rounds were lower than the previous round. To get a sense of how fast the prices decrease on average, we ran a regression of average prices on their round numbers. The results are reported in **Table II**. The average price in the first round was 534.14, and it dropped on average per round by 71.33. We also ran log price on the number of rounds and find that the average prices decreased in each round by 28%. Although the coefficients are highly significant despite the small sample size, they are simply descriptive statistics and have no structural interpretation contents. In fact, that pattern of decrease in the average prices is far from linear, which is an important fact that we will discuss in Result 3.

[Table II]

(ii) *The number of bids decreases.*

The total number of bids in the rounds of the six experiments is plotted in Figure IV. Although there are a few "rebounds" in the number of bids, it is still clear that the number of bids falls over rounds. The rate of decrease in bid number can be found in **Table II** above. On average, the number of bids dropped by 11 bids per round. Furthermore, the regression of log bids on rounds indicates the number of bids decreased by 41% per round. Just as the decrease in prices, the decrease in bids is also not linear, which will be discussed further in Result 3.

[Figure IV]

(iii) The duration of the auction decreases.

The duration of the auctions are plotted in **Figure V.** Although there are occasional rebounds in the duration of some rounds, the downward trend toward perfect collusion is very clear. To get a quantitative sense about the decrease in duration, we find in **Table II** that on average the duration decreased by 54 seconds in per round. We also regress log duration on rounds and obtain that the duration decreases by 39% each round. As in prices and bids, the decline in durations is again nonlinear and will be discussed in Result 3.

[Figure V]

Results 3: The convergence toward perfect tacit collusion depends on behavior of the subjects in the first round. In experiments with less than two competitive bidders in the first round, collusion is immediate. In other experiments, subjects switch sequentially from competitive bidding to collusive bidding. Once a subject bid collusive, he rarely reverts back.

Support: Recall that a subject is classified as a tacit colluder if he only bids on items that satisfy one of the following three criterions:

1) the item "belongs" to the subject

2) the item remains at the reservation price for more than 60 seconds.

3) the item "belongs" to a subject who has previously bid on the subject's item.

Otherwise, the subject is considered a non-colluder.

Table III below classifies the subjects as either tacit colluders or non-colluders according to the definition above. Every subject is denoted as 0 if he is a colluder in a given round and is denoted as 1 otherwise.

[Table III]

From the Table, we see that in experiment 3 and 6, seven out of the eight subjects were tacit colluders in the first round. In these two experiments, perfect tacit collusions were both reached by round three. In other experiments, there were between three to five tacit colluders in the first round, and it took significantly longer rounds to reach perfect tacit collusion. In general, experiments with fewer tacit colluders in the first round also take longer to reach perfect collusion. The correlation between the number of tacit colluders in the first round and the number of rounds to reach perfect collusion is -0.80. The most striking feature of the table is that the evolution of bidding behavior mostly goes only in one direction: once a subject becomes a tacit colluder, he almost always remains a tacit colluder. In the 184 transitions in Table III, there are only 6 cases where bidders switched back to competitive bidding from collusive behavior. Furthermore, most of these cases are due to the insufficiencies of our method of classifying collusive behavior.

There are two leading possibilities for the failure of our classification methods. First, if the price of a collusive bidder's item has been raised to a very high level through repeated bidding by a competitive bidder, then the collusive bidder might retaliate in the next round by opening the bidding on the competitive bidder's items. By our definition, this bidder will then be classified as non-colluder in that round. Such situations indeed happened several times in our experiments.

Second, a competitive bidder might be accidentally classified as a colluder. For example, when two non-collusive bidders i and j share high valuations on two items and if i bids on both items before j does, then B will be classified as a colluder as long as he only bids on these two items. This may cause a switch from tacit colluder to non-colluder for j. We also observed a few such cases in our experiments.

Another dimension that the definition does not capture is the variation of bidding behaviors of subjects within the same group. Even if the colluders bid only on their own items, they do not always start bidding reservation price: some bidders start out a bid of 500 francs on their own items. Among the non-colluders, some subjects are a lot more competitive than others. This variation in the intensive margin requires a more detailed look at the dynamics of bidding behavior, which leads us to Result 4.

Results 4: In experiments where collusions weren't immediate, prices and bidding behaviors had a tendency for discontinuous development, similar to a regime shift, toward perfect collusion.

Support: We list our results separately for bids and prices.

I. Distribution of bids and Bid War

It is clear from **Figure IV** that the number of bids did not decrease at a constant speed. In most rounds, the bid number decreased by less than 20 bids with an average of 11 bids per round. However, after round 2 of Experiment 1, round 5 of Experiment 2, round 1 of E4, and round 1 of Experiment 5, the number of bids dropped by more than 65 bids. These four rounds are also the ones with the most bids in the respective experiments (except in Experiment 2 in which round 5 is only two bids less than the round with the most bids). Furthermore, perfect tacit collusion emerged rapidly after these rounds. In this sense, the dynamics of the auctions experienced a "regime shift" in these rounds. Table IV below reports the average prices and number of bids at and after "the regime shift". The decreases in the number of bids in these rounds are six times of the average decrease (11 bids per round); the decrease in average prices in these rounds is three times of the average (71 francs per round).

