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

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The paper studies bidder behavior in simultaneous, continuous, ascending price auctions. We design and implement a "collusion incubator" environment based on a type of public, symmetrically "folded" and "item-aligned" preferences. Tacit collusion develops quickly and reliably within the environment. Once tacit collusion developed, it proved remarkably robust to institutional changes that weakened it as an equilibrium of a game-theoretic model. The only successful remedy 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." (*JEL* L50, L94, D43)

I. INTRODUCTION

The research reported here explores both 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 four broad questions. Can we create economic environments within which tacit collusion emerges (in the absence of conspiracy)? Such an environment can be viewed as a "tacit collusion incubator." A successful incubator would provide an opportunity to study the details of phenomena that have difficulty surviving in other environments. Can the evolving behavior be understood in terms of *game*-theoretic models and if so, can the behavior be understood in terms of equilibrium selection? Is the underlying model robust in the sense of predicting behavior when possibly collusion breaking, institutional perturbations are imposed? The overall goal is to direct focus on the principles that operate in the hope that an understanding of the principles will help us understand the phenomenon in the numerous, different, complex environments found naturally occurring.

The institutional setting is an auction in which *game*-theoretic models have a natural interpretation within which multiple equilibria exist. 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

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ABBREVIATIONS

NE: Nash Equilibrium
SAA: Simultaneous Ascending Auction
SPE: Subgame Perfect Equilibrium

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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 the aid of side payments. We call it the "collusion incubator" environment. Second, 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" or "collusion incubator." It was designed with the purpose of creating an environment in which tacit collusion would evolve. This environment necessarily abstracts from parameters that might exist naturally and differs dramatically from the parameters studied in other experiments. The purpose is to create and study phenomenon that is difficult to find in any form. Indeed, tacit collusion in a multiple item auction has never been (convincingly) observed. The reliable creation of phenomenon that is thought to exist is a first step to understand the conditions under which it might be found, observe the basic principles at work in its evolution, and identify how it might be detected if it exists in more complex environments. Thus, as is the case with experimental methods in all science, the extreme divorce of the experimental environment from the naturally occurring environment is very useful, if not necessary.

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. 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 on Item X agent i had the m-th highest value and agent j had the n-th highest value, then agent i had the n-th highest value on the item where individual j had the m-th 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 also 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 where *j* has the highest value. 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 face 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.[1] 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 in more complex environments prices almost always converge to near the competitive equilibrium.[2]

The first basic result is that within the collusive conducive 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 context of these results needs emphasis. While the study answers some questions, it certainly does not answer all questions. Exactly what theory might be applied remains open, including more detailed analysis of "one shot" game models, the application of repeated game concepts, or whether or not game theory itself is an appropriate tool for understanding the phenomenon. How the results might be translated to complex fieldwork remains unaddressed. The questions posed here are primarily empirical with only crude steps toward adequate theory and the results are reported in the hope that theorists will be challenged to provide convincing theory of what is observed.

The paper is outlined as follows. In Section II, the background experimental work is discussed. Our experiments build on that literature. Section III contains the details of the experimental environments. The details of the preferences and institutions are found there. Section IV is the experimental design that explains the number of experiments and

1. The paper provides a sufficient condition/environment for the emergence of stable tacit collusion, but it does not investigate what features of the collusion incubator are most critical. Instead, it investigates what remedies can be applied to break the collusion once it has emerged.

2. The posted price effect discovered by Plott and Salmon (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.

the conditions that were in place for each experiment. Section V discusses models and theory. The correspondence between the *game*-theoretic solutions and the experimental procedures in the auctions are discussed in detail. Section VI 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 VII is a summary of conclusions.

II. 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 Porter (1988) study the bidding of drainage leases on the Outer Continental Shelf. Their findings suggest that there are coordination in bids among firms that own tracts adjacent to the lease for sale. Cramton and Schwarz (2000) report what appear to be attempts to collude in FCC spectrum auction but have no evidence of actual, price influencing collusion. In particular, they point out how bidders used the last several digits of the bids to signal their intents.

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 chosen by the experimenters. Isaac and Plott (1981) are the first to study conspiracy experimentally. Isaac and Walker (1985) allow explicit communications among bidders in auctions, and they observe conspiracies in 7 out of 12 auction series. Tacit collusion in auctions with standard procedure, however, is rarely observed in earlier experimental studies. Even when it is observed, tacit collusion is unstable and the prices easily converge back to competitive levels; see, for example, Burns (1985) and Clauser and Plott (1993). In a related industrial organization context, Isaac and Smith (1985) search for predatory behavior in constraint of competition and do not find any. Kagel (1995) surveys earlier experiments on collusions in auctions.

Recently, a sequence of experiments successfully observed robust tacit collusion in special auction institutions. Sherstyuk (1999) studies ascending auctions under common values. In her experiments, each auction consists of two units of items and three bidders, who demand one unit only. She introduces 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 reports persistent and stable tacit collusions: bidders match each other's low bids in most of the auctions. Sherstyuk (2002) obtains similar results under private values.

Robust tacit collusion in auctions with "standard institutions and procedures" is first observed by Kwasnica and Sherstyuk (2007). In their environment, there are two items for sale in an ascending auction with either two or five bidders, who value both items. The experimental environment conforms to the theoretical conditions of Brusco and Lopomo's (2002), and the auction results are broadly consistent with the theoretical predictions: when there are two bidders only, they often tacitly collude through splitting the two items. No collusion is found in auctions with five bidders. Kwasnica and Sherstyuk (2007) also examine the role of complementarity in collusions. They find that complementarities between items reduce collusion. However, when the level of complementarity is moderate, bidders still tacitly collude by taking turns to win the auction. A survey of recent results on collusion in auction can be found in Sherstyuk (forthcoming).

III. COLLUSION INCUBATOR/COLLUSION-CONDUCIVE ENVIRONMENTS

Each experiment starts with a collusion-conducive 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 of Items and Preferences. The details of the auction architecture will be in the institution environment subsection.

