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BERTRAND-EDGEWORTH COMPETITION IN EXPERIMENTAL MARKETS

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The Bertrand-Edgeworth (BE) model describes competition among a group of price setting sellers, each of whom faces a production capacity constraint. We report on laboratory experiments that were designed so as to capture essential features of BE competition. These experiments permit us to evaluate different theories of BE competition: Competitive equilibrium (CE) pricing, Edgeworth cycles in prices, mixed strategy Nash equilibrium (NE) in prices, and tacit collusion.

The experimental results indicate that while each of the theories helps to explain some aspects of the data, none of these theories are completely consistent with the data. In relative terms, the Edgeworth cycle theory provides better predictions than the other three theories. Most sellers adjusted their prices partially to their predicted Edgeworth price. The Edgeworth cycle theory is the only theory that predicts the kind of time dependence and cycling that was observed in most experiments.

KEYWORDS: Price formation, Edgeworth cycles, mixed strategies, laboratory experiments.

1. INTRODUCTION

OLIGOPOLY MARKETS HAVE BEEN THE TOPIC of extensive theoretical and experimental research. Oligopoly market models with price setting firms provide the opportunity to explore price formation in ways that are not possible using a quantity choice (Cournot) formulation. In particular one can consider the implications of various equilibrium and disequilibrium models of seller pricing behavior. This study explores capacity-constrained price setting behavior in a four seller laboratory environment. We focus on patterns of prices that arise over a relatively long time horizon (60 periods) and examine the effect of three different levels of aggregate production capacity and three levels of information about demand and rivals' costs.

Rivalry among price setting sellers has been investigated in several prior experimental studies that have used the posted offer environment. Prior posted offer experiments examined a number of issues: the effects of changes in the number of sellers, the effects of the amount of information provided to sellers, the role of subject experience, the extent of market power for sellers, and the effects of changes in the market exchange institution itself. Results from many of these posted offer experiments are discussed in Ketcham, Smith, and Williams

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(1984) and in survey articles by Plott (1982) and Holt (1989). Experimental price and quantity outcomes have typically been compared to the competitive equilibrium, the collusive prediction, and the quantity-Cournot prediction.

Theoretical analysis of price setting rivalry began with Bertrand's duopoly analysis of price setting firms and the subsequent extension of Edgeworth (1925) that considered the role of production capacity constraints. Rivalry among firms that set prices, produce at constant marginal cost up to a capacity constraint, and offer a homogeneous product is typically referred to as Bertrand-Edgeworth (BE) competition. Game theoretic analyses of single period models of BE competition appeared in Beckman (1965) and Levitan and Shubik (1972). Allen and Hellwig (1986), Dasgupta and Maskin (1986), Davidson and Deneckere (1986), Osborne and Pitchik (1986), and Vives (1986) extended the static, game theoretic analysis in various ways. Results from these analyses indicated that, in many cases, pure strategy equilibria in prices do not exist. This led game theorists to offer mixed strategy equilibria as an explanation of price formation under BE competition. Repeated interaction of sellers under BE competition was analyzed in Brock and Scheinkman (1985), Benoit and Krishna (1987), and Davidson and Deneckere (1990). These papers focused on the roles that the number of sellers and their capacity constraints play in the enforcement of collusive pricing schemes.

Most prior posted offer experiments were not designed in a way that permits results to be compared to predictions from the full range of theories of BE competition. For many prior posted offer experiments, pure strategy Nash equilibria do not exist and mixed strategy equilibria in prices were typically not computed.[2] Given the designs used in most prior posted offer experiments, numerical computation of equilibrium mixed strategies would be a formidable task.[3] Also, the role of excess capacity held by sellers was typically not considered as a treatment variable in prior experiments. In the Industrial Organization literature excess capacity has been identified as a key factor influencing the viability of tacit collusion for price-setting sellers.