[Table IV]

Some detailed look at the bidding behavior right before the regime change can be illuminating. Take Experiment 2 as an example, there were 86 bids in round 5 and only 8 bids in round 6. In round 5, 39 bids of the 86 came from subject 103, and another 23 bids from 107.

Subject 103 had always bid competitively and entered largest number of bids in all previous rounds. Subject 107, however, had discovered the opportunity for collusion rather early: it entered only two bids in both round 3 and round 4. To understand why 107 suddenly entered 23 bids in round 7, we look at Table V which shows the valuation of 103 and 107 on item 1 and 3.

[Table V]

Table V shows that 103 and 107 share high valuations on item 1 and item 3. A price war can arise if 103 attempts to win both items. We report in **Table VI** the sequence of bids made on Item 1 and Item 3 in round 5. Subject 107 started by bidding

the reservation price on "his item", item 3. Soon after, however, 103 also bid on item 3. In response to this, 107 initially added the minimal increment onto item 3, probably hoping that 103 can stop bidding. The hope was unrealized and 103 continued to raise bids on item 3. This caused 107 to retaliate and bid on item 1, which is 103's item. A bidding war broke out between 103 and 107 on item 1 and 3 and a total of 43 bids had been placed onto these two items. When round 6 ended, 103 won item 1 at a price of 801 francs and 107 won item 3 with 773.

[Table VI]

It is worthwhile noting that 107 placed on item 1 a bid of 791, which was 20 francs larger than his valuation. If 107 won the item at that price it would be at a loss. Since bidding above one's valuation is a weakly dominated action, one might think 107 is irrational. In the experiment, however, this bid seems to have surprised 103 and caused him to think more carefully about his strategy. Indeed, only 8 bids were cast the next round. We believe that these "spiteful" actions are helpful in changing the behavior of other subjects. A similar incidence happened in round 5 of experiment 1, in which 102 (a collusive bidder) suddenly raised the price by 240 on the item of 103, who has been bidding competitively. After the "spiteful" behavior of 102, 103 stopped bidding competitively in the next round.

6.2. Remedies to Prevent a Collusive Equilibrium

Once perfect collusion emerged and persisted, various treatments were applied to break it. These methods included: a) forced anonymous bidding, b) removed common knowledge of preference, c) changed ending rule of the auction, d) removal of several items for sale, e) changed expectations of the subjects, and f) announcement of the final round.

In the first three experiments, we examined the effects of these treatments in a very exploratory manner. As our understanding increased, we consistently applied these treatments in the same order as listed in the previous paragraph in the last three experiments. New treatments were applied only if the previous treatment had failed to cause or sustain competition and the bidding returned to tacit collusion. When new treatments were applied, we kept all the previous treatments. In this way, we were able to

measure the combined effects of all the treatments. The effects of these methods on breaking the collusion are similar in all six experiments.

Result 5: Forced Anonymity in bidding had no effect.

Support: Once perfect tacit collusion persisted for two rounds, the first step we most often took to disrupt the collusion was to force anonymous bidding. As mentioned in Section 5, the intention for blanking the ID is to weaken the monitoring technology of the subjects by transforming the information structure from perfect information to imperfect public monitoring. This makes the punishment strategy less credible and deviation from collusive equilbrium more tempting.

To implement anonymous bidding, we blanked the ID associated with the bids, so that subjects no longer knew who had entered which bids except for the bids of their own. Forced Anonymity had virtually no effect in breaking the tacit collusion.

[Table VII]

Table VII documents the various statistics of prices, bids, and durations of the auctions once the IDs were blanked. Average price was below 110 francs in 12 out of 15 rounds and never exceeded 160 francs. Occasionally, there were a few attempts that moved the outcome away from equilibrium. But, these attempts almost never generated a price above 200, and the average prices fell below 105 francs within fours rounds.

Result 6: Removal of common knowledge of preferences by taking away the valuation sheet had little effect on breaking the tacit collusion.

Support: Once the subjects returned to the perfect collusive equilibrium with their IDs blanked, the next step we most often took was to remove common knowledge of preferences. Lack of common knowledge forces the subjects to form their own expectations of the valuations of other subjects and complicates the coordination of tacit collusion. Since the IDs of the subjects also remain blanked, it should be enticing for the subjects to bid on more than one items and destroy the collusive equilibrium.

To remove common knowledge of preferences, we stopped passing out valuation sheets before each round of auction. Instead, they learned about their own valuations from the computer screens. The removal of common knowledge of preferences had very small effects in breaking the collusion.

Table VIII documents the effects. After the valuation sheets were removed, some subjects did fight over a few items in some rounds. But the fights were uncommon and in general of small scale. The winning prices were rarely above 200. Moreover, bidding wars never lasted more than one round: the average winning prices fell below 105 francs in one round after the valuation sheets were first taken away. In other words, within two rounds after the valuation sheets were taken away, the auction converged back to the tacit collusive equilibrium.

[Table VIII]

It is interesting to note that in Table VIII the final winning prices were not always 100. For example, in round 7 and 8 of experiment 6, subject 104 bid 104 instead of 100. This suggests that the last digit number of the bid might be used to signal the identity of the bidder and used to enforce the collusive equilibrium.