FIGURE 1
A Sample Valuation Sheet

Subject\Item	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8
101	514	123	446	730	263	869	388	615
102	784	312	244	585	427	649	116	802
103	153	584	889	349	671	476	707	211
104	387	732	658	153	879	298	548	430
105	492	873	566	206	787	124	618	302
106	636	217	361	853	160	738	494	506
107	824	403	179	626	352	561	202	728
108	253	645	755	443	513	363	899	181

The information structure is discussed in a separate subsection.

Once perfect tacit collusion[3] has emerged and has persisted, the experimental environment is transitioned into a competition-conducive environment through various treatments. These treatments are exploratory in nature and occasionally differ in experiments. We document these treatments in detail in the experimental procedure and design section.

A. Items and Preferences

Each experiment has eight subjects, numbered from 101 to 108 anonymously. In the collusive environments, there are eight items for sale, numbered from 1 to 8. The subjects' valuations for each item range from 50 to 900 francs, where one franc can be exchanged after the experiment for 1 cent. There is no complementarity between items: a subject's valuation of a group of items is the sum of his valuations of each item in the group.

The valuations are kept identical across experiments to facilitate comparisons. Within each experiment, the valuations differ round by round and are designed to facilitate tacit collusion in earlier rounds. Figure 1 below gives a sample valuation sheet that has been used in the experiments.

In Figure 1, subject 107 has the highest valuation on Item 1 at 824 and subject 102 has the second highest valuation at 784. The relative position of the two is reversed on Item 8, where subject 102 now has the highest valuation at 802 and 107 has the second highest one at 728. This illustrates a symmetry in the valuations: if subject A has the highest valuation on an item where subject B has the second highest valuation, then A has the second highest valuation on the item where B has the highest valuation.

In Figure 1, if 102 and 107 do not "compete" with each other on these two items, then the competition they face (on these items) will be considerably lower. To encourage tacit collusion as much as possible, in the first five rounds of the experiment, we design the valuation sheet so that the third-highest valuation on each item is lower than 400 francs while the top 2 are above 700. This gap in valuations increases the gain of tacit collusion from the top.

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. We design the valuations such that, if subject i is m-th and subject j is n-th on an item, then j is m-th on the item where i is n-th. In Figure 1, 101 is second and 105 is seventh on Item 4. Then on Item 5, where 105 is second, 101 is seventh. For the purpose of collusion, it is enough to note that for any subject i and j, if j is n-th on an Item i is first, then i is n-th on the item where j is first.

The general ordinal structure of folded preference remains throughout the collusion-incubator environments, while the exact valuations of subjects differ from round to round. In general, the pairs of subjects who share the highest two valuations on the same items in any given round are typically not "paired together" in the next round.

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

3. We define an auction outcome as perfect tacit collusion if all items are sold efficiently at their reservation price.

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 1: subject 108 has the highest valuations among all subjects for Item 7. Consequently, 108 by design values Item 7 most among all items. This "item-aligned" feature suggests that 108 would be a natural winner of Item 7. In this sense, we denote Item 7 as "108's item." From now on, we also denote the item on which subject *i* has the highest valuation as *subject i's item*.

Finally, it is worthwhile to point out that there are no ties in valuations: no two subjects or more share the same valuation on any item; no subject has the same valuations on any two or more items.

The total payoff of a subject in any given round in an experiment is calculated by summing his payoffs from all the items he wins. The subject's payoff on each of his winning item is equal to his valuation of the item minus his winning bid price. In particular, the subject can incur a loss on an item if his winning price exceeds his valuation. The subject's total payoff in the experiment is the sum of his payoffs in all rounds.

B. 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 bid for and the associated bid price, while satisfying two restrictions. First, there is a *reservation price* of all items: the smallest bid that can be entered on any item is 100 francs. Second, the *minimal bid increment* is 10 francs so that a new bid on an item is required to be at least 10 francs higher than the existing 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 when no new bid is entered for any item for consecutive 30 sec. That is, all items are open for bid until the auction closes. The highest bidder of an item wins it and pays his bidding price. A bidder can win multiple items in a round of auction.

Information Structure

In the collusion incubator 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 observe from the computer screen who (given by the ID number) have bid what price on which item. The only information missing for the subjects is that they do not know the total number of rounds, except in two experiments where the experimenters announce immediately before the final round that it is the final round.

When the experiment transitions into the competition-conducive phase, various treatments are applied to reduce information. We discuss the details in the next section.

IV. EXPERIMENTAL PROCEDURES AND DESIGN

A. Experimental Procedures

The subjects in the experiments are mostly Caltech undergraduates, with a few graduate students in non-economics departments in some experiments. All of the experiments last between 1½ to 2½ h and take place in the Laboratory of Experimental Economics and Political Science. Upon entry into the experimental laboratory, subjects are randomly assigned an ID number and a seat. They also receive an instruction sheet and a sample valuation sheet and are asked to read them carefully. Several minutes after all subjects have arrived, the experimenter reads the instruction sheet out loud in the laboratory. To make sure all subjects understand the rules, the experimenter encourages the subjects to raise their hands and ask questions about the experiment. The experimenter answers the questions in public until no more questions are asked. All subjects then go through a practice round, which is identical to a real round except its outcome is not counted in the total payoffs. After the practice round is over, subjects are again encouraged to ask questions, and the experimenter answers them in public. The first real round starts only when no further questions are asked.

In the first several rounds of the experiments until perfect tacit collusion has emerged and persisted, i.e. in the collusion incubator stage of the experiment, all subjects receive a valuation sheet from the experimenter at the beginning of each round. The sheet contains information about the valuation of all subjects on every item in that round. The subjects are asked to read the valuation sheet carefully and raise their hands once they are ready for the auction. The experimenter waits for all of the subjects to raise their hands before starting the auction. The auction is conducted in the format described in Section III. Once the auction ends, the subjects are asked to record their earnings on the sheet at the end of their instruction sheet. The experimenter waits for 1–2 min for the subjects to record their earnings before starting another round by passing out new valuation sheets.