In the present paper we report results from a series of experiments that were designed to (i) capture essential features of BE competition and (ii) permit game theoretic equilibria to be computed as a basis for comparisons with the data. These experiments allow us to evaluate the predictive power of theories of BE competition in a controlled experimental laboratory setting. Competing hypotheses about price setting behavior are based on four principle theories: competitive equilibrium (CE) pricing, Edgeworth cycles in prices, mixed strategy Nash equilibrium (NE) in prices, and tacit collusion. The experiments that

[2] The recent experimental study by Davis, Holt, and Villamil (1990) is an exception. They investigate market power of sellers in a posted offer environment and provide explicit calculations of the mixed strategy NE in prices for their design.

[3] Holt and Solis-Soberon (1994) illustrate how one can calculate mixed strategy NE in prices for the type of step demand and cost structures that are often used in experiments. They show how these calculations become progressively more complex as more steps and more heterogeneity among agents is introduced.

we report were designed to provide more information about capacity-constrained pricing behavior and to learn what existing theories contribute to our understanding of pricing behavior.

2. EXPERIMENTAL BACKGROUND

A number of experimental studies over the past twenty-five years have tested the predictive implications of pure strategy noncooperative (Nash) equilibrium theory in a variety of institutional contexts. The first such tests, using data from 17 experiments, were reported by Fouraker and Siegel (1963) in their classic work on bargaining behavior. These experiments compared the observational support for Nash equilibrium, competitive, and monopoly theory under three different institutions: (i) price leadership bilateral monopoly, (ii) Bertrand price setting duopoly and triopoly, and (iii) Cournot quantity setting duopoly and triopoly. We focus on institution (ii) since this is a variation on "posted offer" oligopoly pricing.[4]

In Fouraker and Siegel's Bertrand price adjuster experiments, the oligopolists each post a take-it-or-leave-it price (there were no capacity constraints so the NE corresponds to the CE). Demand is then simulated (with fully revealing buyers), with the low priced seller getting the entire market and tied price sellers sharing the market equally. These experiments were run under conditions of private information, in which subjects were informed of their own payoff schedule but not the payoff schedule(s) of their rival(s), and under public information, in which subjects were informed of payoff schedules for all participants. In these repeat transaction experiments, strong support for the pure strategy Nash (-competitive) equilibrium is observed under private information duopoly and triopoly. This support is weakened in the direction of the monopoly outcome under public information duopoly, but not under public information triopoly. That is, the triopoly condition dominates the information condition yielding Nash (-competitive) outcomes.

In summary the Fouraker and Siegel posted offer oligopoly experiments generally yield strong support for the complete information, pure strategy Nash equilibrium concept in environments with *private information* but not necessarily in environments with (common knowledge) public payoff information. These experimental results indicate that a complete information Nash equilibrium for a single play model can provide good predictions for repeated trial (market period) environments in which agents have only private information.

In Ketcham, Smith, and Williams (1984) the performance of the posted offer institution is compared to the double oral auction in two different experimental designs. These are private information experiments—a seller knows only his own cost schedule, a buyer knows only his own redemption values. Each seller

[4] For a more complete discussion of the Fouraker and Siegel experimental results see Smith et al. (1982, pp. 64–65).

posts a price and a maximum number of units offered for sale in each period. Most of the experiments were run for 25 market periods. In design I (4 buyers, 4 sellers) posted prices tend to converge to the CE (this CE is not a NE) from above; a NE is not computed for this design. In design II (4 buyers, 3 sellers) a pure strategy NE exists and is computed. Posted prices tend to deviate from the CE in the direction of the NE in the design II experiments.

Davis, Holt, and Villamil (1990) report on a series of two-seller and three-seller posted offer experiments with computer simulated buyers. Their experiments were designed to investigate the impact of static market power; static market power exists when static NE prices exceed the CE price. Sellers were fully informed about buyer demand. A random stopping rule was used after period 15 in these experiments. Static market power leads to higher prices for both two and three seller experiments, with a significant effect for three seller experiments. Their results for market power experiments were generally unsupportive of the mixed strategy static NE; median prices in two-seller experiments tended to be below their predicted values and median prices for three-seller experiments tended to be above their predicted values. Davis, Holt, and Villamil find some evidence of tacit collusion in each of their treatments. However, collusion is typically imperfect with prices below the monopoly price.