Results 7: Changes in the structure of the game to eliminate the collusive equilibrium by switching the ending rule to fixed length had little effect in prices. Support: When removal of information failed to break tacit collusion, we changed the ending rule in one experiment. In the collusive conductive environment, an auction ends only if no new bids are entered for a consecutive 30 seconds. By turning the variable ending rule into a fixed duration rule, we changed the structure of the auction by transforming it from a possibly infinite horizon game to one with a finite horizon. Theoretically, the new ending rule encourages subjects to deviate from the collusive equilibrium immediately before a round ends. Anticipating this, the subjects might engage in competitive bidding earlier on.

We changed the ending rule in round 11 and 12 in Experiment 2 by canceling the time reset option. In these two rounds, the auctions were changed to a fixed duration of 30 seconds, so all legal bids had to be entered within 30 seconds after the auction started. This had little effect in breaking the collusion.

[Table IX]

Table IX documents the effect of fixed ending rule. The prices of the winning items remained low, although the allocations of the items were no longer efficient. There

were some deviations at the end of the auction. In round 11, subject 107 bid 120 at the last second on item 2, which is 102's item. In round 12, we again saw 107 bidding on item 8, which was 106's item. Subject 107's behavior was consistent with Ockenfels and Roth (forthcoming), where they reported that various EBay bidders entered their bids in the last second. In our environment, we had eight subjects, and 107 was the only deviator in both rounds. After these two rounds, we restored the old ending rules in later rounds. We did not observe retaliations from subjects whose items were bid away by others at the last second.

We restored the old ending rule mainly because there was a technical problem with the computer system in round 12, as one subject complained that his last-second bid failed to go through. As a result, there was no winner for item 5. We were concerned that if many subjects entered their bids in the last several seconds, many bids might not go through, and confusion would result thus making the experimental outcome hard to interpret and was not the direction we wanted to pursue. Because of this, we did not test the effects of fixed duration ending rule in later experiments.

Result 8: Destruction of short-term symmetry had some effects, but the experiment still converged to perfect tacit collusion in the end.

Support: Two crucial design features that could facilitate tacit collusions are the symmetry and "item alignedness" properties of preference. Theoretically, symmetry and "item alignedness" makes the tacit collusion the unique Pareto Equilibrium, which is very attractive to subjects. In experimental literature, symmetry can also help facilitates the collusion equilibrium by making it focal. Our expectation was that the removal of these features would break tacit collusion.

To implement this, we removed several items for sale in some of the experiments. Experiment 3 is the first time we removed items for sale. In that experiment, we rotated the items to be removed. From Round 4-7, three items were removed for sale. From Round 8-11, five items were removed in each round. In later experiments, we standardized our method and always removed item 1 to 3. Surprisingly, the destruction of

these two features did not move the equilibrium to competitive outcome, and perfect tacit collusion returned in all experiments.

[Table X]

Table X reports the price, bid, and duration of the auctions with items removed for sale. Removing the items for sale had greater (incremental) effect in pushing the subjects away from collusive equilibrium than the previous treatments. In Experiment 5, the average price jumped to 680 francs immediate after the first three items were blocked for sale. Furthermore, prices stayed in high level for another two rounds and even attained an average price of 743 in round 15, which exhibited one of the most competitive scenarios in the experiment: 117 bids had been entered and the auction lasted for 682 seconds, the third-longest round in the entire experiment series.

Although removing the items for sale had more impacts than the previous treatments, its effects remain modest and diminish over time. In Experiment 3, perfect collusion persisted even when 5 items were blocked in some rounds. In Experiments 4 and 6, although the prices rose somewhat after the items were blocked, their levels were low and the auctions were still filled with collusive behavior. Even in Experiment 5, where removal of items lead to the most competitive behaviors among the experiments, the prices converged to the perfect collusive level after six rounds.

Result 9: Destruction of common expectations by surprise competitive entry a): Leads to competitive biddings on the item with entry b): Spreads the competitive behavior to items with single high-valued bidder, and c): Causes price wars in future rounds of auctions with symmetry.

Support: In the collusive equilibrium, a subject with a valuation above 800 on an item wins it at the reservation price. Once collusion has persisted for more than 10 periods, it is natural for the subjects to expect that this will continue to happen. To destroy this common expectation, we typically switched the valuations of some subjects so that there were multiple bidders with valuations above 800 on some items. Take Figure I as an example, where subject 103's original valuation is 782 on item 5 and 808 on item 7. We switch his valuations on these two items (of course without 103's knowledge), so subject 103's new valuations become 808 on item 5 and 782 on item 7. This change destroys the

symmetry of valuation by adding a surprise entry: there are now two bidders, 103 and 104, both having valuations above 800 on item 5. It also destroyed the "item aligned" property of the preference: 103 no longer had the highest valuation on the item 5, the item he valued most. In each experiment, this surprise entry took place in two consecutive rounds. After these two rounds, we removed this treatment so that each item had again only one subject with valuation above 800.