Once the experiment transitions to the competition-conducive phase, the experimenters stop passing out valuation sheets under conditions to be discussed later, and the subjects obtain their own valuation through a computer screen. In some experiments, the experimenter also announces before the final round that it is the final round. Once all auctions are finished, subjects receive their payoffs from the experimenter. This concludes the experiment.

B. Experimental Design

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

The design calls for all experiments to begin with the collusion incubator environment. The collusion incubator stage of the experiment starts from the first round and lasts until the subjects reach two consecutive rounds of perfect collusion. The experiment then transitions into the competition-conducive stage. In this stage, the experimenter applies several treatments sequentially in an attempt to break the collusion.[4]

The treatments are motivated by the six experimental design features, which are particularly conducive to tacit collusion. We discuss these features in Section V. For each of the features, 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 to remove the "folded preference" feature; (v) destroying expectations of subjects by unexpectedly changing the structure of the preferences to eliminate the folding and item-alignedness features; and (vi) announcing the final round.

These treatments are applied in roughly the same order as above in most experiments where occasional differences in orders come from the exploratory nature of the treatments. We follow the general rule that a new treatment is implemented only if the previous treatment fails to sustain a competitive outcome and tacit collusion returns. When applying the new treatment, we retain all the previous treatments. In this way, we examine the combined effects of the treatments. Since the speed to reach perfect tacit collusion after each treatment varies in different experiments, the number of rounds in each experiment also differs. Table 1 below documents the details of these treatments.

Four of the experimental treatments are straightforward, including blanking the bidder 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. When we remove the items for sale, we start from the same structure of valuations and block several items for sale. Typically, three items are taken out of the eight items, but in one experiment five items are removed. When we destroy the expectations, we create multiple subjects with valuations above 800 francs on some items.[5] In this way, all subjects with valuations above 800 francs on an item might want to bid for it, and this could lead to a destruction of expectations. Details on how items are

4. Of course, this design is unknown to the subjects.

5. In the preplanned valuation sheet (that is unknown to the subjects), on each item there is exactly one bidder with valuation above 800 francs. To create multiple bidders with valuations above 800 francs on the same item, we typically switch the valuations of two items for some subjects. For example, if we switch the preference of 101 on Items 4 and 6 in Figure 1, we create two bidders (101 and 106) with valuations above 800 francs on Item 4.

TABLE 1
Summary of Experimental Environment

Experiments	E1	E2	E3	E4	E5	E6
Date	February 18, 2002	April 19, 2002	May 10, 2002	June 12, 2002	June 21, 2002	June 29, 2002
Total rounds	11	14	18	23	26	17
Collusion incubator rounds	1–		1–5	1–7	1–6	1–3
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

removed and how valuations of items are switched are documented in detail in Section VI and can be found in Table 10 and Table 11.

V. MODELS

As is well known, game theory lacks precision when the environment applied has multiple *Nash Equilibria* (NE). In some situations, the prediction can be so broad that almost any pattern of outcomes can be described as a NE. 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 NE. See, for example, Milgrom (1987) and Menzies (1996). Recently, Brusco and Lopomo (2002) and Engelbrechet-Wiggans and Kahn (2005) show 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, the multiple equilibria issue also exists. In particular, there is a continuum of Subgame Perfect Equilibrium (SPE) when each round of auction is treated as a separate game. 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, each individual bidder will place his bid on the item that maximizes his surplus given the current prices in the auction. The second is a *minimum bid principle,* which 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, if each subject uses a strategy implied by these two principles, these strategy profiles can be shown to form an SPE. Moreover, the equilibrium price of each item is equal to the second highest valuations on it, at which the individual with the second highest value stops bidding.

The second equilibrium corresponds to perfect tacit collusion.[7] If we treat all buyers as a group, perfect tacit collusion occurs when the equilibrium prices and allocations 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(Total Profit) = (Maximum Surplus − Total Profit)/(Maximum Surplus − Competitive Profit) as a measure of the competitiveness of the market. In this definition, Maximum Surplus is the largest possible sum of profits of the buyers, obtained when perfect tacit collusion arises. Competitive

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 definition here refers to the collusive equilibrium outcome. There are many strategies that lead to the same tacit collusion outcome. One such strategy is outlined in the next page when we discuss the continuum of equilibrium.

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, obtained when the competitive equilibrium arises. 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.

While the tacit collusion is defined in terms of prices and allocations, it is also useful to describe collusion in terms of the actions of the bidders. A subject is defined as a tacit colluder only if he only bids on items that satisfy 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 sec.[8]

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

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 Section VI, 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 another subject's item if and only if either (1) the item has not been bid on at all for a long time, or (2) the item belongs to a non-collusive subject who has bid on another bidder's item. In the first case, the tacit colluder tries to exploit the possible negligence of some bidder. In the second case, some other subject has bid on the tacit colluder's item. The tacit colluder bids on the other subject's item to punish him and possibly to push him away from competitive bidding. Under this definition, perfect tacit collusion arises 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 particular, any efficient allocation with a price vector between the reservation price and the second highest valuations can be supported as an SPE. To see this, we construct a strategy profile as follows. In his first bid, each subject bids on his item at the specified 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 an 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 NE or even SPE in our collusion-conducive 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 an SPE. However, since the collusive and competitive equilibria corresponds to clear bidding behaviors and the other 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.

On the one hand, one might think the competitive equilibrium is the natural outcome because it can be supported by natural and simple bidding strategies. Moreover, the competitive equilibrium has been observed in virtually all previous experimental studies on ascending auctions. On the other hand, the profits of the subjects under the competitive equilibrium are very low compared to that under perfect tacit collusion. Furthermore, the typical difficulties to obtain a collusive equilibrium, which requires a grand collusion among all subjects, are drastically reduced in our environment. Our symmetrical and "item aligned" feature of the preferences helps replace a grand collusion with many subjects into a sequence of smaller collusions with two subjects. Since there are no a priori reasons for which types of equilibrium will be selected, the experimental designs help uncover institutional features that favor one type of equilibrium over the other.