Alger (1987) also reports on a series of two and three-seller posted offer pricing experiments with simulated buyers. Most experiments involved private information—subjects knew their own costs, but were not informed about rivals' costs or about demand. The focus of Alger's study was a search for a behavioral equilibrium in the experimental data. An experiment was terminated only after a series of market outcomes were observed that satisfied the operational definition of equilibrium (this was essentially a condition that prices stabilize over several market periods). As a consequence of this termination rule, some experiments were run for a large number of periods (e.g., 120 periods). Most prior posted offer experiments had been run for a fixed, maximum number of periods (e.g., 20 periods). Alger found that market prices plotted over time tend to be U-shaped; prices typically fall in initial periods, then rise in later periods, finally stabilizing at a price level above the CE. Disequilibrium prices were found to be significantly different from equilibrium prices.

Alger's results for experiments with long time horizons are similar to results reported by Stoecker (1980) and Friedman and Hoggatt (1980) for duopoly experiments with experienced subjects. Convergence to the CE was not the characteristic result; prices were more likely to be near the (quantity) Cournot price or the joint profit maximizing price.[5]

[5] In the experimental studies of Alger (1987), Davis, Holt, and Villamil (1990), Stoecker (1980), and Friedman and Hoggatt (1980), fully revealing demand behavior was simulated. Brown-Kruse (1991) reported experiments comparing the effect of real as opposed to simulated buyers. Mean price paths were significantly higher when buyer behavior was simulated than when subject buyers were used, suggesting that the reported instances of tacit collusion may depend upon simulated fully revealing demand behavior.

3. EXPERIMENTAL DESIGN, PROCEDURES, AND PREDICTIONS

A group of four subjects participated as sellers in each multi-period posted offer experiment. The four sellers in an experiment had identical average costs of production and identical capacity constraints. These average cost and capacity conditions were held constant over all market periods of an experiment. Aggregate demand was comprised of many computer simulated buyers.

The experiments are divided into five cells (or groups) based on two primary treatment conditions: the amount of information provided to subjects and the aggregate capacity. This is illustrated as a "cross design" in Table I.

There were three levels of information provision. In PRIVATE information experiments, subjects (sellers) were informed about their own average cost and capacity but were not informed about their rivals' costs and capacities, nor were they informed about market demand. In MIXED information experiments, subjects were told all sellers' costs and capacities but were not informed about market demand. In PUBLIC information experiments subjects were given information about all sellers' costs and capacities and about aggregate demand.

There were three levels of aggregate seller capacity. In LOW capacity experiments each seller had 145 units of capacity. In MEDIUM capacity

TABLE I

EXPERIMENTAL DESIGN[a]

		Capacity Level		
		LOW $K = 145$	MEDIUM $K = 185$	HIGH $K = 225$
Information Provision	PRIVATE		MRI1 MRI2 MRE1 MRE2 600	
	MIXED	LMI1 LMI2 LME1 LME2 1000	MMI1 MMI2 MME1[b] MME2 600	HMI1 HMI2 HME1 HME2 400
	PUBLIC		MUI1 MUI2 MUE1 MUE2 600	

$n = 4$ sellers
$K =$ production capacity per seller
$AC = 5$ pesos per unit of output, for output up to K
$m = 100$ (simulated) buyers
$D(p) = \Sigma_{j=1}^{m} d_j(p) = 5094p^{-1.15} =$ market demand

[a] A four character string identifies each experiment. The first character indicates a capacity level from the set (Low, Medium, High). The second character indicates the information provision, (PRivate, Mixed, PUblic). The third character indicates subject experience (Inexperienced, Experienced). The final character is an index number for the experiment.

[b] The exchange rate of pesos per dollar is listed at the bottom of the box for each treatment condition. The exchange rate for experiment MME1 was 400 pesos per dollar.