[Table XI]

Table XI reports the details of the change and the winning prices of all items for sale. Three patterns emerge out of destruction of common expectation. First, the prices of items with multiple high-valued subjects rose to very high levels except in round 17 of experiment 4 and in round 12 of experiment 6. Furthermore, the prices on some items were even above the competitive levels. For example, in round 13 of experiment 6, item 4, 5 and 6 were sold at 834, 863, and 862 respectively, which were significantly higher than 746, 834, and 808, the second-highest valuations on these items. This is an indication that subjects had used spiteful behavior either as pure retaliation or as an urge for return to collusive equilibrium.

Second, there is a contagion of price war from initially contested items to items with single high-valued subject. In round 13 of experiment 6, only item 5 and 6 had more than one subject with valuations above 800. Consequently, the only initial bid wars were between 101 and 102 on item 6 and between 106 and 107 on item 5. The price of item 4 remained at 104 francs even when the prices of item 5 and 6 had both risen above 800. Subject 101, who was potentially frustrated by his loss in the price war on item 6, soon started to bid on item 4. The price of item 4 rose quickly, and 101's final bid on it was 800, more than 100 above his valuation. Similar patterns of bidding wars existed in other experiments as well.

Third, once the common expectation is broken, price wars appear in later rounds where all items have a single subject with valuation above 800 francs. Some of the bidding wars seemed to result from frustrations and angers in the previous round. For example, subject 104 didn't win any item in round 13 of Experiment 4, even though his valuation on item 2 was above 800. In round 14, 104 started out by bidding 749 on item 1

and 769 on item 3, even though his valuations for these two items are only 249 and 190 francs respectively.

The spiteful behaviors gradually die out and prices fall down to collusive levels in most experiments after more rounds of auction once the treatment was removed. However, the convergence toward collusive equilibrium is more difficult after expectations have been destroyed. In Experiment 3, for example, the prices never fell to the perfect collusive level after common expectations were destroyed. There were two items sold at above 500 francs five rounds after the treatment was removed. Furthermore, even if the prices approached the collusive level, the collusive equilibrium did not seem to be very robust. This can be seen from the "last round" behaviors of the subjects.

Result 10: Destruction of the repeated nature of the game creates competition if there are fewer items than bidders and common expectations were destroyed before.
Support: In Experiments 1 and 4, the experimenter announced before the last round that "the next round will be the last round of the experiment". Two dramatically different behaviors were observed. In Experiment 1, the experimenter announced that Round 11 was the last round. The subjects responded very little to this announcement. The prices remained low, as the highest price of the items is only 120 and the average price is 103.75. This was very close to the perfect tacit collusion.

In Experiment 4, however, the subjects responded dramatically to the announcement that round 23 was the last round. Before that, the outcome of round 22 was rather collusive: the highest price is only 200 and the average price was 143. In round 23, subjects bid aggressively on all of the five items. The average price was 694.75, and there were three items priced above 700. Furthermore, item 3 was sold at 824, 25 francs higher than the second highest-valuation on this item.[8]

There are two possible reasons for the competitive bidding behaviors. First, there were only five items for sale in this round. Therefore, perfect collusion cannot be supported as a N.E. if the subjects follow undominated strategies. Second, it could be that collusive equilibrium is less stable after the common expectations have been destroyed.

[8] However, there is no spiteful behavior here, as the high price results from a jump bid of the winner.

7. SUMMARY OF CONCLUSIONS

The fundamental results reflect the discovery of an environment in which tacit collusion evolves naturally without conspiracy and without intervention or encouragement by the experimenter and without any special facilitating device. The allocation, including prices, is predicted accurately by a specific solution to a game theoretic model of the auction process. In this environment, the folding pattern of preferences are known and opportunity of coordination into mutually beneficial patterns of behavior can be easily identified. In addition, the institutional environment supplies opportunities for retaliation for unwanted competitive behavior. In this environment, perfectly collusive strategies develop quickly.

The dynamics of adjustment in this environment exhibit distinct patterns. In some cases, the tacit collusion is immediate. That is, from the structure of the environment alone agents deduce and implement a commonly held strategy of tacit collusion. In these cases there is no learning, retaliations, or adjustments. The advantages of tacit collusion result from cognition alone and are implemented. In the cases in which the tacit collusion does not occur immediately, the system typically starts with the competitive equilibrium outcome. As the rounds proceed, prices decline gradually, until there is one round that appears as a "regime shift" and perfect tacit collusion is reached immediately afterwards.

Several experiments were conducted using the “exploratory methodology” and using the opportunity of an existing tacit collusion to explore the many dimensions that can be imagined as “remedies”. Rather than choose one “remedy” and collect many observations on it, many remedies were explored and done so in sequence. Thus, we have produced a preliminary “map” of a varied and complex landscape of institutions together with strong hints about where different remedies might lead. It is hoped that this map will guide researchers using more surgically precise experimental designs through this complex terrain. Our summary that follows should be read from that perspective.

Once collusion has developed it is difficult to disrupt and appears to be held in place by a pure system of belief as opposed to institutions and information that enable the maintenance of a Perfect Bayesian Equilibrium. The sequential removal of informational and institutional features that are prominent in the creation of equilibria in the models consistent with the collusive pattern of behaviors do nothing to change the behavior.

Tacit collusion remains, or if disrupted by the environmental change, returns as the prominent pattern of behavior.