Together with the symmetrical and "item-aligned" feature, there are six key features of the collusion-conducive environment of this auction that facilitate the tacit collusion model as an equilibrium to be selected. We focus on these because their removal or perturbation could eliminate important support for

8. 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 sec will not make any difference in our definition of tacit colluders.

the collusive equilibrium and thus lead to the identification of tools that help establish and enforce the competitive outcome.

(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 facilitates the punishments necessary to enforce the collusive equilibrium. For example, if subject *i* enters a bid on subject *j*'s item, *j* knows *i* has made the bid and can target his punishment at *i*. 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 sec. 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, Roth and Ockenfels (2002) and Ockenfels and Roth (2006).

(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 do not win any item in one round will be compensated in the future. The symmetry supports tacit collusion as an equilibrium within each round without relying on such dynamic tradeoffs.

(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. In particular, the item aligned property implies, in the collusive equilibrium, no subject prefers the allocation (the items won and the total price paid) of another subject over his own. In other words, the collusive equilibrium is the unique Pareto equilibrium and it is also envy-free.[9] 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 Pareto-optimal SPE 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 SPE outcome 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 an 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 outcome can be enforceable as an SPE outcome if the subjects have sufficiently high discount

9. While the competitive equilibrium is envy free, this property is not true for collusive equilibrium in general. Another feature of this collusive equilibrium is that its allocation is efficient.

rates. 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. In summary, the repeated structure brings extra instruments to sustain the tacit collusion outcome.

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.

VI. RESULTS

The Results section is divided into two subsections. The first subsection summarizes the patterns of behavior within the collusion incubator environment. The second subsection 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.

A. Collusion and Features of the Collusion Formation Process

Result 1. In the collusion incubator environments, perfect tacit collusion is reached.

Support. We use the competitiveness of the market to measure the degree of tacit collusion. Recall that (c(Total Profit) = (Maximum Surplus − Total Profit)/(Maximum Surplus− Competitive Profit)) is a normalized measure for market competitiveness: $c = 1$ (so the auction market is perfectly competitive) when items are sold on average at a price that equals the second highest valuation. When $c = 0$, every item is sold to the highest-valued bidder at its reservation price, and perfect tacit collusion is reached. Figure 2 below shows the evolution of c in all six experiments.

Perfect collusions are reached in all six experiments. Furthermore, the speed they are 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 continue to do so (for at least one more round) before any treatments are 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 parts. Each addresses a separate feature of the process.

(i) *Prices fall over rounds.* Figure 3 plots the average winning prices per round until perfect. All six experiments display solid decreases in prices and convergence toward perfect tacit

FIGURE 2
Competitiveness of the Market

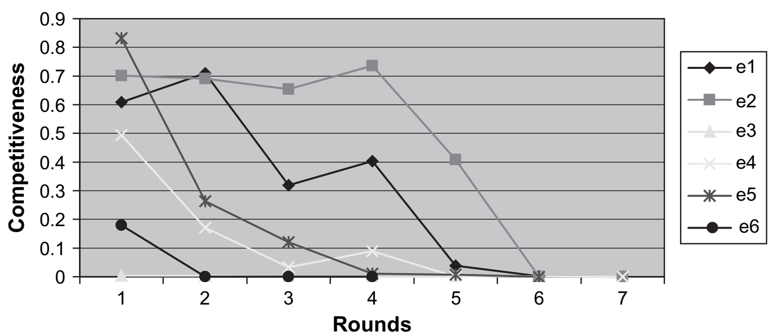


TABLE 2
Price, Bids, and Duration on Number of Rounds Played*

Dependent Variables	Constant	Rounds	R^2	Number of Observations
Prices	534.14** (70.48)	−71.33** (12.86)	.23	30
Log Prices	6.39** (0.26)	−.28** (.05)	.24	30
Bids	81.42** (15.80)	−11.15** (3.40)	.19	30
Log Bids	4.35** (.48)	−.41** (.07)	.07	30
Duration	456.29** (111.93)	−54.37** (24.5)	.12	30
Log Duration	6.07** (.56)	−.39** (.11)	.07	30

*Estimated from random effects model. Standard errors in parentheses.
**Means significant at 5% level.

collusion. The average prices in all but four rounds are 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 2. The average price in the first round is 534.14, and it drops on average per round by 71.33. We also ran log price on the number of rounds and find that the average price decreases 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.

(ii) *The number of bids decreases over rounds.* The total number of bids in the rounds of the six experiments is plotted in Figure 4. Although there are a few "rebounds" in the number of bids, it is clear that the number of bids falls over rounds. The rate of decrease in bid number can be found in Table 2 above. On average, the number of bids drops by 11 bids per round. Furthermore, the number of bids decreases by 41% per round on average. Just as the decrease in prices, the decrease in bids is also not linear and will be discussed further in Result 3.

(iii) *The duration of the auction decreases over rounds.* The duration of the auctions are plotted in Figure 5. 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 2 that on average the duration decreased by 54 sec per round. In addition, the duration of the auctions decreases by 39% each round on average. As in prices and bids, the decline in durations is again nonlinear and will be discussed in Result 3.