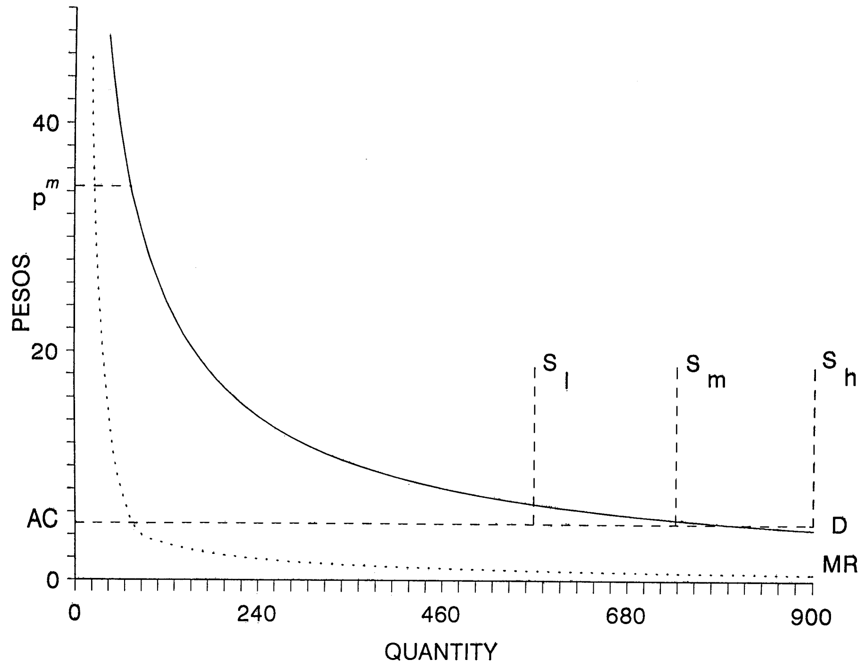

FIGURE 1.—Demand and supply configurations.

experiments each seller had 185 units of capacity. HIGH capacity experiments were run with 225 units of capacity per seller. HIGH capacity experiments were designed so that there is substantial excess capacity at the competitive equilibrium (with price equal to the constant average cost, AC), as illustrated in Figure 1. In both MEDIUM and LOW capacity experiments the competitive price is above AC and sellers fully utilize their capacity in a competitive equilibrium (see Figure 1).

Subjects for the experiments were recruited from undergraduate economics and business classes at the University of Arizona. Each subject was paid $3 for arriving on time for the experiment. Subjects were told that the experiment would run for up to two hours. A typical experiment lasted about one hour and 15 minutes.

Four experiments were run for each of the five cells in Table I. Two of the four experiments in each cell were run with inexperienced subjects. The other two experiments in each cell were run with experienced subjects; experience means previous participation in one or more of the posted offer experiments in our design.[6]

[6] Subjects who had previously participated in a MIXED or PUBLIC information experiment were not chosen for another experiment with a lower provision of information.

The experimental design and market parameters are summarized in Table I. Prices, costs, and profits were denominated in experimental "pesos." The names of the experiments and the exchange rate used are listed in each cell.

The buyer side of the market was identical for all experiments. A large number ($m = 100$) of computer simulated buyers were used. Each buyer followed a demand-revealing purchasing rule. Inverse demand for an individual buyer was of the form

$$p_j = \alpha_j q_j^{-1/\eta} \qquad (j = 1, \ldots, 100). \tag{1}$$

The α_j parameters were assigned according to draws from a log-normal distribution to reflect a distribution of income across the simulated buyer population. A single drawing of 100 α_j parameters was used for all experiments. The aggregation of individual demand maintains the property of constant own price elasticity in the market demand,

$$D(p) = \theta p^{-\eta}; \qquad \eta = 1.15, \qquad \theta = \sum_{j=1}^{100} \alpha_j^{\eta} = 5094.0. \tag{2}$$

A random ordering of buyers was drawn at the start of each market period. Buyers at the front of the queue choose the seller with the lowest price. If this seller has sufficient capacity to satisfy all buyers at his posted price, then all purchases are from this seller. If $D(p_i) > K_i$ (where seller i has the lowest price, p_i, and has capacity K_i), then some buyers must go to the seller with the second lowest price. If the seller with the second lowest price does not have enough capacity to satisfy the remaining buyers, then buyers further back in the queue go to the seller with the third lowest price, and so on.