The treatment or "remedy" that effectively eliminates the collusion is a change that creates competition in one or two of the markets. If an agent finds himself or herself with a competition for his/her item the competition spreads to other markets. In a sense, the unexpected introduction of a "maverick" under circumstances in which almost all of the features of the collusive compatible environment have been removed destroys the collusive behavior. The dramatic change in behavior could be the result of destroyed beliefs about the behavior of others coupled with an inability to determine otherwise due to the institutional environment. This change nudges competition from the contested market to other markets. An understanding of this process of contagion is needed.

Appendix: Proof of Proposition 1.

Lemma 1: Let m be the minimal bid increment. Assume that for every item k, we have $2m < V_k - V_k^2$, where V_k is the highest valuation on item k and V_k^2 is its second highest valuation. If bidder i does not win any item in a subgame perfect equilibrium outcome, the final price on i's item must be larger than equal to $V_i - m$.

Proof: Suppose the contrary. Then bidder i's profit is zero, and the price on his item, p_i, is larger than or equal to $V_i - m$. Now suppose i bids $Max\{V_i - m, p_i + m\}$ on item i and bids $V_j - m - \varepsilon$ on items such that $V_j - 2m > p_j$ for $j \neq i$, where $\varepsilon = \underset{j \neq i, V_j - 2m > p_j}{Min} \{V_j - 2m - p_j, m\}$. In this way, the price of each item is larger than its highest valuation minus twice of the minimal bid increment, which is larger than the second highest valuation. Therefore, any Nash Equilibrium of this subgame must have that no bidder will want to bid on item that he doesn't have the highest valuation and that each bidder j whose item has been bid by i will bid on his own item. Therefore, bidder I can guarantee himself positive payoff in this subgame, which is a contradiction. Q.E.D.

Proof of Proposition 1:

First, the discussion above indicates that every bidder winning his item at the reservation price can be supported as a S.P.E. This implies that for a subject, call it subject A, to acquire a higher level of profit than in perfect collusion, he must obtain positive profits from at least two items. This implies that A wins at least two items. Now we partition the set of items into W and L, where W includes all of items whose highest-valued bidder is a winner (wins at least one item) and L includes items whose highest-valued bidder does not win any item. Since A wins at least two items, at least one bidder is itemless, so L is not empty. Now by lemma 1, the prices of items in L must be higher than the second highest valuations on these items. This implies that the winners of these items in L must suffer losses from them. Because A has positive profits from at least two items in W, one winner must win zero item from W. The only items this winner wins must come from L and thus his total profit from the auction is negative. This leads to a contradiction because in equilibrium any bidder can at least guarantee himself nonnegative profits. Q.E.D.

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Subject\Item	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8
101	833	212	706	101	290	180	317	94
102	787	164	893	69	325	223	266	146
103	327	121	284	214	782	76	808	187
104	252	55	303	158	856	105	738	241
105	238	844	194	343	81	745	106	277
106	159	788	218	276	122	841	75	340
107	143	303	52	848	157	280	235	796
108	81	266	116	795	215	342	181	827

Figure I: A Sample Valuation Sheet

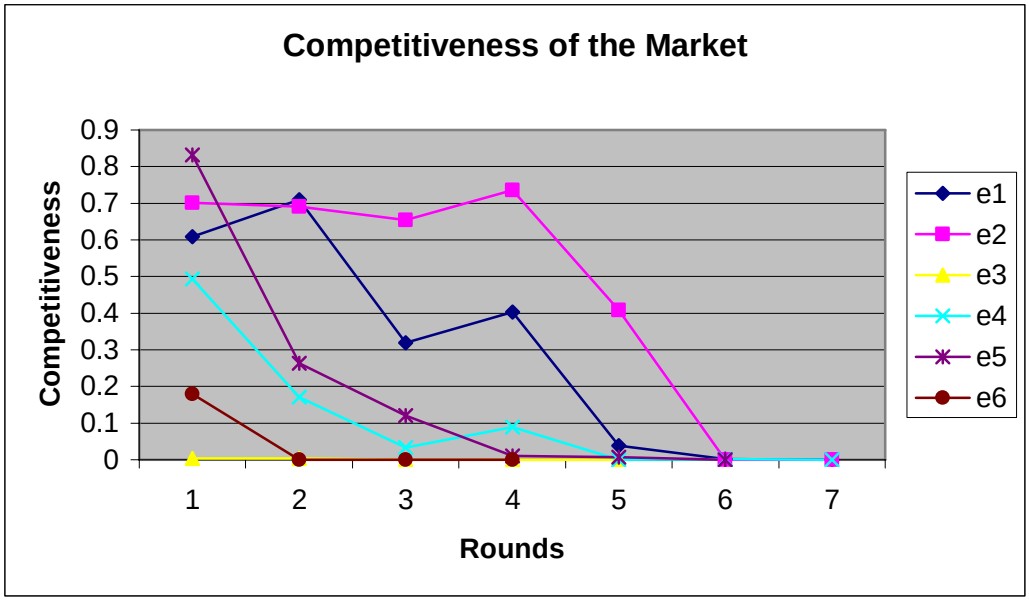

Figure II. Competitiveness of the Market

Figure III shows the average price series for the six experiments.