Result 3. The convergence toward perfect tacit collusion depends on the behavior of the subjects in the first round. In experiments

FIGURE 3
The Figure Shows the Average Price Series for the Six Experiments Until Perfect Collusion

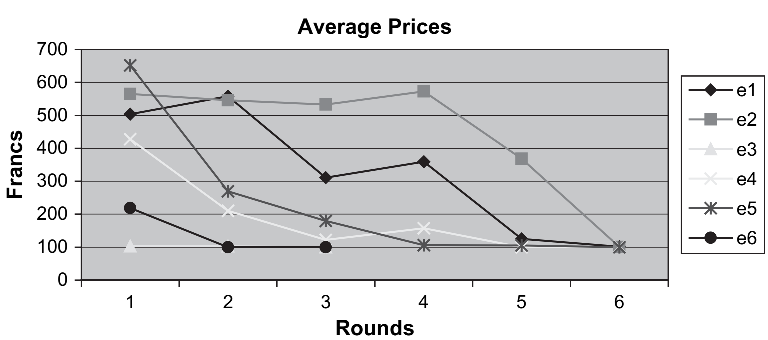
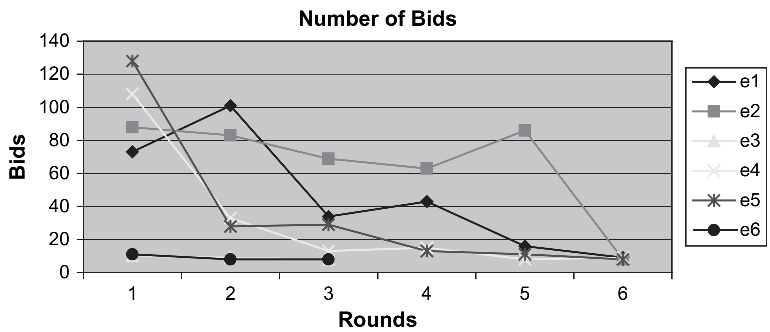


FIGURE 4
Number of Bids Until Perfect Collusion



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 becomes a collusive bidder, 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 criteria:

(1) The item "belongs" to the subject.
(2) The item remains at the reservation price for more than 60 sec.
(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 3 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.

From Table 3, we see that in Experiments 3 and 6, seven out of the eight subjects are tacit colluders in the first round. In these two experiments, perfect tacit collusions are both reached by Round 3. In other experiments, there are between three to five tacit colluders in the first round, and it takes significantly more rounds and longer rounds to reach perfect tacit collusion. The correlation between the number of tacit colluders in the first round and the number of rounds to reach perfect collusion is $-.80$.

The most striking feature of the table is that the evolution of bidding behavior moves in only one direction: once a subject becomes a tacit colluder, he almost always remains a tacit colluder. In the 184 transitions in Table 3, there are only six cases where bidders switch back to competitive bidding from collusive behavior.

FIGURE 5
Duration of the Auctions Until Perfect Collusion

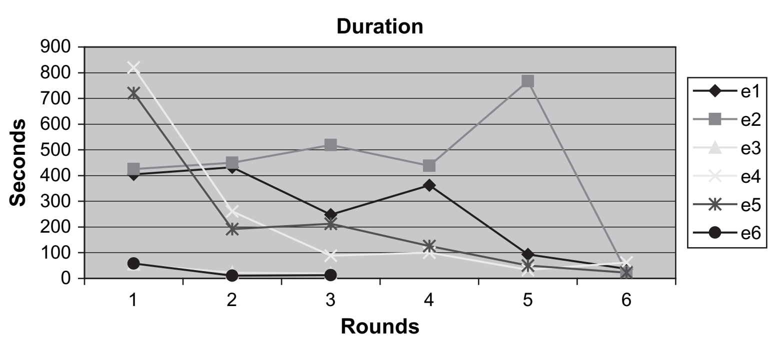


TABLE 3
Summary Statistics for Colluders

Experiment/Round	101	102	103	104	105	106	107	108
E1 (February 18, 2002)								
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
E2 (April 19, 2002)								
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
E3 (May 10, 2002)								
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
E4 (June 12, 2002)								
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
E5 (June 21, 2002)								
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
E6 (June 29, 2002)								
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.

Furthermore, most of these cases are due to the insufficiencies of our method of classifying collusive behavior. In particular, 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 situation happens 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 the highest two valuations on two items and if i bids on both items before j does, then j is 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 at the reservation price: some bidders start out at a bid of 500 francs on their own items. Furthermore, 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.

Result 4. In experiments where collusions are not immediate, prices and bidding behaviors have a tendency for discontinuous development, similar to a regime shift, toward perfect collusion.

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

Distribution of Bids and Bidding Wars. It is clear from Figure 4 that the number of bids did not decrease at a constant speed. In most rounds, the bid number decreases 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 Experiment 4, and Round 1 of Experiment 5, the number of bids drops by more than 65 bids. These four rounds also have the most bids in their respective experiments (except in Experiment 2 in which Round 5 is only two bids less than the round with the most bids).

Interestingly, perfect tacit collusion emerges rapidly after these rounds. In this sense, the dynamics of the auctions experience a "regime shift" in these rounds. Table 4 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 4
Number of Bids and Average Prices at and after the Regime Shift

Experiment	Round	Number of Bids	Average Prices
E1 (February 18, 2002)	2	101	558
	3	34	310
E2 (April 19, 2002)	5	86	368
	6	8	100
E4 (June 12, 2002)	1	108	427
	2	33	210
E5 (June 21, 2002)	1	128	651
	2	28	269

Some detailed look at the bidding behavior right before the regime change can help understand why the regime shift takes place. Take Experiment 2 (April 19, 2002) as an example; there are 86 bids in Round 5 and only eight bids in Round 6. In Round 5, 39 bids of the 86 come from Subject 103, and another 23 bids from 107.

Subject 103 has always bid competitively and entered largest number of bids in all previous rounds. Subject 107, however, has discovered the opportunity for collusion rather early: it enters 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 5, which shows the valuation of 103 and 107 on Items 1 and 3.