If buyers were atomistic, then sales for seller i would be x_i (see Allen and Hellwig (1986)):

$$x_i = \min\left\{K_i, \max\left\{0, \left(1 - \sum_{p_j < p_i} \frac{K_j}{D(p_j)}\right) D(p_i) \frac{K_i}{\sum_{p_s = p_i} K_s}\right\}\right\}. \tag{3}$$

This queuing scheme rations up to the fraction

$$\left(1 - \sum_{p_j < p_i} K_j / D(p_j)\right)$$

of all buyers to sellers who have chosen price p_i. For example, suppose that $p_1 < p_2 < p_3 < p_4$ and $K_1 < D(p_1)$. Then the fraction of buyers $(1 - K_1/D(p_1))$ is available to purchase from seller 2.

In our experiments sales to seller i can deviate from x_i in (3) because we allow only sales of discrete units and because buyers are not atomistic. However, (3) provides a good approximation to actual sales because many units of output are traded in the market and because each of the 100 buyers represents a small fraction of total demand.[7]

Experiments were run for up to 60 market periods.[8] Subjects were not informed about the number of periods in the experiment. There were two main reasons for having more market periods than most prior posted offer experiments. First, we wanted to have enough periods to be able to construct frequency distributions of prices for individual sellers and perform statistical tests on the distributions. Second, Alger's (1987) results suggest that in some environments posted prices during the first 20 or 25 periods may not be representative of results over a longer sequence of periods. We did not attempt to use a termination rule based on some operational equilibrium definition. Our experimental environment is one in which we would not necessarily expect prices to stabilize (see the discussion of Edgeworth cycles and mixed strategies below).

Each subject (seller) makes a single decision in each market period; namely, which price to post. A seller does not choose a maximum quantity to sell, as in most previous posted offer pricing experiments. The capacity constraint (set by the experimenter) takes the role of the quantity limit. After prices are posted and all buyers finish making purchases, each seller observes all prices posted for the period, his sales and profit for the period, and total market sales for the period. The history of posted prices for the previous seven periods is also displayed on each subject's computer screen. The instructions for sellers appear in Appendix One.[9]

There are several types of theoretical predictions that might explain the behavior of sellers in our experiments. Operational versions of these predictions are described below.

3.1. *Competitive Pricing*

The competitive theory predicts that each seller sets the market clearing price, p^c. Market clearing prices are 5, 5.35, and 6.62 pesos for HIGH, MEDIUM, and LOW capacity experiments, respectively. Competitive pricing yields positive profits for sellers in the LOW and MEDIUM capacity treatments and zero profit in the HIGH capacity treatment. Setting a competitive price is not a best response to competitive pricing by all other sellers in any of the

[7] An alternative experimental design would be to use the sales function (3) directly, rather than specify demands for individual buyers. Our approach of specifying individual buyer demands has the advantage of permitting parallel experiments using human buyers, at some point in time.

[8] All experiments except MMI1 have 60 periods. Experiment MMI1 was terminated after period 54 because of a computer error.

[9] The instructions in Appendix I reproduce the computer screens that the subjects observed at the beginning of an experiment. The instructions refer to a production facility that is jointly owned by the sellers. This wording was to facilitate parallel experiments in which sellers share some production costs. Seller costs and capacities are not shared or interdependent in the experiments reported in the present paper. Subjects were also given supplementary verbal instructions and were given the chance to ask questions about their instructions. The verbal instructions repeated the information about the random buyer queuing routine.

treatments; the CE is not a static NE for our experiments. Since competitive pricing does not involve mutual best responses for sellers in a single period, sellers in our experiments have static market power as Holt (1989) defines the term.