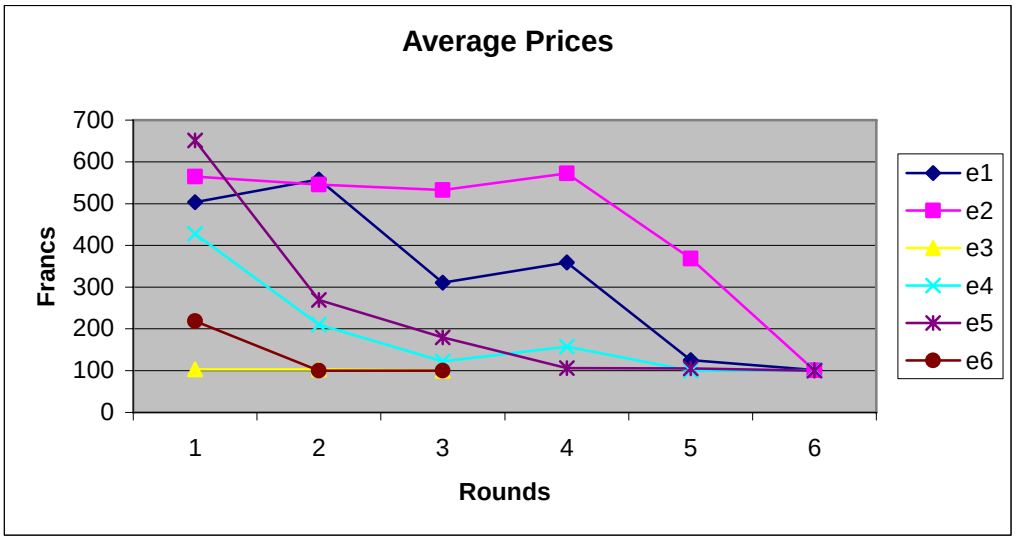

Figure III. Average Prices until Perfect Collusion

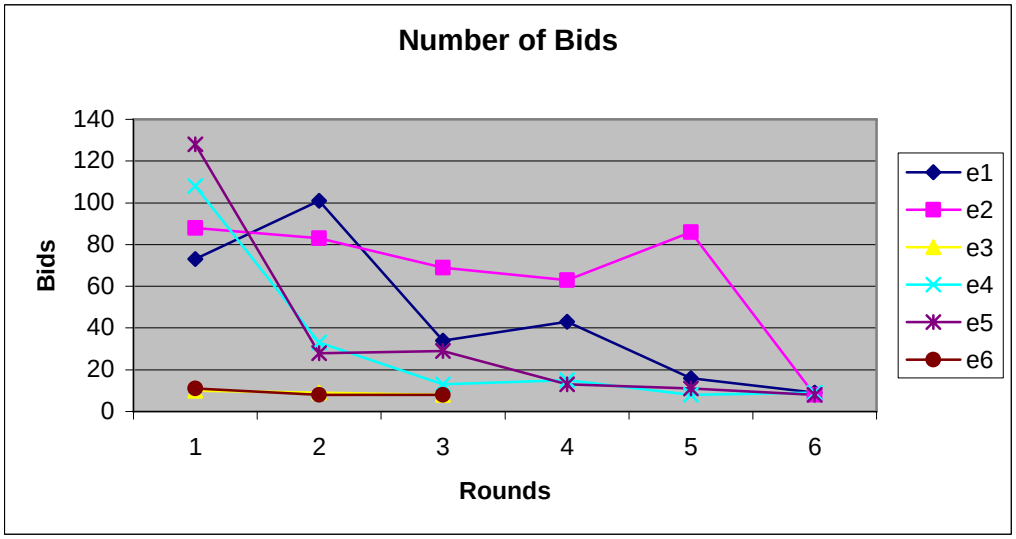

Figure IV. Number of Bids until Perfect Collusion

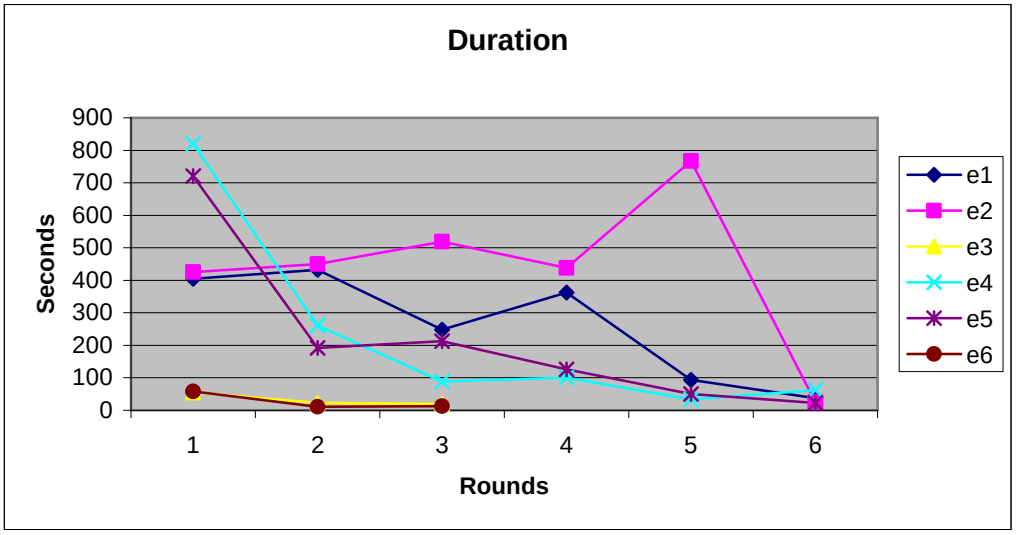

Figure V. Duration of the Auctions until Perfect Collusion.