Table 5 shows that 103 and 107 share high valuations on Items 1 and 3. A price war can arise if 103 attempts to win both items. We report in Table 6 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, possibly hoping that 103 can stop bidding. This did not happen and 103 continued to raise bids on Item 3. Soon after, 107 retaliated and bid on Item 1, which is 103's item. A bidding war broke out between 103 and 107 on Items 1 and 3 and a total of 43 bids were placed onto these two items. When Round 6 ended, 103 won Item 1 at a price

TABLE 5
Valuation of 103 and 107 on Items 1 and 3

Subject/Items	1	3
103	867	773
107	771	861

TABLE 6
A Bidding War

Time	Item	ID	Price
3,055	3	107	100
3,069	1	103	200
3,077	3	103	200
3,099	3	107	210
3,120	3	103	220
3,132	3	107	230
3,144	3	103	300
3,160	3	107	310
3,173	3	103	400
3,178	1	107	300
3,185	3	107	410
3,199	1	103	310
3,211	1	107	350
3,226	1	103	360
3,237	1	107	400
3,247	1	103	450
3,257	1	107	500
3,264	3	103	500
3,276	1	107	510
3,282	3	107	510
3,291	1	103	520
3,302	3	103	520
3,309	3	107	530
3,326	3	103	550
3,334	3	107	560
3,341	1	107	550
3,344	3	103	600
3,356	3	107	610
3,367	1	103	600
3,376	3	103	650
3,387	1	107	650
3,392	3	107	700
3,417	1	103	761
3,429	3	103	710
3,436	1	103	771
3,445	3	107	720
3,453	1	103	781
3,472	3	103	730
3,482	3	107	740
3,507	3	103	752
3,523	3	107	773
3,529	1	107	791
3,546	1	103	801

of 801 francs and 107 won Item 3 with 773 francs.

It is worthwhile noting that 107 placed on Item 1 a bid of 791 francs, 20 francs higher 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 may have surprised 103 and caused him to revise his bidding behavior. Indeed, only eight bids are cast the next round. We believe that these "spiteful" actions are helpful in changing the behavior of other subjects. A similar incidence happens in Round 5 of Experiment 1, in which 102 (a collusive bidder) suddenly raises the price by 240 on the item of 103, who has been bidding competitively. After the "spiteful" behavior of 102, 103 stops bidding competitively in the next round.

B. Remedies to Prevent a Collusive Equilibrium

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

In the first three experiments, we examine 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. New treatments are applied only if the previous treatment has failed to cause or sustain competition and the bidding returns to almost perfect tacit collusion. When new treatments are applied, we keep all the previous treatments. In this way, we are able to measure the combined effects of all the treatments.

Result 5. Forced anonymity in bidding has no effect.

Support. Once perfect tacit collusion has persisted for two rounds, the first step we most often take to disrupt it is to force anonymous bidding. As mentioned in Section 5, anonymous bidding weakens the monitoring technology of the subjects, so they cannot target their punishment on the particular deviator. This makes deviation from collusive equilibrium more tempting and the collusion less sustainable.

To implement anonymous bidding, we blank the ID associated with the bids, so subjects only observes that a bid is entered and not which subject made the bid. Forced anonymity has virtually no effect in breaking the tacit collusion.

Table 7 documents the various statistics of prices, bids, and durations of the auctions once the IDs are blanked. The average prices are below 110 francs in 12 out of 15 rounds and never exceed 160 francs. Occasionally, there are a few attempts that moved the outcome away from equilibrium. But, these attempts almost never generate a price above 200, and the average prices fall below 105 francs within four rounds.

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

Support. Once the subjects return to the perfect tacit collusion with their IDs blanked, the next step we most often take is 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 remain blanked, it is even more enticing for the subjects to bid on more than one items and destroy the tacit collusion.

We remove common knowledge of preferences by stop passing out the valuation sheets. Instead, subjects learned about their own valuations from the computer screens. The removal of common knowledge of preferences has very small effects in breaking the collusion.

Table 8 documents the effects. After the valuation sheets are removed, some subjects fight over a few items in some rounds. But the fights are uncommon and in general of small scale. The winning prices are rarely above 200. Moreover, bidding wars never last more than one round: the average winning prices fall below 105 francs in one round after the valuation sheets are first taken away. In other words, within two rounds after the valuation sheets are taken away, almost perfect tacit collusion reappears.

TABLE 7
Summary Statistics after IDs are Blanked

Experiment /Round	Highest Price	Lowest Price	Average Price	Duration Time	Total Bids
E1 (February 18, 2002)					
Round 9	100	100	100	22	8
Round 10	200	100	113.5	29	8
Round 11	100	100	100	14	8
E3 (May, 10, 2002)					
Round 6	100	100	100	14	5
Round 7	100	100	100	15	5
E4 (June 12, 2002)					
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
E5 (June 21, 2002)					
Round 7	160	120	151.25	214	45
Round 8	160	100	107.5	15	8
Round 9	110	100	101.25	37	9
E6 (June 29, 2002)					
Round 4	100	100	100	19	8
Round 5	120	100	102.63	44	9
Round 6	101	100	101.13	18	8

It is interesting to note that in Table 8 the final winning prices are not always 100. For example, in Round 7 and 8 of Experiment 6, subject 104 bid 104 instead of 100. This suggests that some bidders have tried to use the last digit number of the bid to signal their identities, possibly trying to enforce the collusive equilibrium.

Result 7. Changes in the structure of the game to eliminate the collusive equilibrium by switching the ending rule to fixed length results in some inefficiencies in allocations but has little immediate effect in prices.

Support. When removal of information fails to break tacit collusion, we change the ending

TABLE 8
Summary Statistics after Valuation Sheets are Taken Away

Experiment/Round	Highest Price	Lowest Price	Average Price	Duration Time	Total Bids
E2 (April 19, 2002)					
Round 9	807	100	263.25	165	20
Round 10	100	100	100	21	8
E3 (May 10, 2002)					
Round 3	100	100	100	20	8
E4 (June 12, 2002)					
Round 12	170	151	160.88	228	37
Round 13	100	100	100	17	8
E5 (June 21, 2002)					
Round 10	310	100	127.5	40	10
Round 11	110	100	101.25	23	8
Round 12	120	100	102.5	19	8
E6 (June 29, 2002)					
Round 7	104	100	100.5	18	8
Round 8	104	100	100.63	19	8

rule in Experiment 2. In the collusive conducive environment, an auction ends only if no new bids are entered for a consecutive 30 sec. By turning the variable ending rule into a fixed duration rule, we change 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 change the ending rule in Round 11 and 12 in Experiment 2 (April 19, 2002) to a fixed duration of 30 sec, so all legal bids have to be entered within 30 sec after the auctions start.