Table I: Summary of Experimental Environment

Experiments	E1	E2	E3	E4	E5	E6
Date	02/18/02	04/19/02	05/10/02	06/12/02	06/21/02	06/29/02
Total Rounds	11	14	18	23	26	17
Blank ID	9-11	N/A	6-18	8-23	7-26	4-6
Remove Valuations	N/A	9-14	3-18	12-23	10-26	7-8
Change End-Rules	N/A	11-12	N/A	N/A	N/A	N/A
Remove Items	N/A	N/A	4-18	14-23	13-26	9-17
Destroy Expectations	N/A	N/A	12-13	17-18	22-23	12-13
Announce Final Round	Yes	No	No	Yes	No	No

Table II. Price, Bids, and Duration on Number of Rounds Played*

Dependent Variables	Constant	Rounds	R^2	Number of Observations
Prices	534.14	-71.33	0.23	30
	(70.48)	(12.86)		
LogPrices	6.39	-.28	0.24	30
	(0.26)	(.05)		
Bids	81.42	-11.15	0.19	30
	(15.80)	(3.40)		
LogBids	4.35	-.41	0.07	30
	(.48)	(.07)		
Duration	456.29	-54.37	0.12	30
	(111.93)	(24.5)		
LogDuration	6.07	-.39	0.07	30
	(.56)	(.11)		

- Estimated from Random Effects Model.

Table III: Summary Statistics for Colluders

Experiment /Round	101	102	103	104	105	106	107	108
2/18/02								
Round 1	0*	1	1	1	0	0	0	0
Round 2	0	1	1	1	0	0	0	0
Round 3	0	0	1	1	0	0	0	0
Round 4	1	0	1	0	0	0	0	0
Round 5	0	0	1	0	0	0	0	0
Round 6	0	0	0	0	0	0	1	0
Round 7	0	0	0	0	0	0	0	0
4/19/02								
Round 1	0	0	1	1	1	1	1	0
Round 2	0	1	1	0	1	1	0	1
Round 3	1	0	1	0	1	0	0	1
Round 4	0	0	1	0	1	0	0	0
Round 5	0	0	1	0	0	0	0	0
Round 6	0	0	0	0	0	0	0	0
5/10/02								
Round 1	0	0	0	0	0	0	1	0
Round 2	0	0	1	0	0	0	0	0
Round 3	0	0	0	0	0	0	0	0
6/12/02								
Round 1	1	1	0	0	0	1	1	0
Round 2	1	0	0	0	0	1	0	0
Round 3	1	0	0	0	0	0	0	0
Round 4	1	1	0	0	0	0	0	0
Round 5	0	0	0	0	0	0	0	0
6/21/02								
Round 1	0	1	0	1	0	1	1	0
Round 2	0	0	0	1	0	1	1	0
Round 3	0	0	0	1	0	1	0	0
Round 4	0	0	0	1	0	1	0	0
Round 5	0	0	0	1	0	1	0	0
Round 6	0	0	0	0	0	0	0	0
6/29/02								
Round 1	1	0	0	0	0	0	0	0
Round 2	0	0	0	0	0	0	0	0

*: In the table, a bidder is marked as a 0 if he is classified as a colluder and 1 otherwise.

Table IV: Number of Bids and Average Prices at and after the Regime Shift

Experiment	Round	Number of Bids	Average Prices
2/18/02	2	101	558
	3	34	310
4/19/02	5	86	368
	6	8	100
6/12/02	1	108	427
	2	33	210
6/21/02	1	128	651
	2	28	269

Table V: Valuation of 103 and 107 on Item 1 and 3

Subject\Items	1	3
103	867	773
107	771	861

Table VI: A Bidding War

time	item	id	price
3055	3	107	100
3069	1	103	200
3077	3	103	200
3099	3	107	210
3120	3	103	220
3132	3	107	230
3144	3	103	300
3160	3	107	310
3173	3	103	400
3178	1	107	300
3185	3	107	410
3199	1	103	310
3211	1	107	350
3226	1	103	360
3237	1	107	400
3247	1	103	450
3257	1	107	500
3264	3	103	500
3276	1	107	510
3282	3	107	510
3291	1	103	520
3302	3	103	520
3309	3	107	530
3326	3	103	550
3334	3	107	560
3341	1	107	550
3344	3	103	600
3356	3	107	610
3367	1	103	600
3376	3	103	650
3387	1	107	650
3392	3	107	700
3417	1	103	761
3429	3	103	710
3436	1	107	771
3445	3	107	720
3453	1	103	781
3472	3	103	730
3482	3	107	740
3507	3	103	752
3523	3	107	773
3529	1	107	791
3546	1	103	801