Table 9 documents the effect of fixed ending rule. The prices of the winning items remain low, although the allocations of the items are no longer efficient. There are some deviations at the end of the auction. In Round 11, subject 107 bids 120 francs at the last second on Item 2, which is 102's item. In Round 12, subject 107 bids on Item 8, which is 106's item. Subject 107's behavior is consistent with what is reported in Ockenfels and Roth (2007), who finds that various EBay bidders enter their bids in the last second. In our environment, we have eight subjects, and 107 is the only deviator in both rounds. After these two rounds, we restore the old ending rules. We do not observe retaliations from subjects whose items are bid away by others at the last second.

We restore the old ending rule mainly because there is a technical problem with the computer system in Round 12, as one subject complains that his last-second bid fails to go through. As a result, there is no winner for Item 5. We are concerned that if many subjects enter their bids in the last several seconds, many bids might not go through. This can lead to confusion, making the experimental outcome hard to interpret. Because of this, we do not test the effects of fixed duration ending rule in later experiments.[10]

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

TABLE 9

Summary Statistics for the Fixed Duration Rule

Experiment/Round	Item 1 Price (Winner)	Item 2 Price (Winner)	Item 3 Price (Winner)	Item 4 Price (Winner)	Item 5 Price (Winner)	Item 6 Price (Winner)	Item 7 Price (Winner)	Item 8 Price (Winner)
E2 (April 19, 2002)								
Round 11	100 (108)	150 (107)	100 (104)	100 (106)	100 (107)	100 (105)	100 (101)	100 (103)
Round 12	100 (107)	100 (104)	100 (108)	100 (105)	N/A N/A	100 (102)	100 (103)	120 (107)

10. On the other hand, it is possible that, as pointed out by a referee, if subject 107 continued to win more than one item in the future periods, the collusion might break up.

TABLE 10
Summary Statistics after Some Items are Removed for Sale

Experiment/Round	Highest Price	Lowest Price	Average Price	Duration Time	Total Bids	Items Blocked
E3 (May 10, 2002)						
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
E4 (June 12, 2002)						
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
E5 (June 21, 2002)						
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
E6 (June 29, 2002)						
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

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

To implement this, we remove several items for sale in some of the experiments.

Experiment 3 is the first time we remove items for sale. In that experiment, we rotate the items to be removed. From Rounds 4 to 7, three items are removed for sale. From Rounds 8 to 11, five items are removed in each round. In later experiments, we have standardized our method to always remove Items 1 to 3. Surprisingly, the destruction of these two features does not move the equilibrium to competitive outcome, and almost perfect tacit collusion returns in all experiments.[11]

Table 10 reports the price, bid, and duration of the auctions with items removed for sale. Removing the items for sale has greater (incremental) effect in pushing the subjects away from collusive equilibrium than the previous treatments. In Experiment 5, the average price jumps to 680 francs immediately after the first three items are blocked for sale. Furthermore, prices stay at relatively high levels for another two rounds and even attain an average price of 743 francs in Round 15, a round with the most competitive scenarios in the

11. One possibility is that subjects treat each round of auction as a stage game in a repeated game and believe that refraining from competing in the current period will be rewarded by collusive behaviors in the future. However, this logic will not go through if the total number of rounds of auctions are known to be finite.

experiment: 117 bids are entered and the auction lasts for 682 sec, the third-longest round in the entire experiment series.

Although removing the items for sale has more impact than the previous treatments, its effects remain modest and diminish over time. In Experiment 3, perfect collusion persists even when five items are blocked in some rounds. In Experiments 4 and 6, although the prices rise somewhat after the items are blocked, their levels are low and the auctions are still filled with collusive behavior. Even in Experiment 5, where removal of items has led to the most competitive behaviors among the experiments, the prices converge 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 francs 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 "switch" the valuations of some subjects to generate multiple bidders with valuations above 800 on some items. Take Figure 1 as an example, subject 103's original valuation is 707 on Item 7 and 889 on Item 3. In this treatment, we switch his valuations on these two items, so subject 103's new valuations become 707 on Item 3 and 889 on Item 7. This change destroys the symmetry of valuation by adding a surprise entry: there are now two bidders, 103 and 108, both having valuations above 800 on Item 3. It also destroys the "item aligned" property of the preference: 103 no longer has the highest valuation on the Item 7, the item he values most. Of course, since the subjects only know about their own valuations at this stage of the experiment, their expectations of the valuations of the other subjects come probably from past experience. Therefore, the subjects probably do not expect this change of valuations to have happened. In each experiment, this surprise entry takes place in two consecutive rounds. After these two rounds, we remove this treatment so that each item has again only one subject with valuation above 800 francs.

Table 11 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 rise to very high levels except in Round 17 of Experiment 4 and in Round 12 of Experiment 6. Furthermore, the prices on some items are even above the competitive levels. For example, in Round 13 of Experiment 6, Items 4, 5, and 6 are sold at 834, 863, and 862 respectively, which are higher than 746, 834, and 808, the second highest valuations on these items. This suggests that subjects have 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 Items 5 and 6 have more than one subject with valuations above 800 francs. Consequently, the only initial bid wars are between 101 and 102 on Item 6 and between 106 and 107 on Item 5. The price of Item 4 remains at 104 francs even when the prices of Items 5 and 6 have both risen above 800. Subject 101, who is potentially frustrated by his loss in the price war on Item 6, soon starts to bid on Item 4. The price of Item 4 rises quickly, and 101's final bid on it is 800, more than 100 above his valuation. Similar patterns of bidding wars exist 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 seem to result from frustrations and anger in the previous round. For example, subject 104 doesn't win any item in Round 13 of Experiment 4, even though his valuation on Item 2 is 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 is removed. However, the convergence toward collusive equilibrium appears difficult after expectations have been destroyed. In Experiment 3, for example, the prices never fall to the perfect collusive level after common expectations are destroyed. There are two items

TABLE 11
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
E3 (May 10, 2002)								
Round 12	1,2	870	873	730				
Round 13	1,2	843	840	669				
E4 (June 12, 2002)								
Round 17	6,8			410	530	460	420	460
Round 18	6,8			860	770	876	751	631
E5 (June 21, 2002)								
Round 22	5,*			750	877	760	440	430
Round 23	5,6			600	580	843	711	800
E6 (June 29, 2002)								
Round 12	5,6			100	200	302	100	100
Round 13	5,6			834	863	862	100	100

Notes: On May 10, 2002, in Round 12, 101's valuation on Items 2 and 5 was switched; 106's valuation on Item 1 and Item 8 was switched. In Round 13, 102's valuation on Items 2 and 6 was switched; 105's valuation on Items 1 and 3 was switched. On June 12, 2002, 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 June 21, 2002, 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 June 29, 2002, in Round 12, 104's valuation on Items 2 and 6 was switched; 107's valuation on Items 1 and 5 was switched. In Round 13, 101's valuation on Items 2 and 6 was switched; 106's valuation on Items 1 and 5 was switched.

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

sold at above 500 francs five rounds after the treatment is removed. Furthermore, even if the prices approach the collusive level, the collusive equilibrium does 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 are 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." Table 12 reports the effects of announcing the final round on the final winning prices. Two dramatically different behaviors are observed. In Experiment 1, the experimenter announced that Round 11 is the last round. The subjects respond very little to this announcement. The prices remain low, as the highest price of the items is only 120 and the average price is 103.75. This is 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 is fairly collusive: the highest price is only 200 and the average price is 143. In Round 23, subjects bid aggressively on all of the five items. The average price is 694.75, and there are three items priced above 700. Furthermore, item 3 is sold at 824, 25 francs higher than the second highest-valuation on this item.[12]

There are several possible reasons for the competitive bidding behaviors. For example, there are only five items for sale in this round. Therefore, perfect collusion cannot be supported as a NE if the subjects follow undominated strategies. It is also possible that collusive equilibrium is less stable after the common expectations have been destroyed. In general, the last-round behavior may be affected by any history of previous competitive outbreaks. It will be interesting to explore further about the key factors that affect the final round behavior.

VII. SUMMARY OF CONCLUSIONS

The fundamental results reflect the discovery of a collusion incubator environment in

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

TABLE 12
Winning Prices after the Announcement of Final Round

Experiment /Round	Item 1 Price	Item 2 Price	Item 3 Price	Item 4 Price	Item 5 Price	Item 6 Price	Item 7 Price	Item 8 Price
E1 (February 18, 2002)								
Round 11	100	100	100	100	100	100	100	120
E4 (June 12, 2002)								
Round 23	N/A	N/A	N/A	750	510	824	610	780

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 solution, which we call the collusive outcome, the allocation maximizes the joint surplus of buyers.[13] In the collusion incubator environment, the folding patterns 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.

Our experiment provides the first environment where tacit collusion arises naturally among more than two subjects. In our design of the environment, we have been conservative and included many potentially collusion-conducive features because past experiments suggest that the competitive force is very strong. Although combination of the features makes it highly special, our environment is an important step toward a better understanding of tacit collusion if not collusion itself. First, our environment generates rapid and robust collusion, so it can serve as the basis for future research on how tacit collusion may be broken. Second, the structural and institutional features in our environment form a sufficient condition to obtain collusion. This provides a starting point for future research to identify a minimalist set of features that can generate collusion. Finally, our environment helps caution the practitioners that collusion is likely to occur if several of our features appear in the auction design.

The dynamics of adjustment in the collusion incubator 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.

Because tacit collusion is successfully created, an opportunity is created to conduct a few experiments using the "exploratory methodology." The fact that a tacit collusion exists enables us to tentatively explore some of the many dimensions that can be imagined as "remedies." Rather than choose one "remedy" and collect many observations on it, several remedies are explored and done so in sequence. Thus, we have produced a preliminary "map" of a varied and complex landscape of institutions together with hints about where different remedies might lead. While the results are "hints" rather than firm conclusions, 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.

13. In the collusive outcome, the final allocation is also envy free.

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. This change nudges competition from the contested market to other markets. An understanding of this process of contagion is needed.

A closing comment about methodology is in order. Some feel that a proper experimental methodology has the experimental environment mirroring some aspect of the naturally occurring world as closely as possible, satisfying some abstract quality of ''external validity.'' While that philosophy might be useful for some questions, it is not useful as a general guide to experimental design and is not applied here. Experimental methods have important uses as tools that allow us to study the principles at work in general. It is not unusual for those principles to be most clearly seen under conditions that nature has not and perhaps never will provide for us. While the collusion incubator environment may never be found occurring naturally, it nevertheless allows us to create and study the development and evolution of tacit collusion in multiple item auctions, which has not been successfully created or studied otherwise.

Clearly the results presented here are primarily empirical. While we are able to provide some theoretical insights, a world of questions remains and even new questions are stimulated by what we report. Such questions are about the detail of the strategies that might be at work, alternative solution concepts that might be applicable, theories of repeated games that might be applied or analyzed with new or extended experiments, learning models that might be applicable, etc. In addition, the simultaneous, increasing price auction has been applied in field settings and there are open questions about how the data from these experiments might help explain field data and whether or not tacit collusion was operating. These are all interesting questions that were not addressed here but we hope that the tools provided here will help answering them.

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 greater than or 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 $\varepsilon = Min_{j \neq i, V_j - 2m > p_j}\{V_j - 2m - p_j, m\}$. 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 SPE. 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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