Table VII: Summary Statistics after IDs are Blanked

Experiment /Round	Highest Price	Lowest Price	Average Price	Duration Time	Total Bids
2/18/02					
Round 9	100	100	100	22	8
Round 10	200	100	113.5	29	8
Round 11	100	100	100	14	8
5/10/02					
Round 6	100	100	100	14	5
Round 7	100	100	100	15	5
6/12/02					
Round 8	121	100	108	115	17
Round 9	150	100	106.25	35	9
Round 10	255	100	135.13	134	16
Round 11	100	100	100	16	8
6/21/02					
Round 7	160	120	151.25	214	45
Round 8	160	100	107.5	15	8
Round 9	110	100	101.25	37	9
6/29/02					
Round 4	100	100	100	19	8
Round 5	120	100	102.63	44	9
Round 6	101	100	101.13	18	8

Table VIII: Summary Statistics after Valuations Sheets are Taken Away

Experiment /Round	Highest Price	Lowest Price	Average Price	Duration Time	Total Bids
4/19/02					
Round 9	807	100	263.25	165	20
Round 10	100	100	100	21	8
5/10/02					
Round 3	100	100	100	20	8
6/12/02					
Round 12	170	151	160.88	228	37
Round 13	100	100	100	17	8
6/21/02					
Round 10	310	100	127.5	40	10
Round 11	110	100	101.25	23	8
Round 12	120	100	102.5	19	8
6/29/02					
Round 7	104	100	100.5	18	8
Round 8	104	100	100.63	19	8

Table IX: Summary Statistics for the Fixed Duration Rule

Experiment /Round	Item 1 Price (Winner)	Item2 Price (Winner)	Item3 Price (Winner)	Item4 Price (Winner)	Item5 Price (Winner)	Item6 Price (Winner)	Item7 Price (Winner)	Item8 Price (Winner)
4/19/02								
Round 11	100 (108)	150 (107)	100 (104)	100 (106)	100 (105)	100 (107)	100 (101)	100 (103)
Round 12	100 (107)	100 (104)	100 (108)	100 (105)	N/A N/A	100 (102)	100 (103)	120 (107)

Table X: Summary Statistics after Some Items are Removed for Sale

Experiment /Round	Highest Price	Lowest Price	Average Price	Duration Time	Total Bids	Items Blocked
5/10/02						
Round 4	100	100	100	14	5	1,4,5
Round 5	100	100	100	14	5	3,4,7
Round 6	100	100	100	14	5	2,5,8
Round 7	100	100	100	15	5	2,3,6
Round 8	100	100	100	6	3	2,3,4,6,7
Round 9	120	100	110	48	6	2,3,4,5,8
Round 10	100	100	100	6	3	1,2,6,7,8
Round 11	100	100	100	3	3	4,5,6,7,8
6/12/02						
Round 14	280	160	196	233	37	1,2,3
Round 15	180	140	160	202	27	1,2,3
Round 16	122	100	104.38	30	7	1,2,3
6/21/02						
Round 13	710	660	682	391	68	1,2,3
Round 14	780	410	596	174	38	1,2,3
Round 15	800	710	743	682	117	1,2,3
Round 16	130	100	110	38	9	1,2,3
Round 17	610	310	428	480	51	1,2,3
Round 18	610	100	229	149	27	1,2,3
Round 19	110	100	102	20	6	1,2,3
Round 20	120	100	104	43	7	1,2,3
Round 21	120	100	106	36	7	1,2,3
6/29/02						
Round 9	110	100	103.38	23	6	1,2,3
Round 10	155	100	113.25	47	9	1,2,3
Round 11	107	100	101.38	9	5	1,2,3

Table XI: Price Statistics after Common Expectation Destruction

Experiment/Round	Chosen/Items	Item 1 Price	Item 2 Price	Item 3 Price	Item 4 Price	Item 5 Price	Item 6 Price	Item 7 Price
5/10/02								
Round 12	1,2	870	873	730				
Round 13	1,2	843	840	669				
6/12/02								
Round 17	6,8			410	530	460	420	460
Round 18	6,8			860	770	876	751	631
6/21/02								
Round 22	5,*			750	877	760	440	430
Round 23	5,6			600	580	843	711	800
6/29/02								
Round 12	5,6			100	200	302	100	100
Round 13	5,6			834	863	862	100	100

*There is an unintended switching, so 101, 104, and 107 all had high values in item 5.

On 5/10/02, in round 12, 101's valuation on item 2 and 5 was switched. 106's valuation on item 1 and item 8 was switched.
In round 13, 102's valuation on item 2 and 6 was switched; 105's valuation on item 1 and 3 was switched.

On 6/11/02, in round 17, 102's valuation on item 6 was switched to 822; 104's valuation on item 8 was switched to 821.
In round 18, 102's valuation on item 3 and item 6 was switched; 108's valuation on item 8 and item 4 was switched.

On 6/21/02, in round 22, 104's valuation on item 2 and item 5 was switched; 107's valuation on item 1 and item 5 was switched.
In round 23, 101's valuation on item 2 and item 6 was switched; 106's valuation on item 1 and item 5 was switched.

On 6/29/02, in round 12, 104's valuation on item 2 and 6 was switched; 107's valuation on item 1 and 5 was switched.
In round 13, 101's valuation on item 2 and 6 was switched; 106's valuation on item 1 and 5 was switched.