For some experimental designs, posted offer experiments have exhibited prices that converged to p^c over time from above. For example, this was a feature of results from design I experiments reported in Ketcham, Smith, and Williams (1984) (recall that the CE was not a NE for those experiments).[10] This pattern of convergence can emerge with as few as three or four sellers. The competitive model is generally thought of as a model of limited or incomplete information; a competitive seller knows his own AC and capacity but need not know payoff information for other market participants. Thus, competitive pricing is most likely to emerge when subjects have limited information, as in our PRIVATE and MIXED information treatments.

3.2. *Edgeworth Price Cycles*

A duopoly model of capacity constrained, price-setting firms was first formulated and analyzed by Edgeworth (1925).[11] Edgeworth examined a multiperiod model in which each seller sets a price in the current period based on the expectation that its rival will maintain its price from the previous period. Edgeworth predicted that a pattern of cycling in prices over time would emerge in some cases. If sellers start with high prices (e.g., near the monopoly level), then each seller initially has an incentive to undercut its rival's price. However, there is some threshold price such that if a rival's price is below the threshold, a much higher price (the monopoly price, when buyers are randomly ordered) is more profitable than undercutting. After both sellers raise their price, the price undercutting process begins again. Market prices thus evolve in cycles.

Edgeworth's duopoly theory is easily extended to our four seller environment. A multiple seller version of the theory predicts that each seller sets an optimal price in a period given the expectation that each of its rivals maintains their actual price from the previous period. We use this "naive price expectations" assumption to generate Edgeworth price predictions for the four sellers in each period after the first period of an experiment. A key difficulty with the Edgeworth cycle theory is that it is a disequilibrium theory in which expectations are inconsistent or irrational. Each seller would continually find that his price expectations do not match what his rivals actually do. In spite of this

[10] However, earlier posted offer pricing experiments differed in some important ways from the current experiments. For example, in design I of KSW (1984) a relatively small number of discrete units were traded, a small number of human buyers were used, heterogeneous sellers had differing marginal cost schedules, and these experiments had a maximum duration of 25 periods.

[11] A game theoretic analysis of an Edgeworth duopoly model appears in Maskin and Tirole (1988). Their analysis assumes an alternating choice framework in which each seller sets a price in every other period. This framework is not directly applicable to our experimental study.

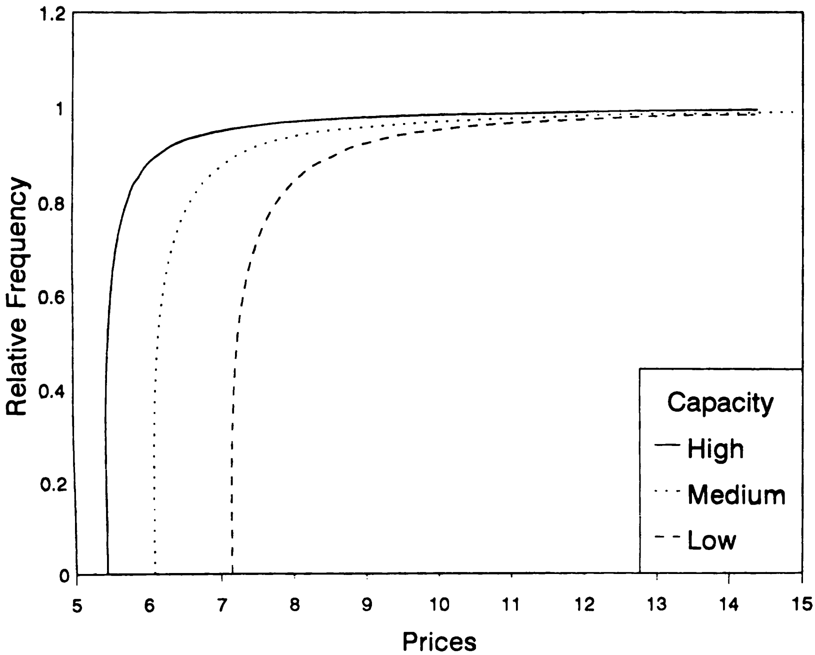

FIGURE 2.—Mixed strategy NE price distributions.

theoretical difficulty, there is evidence of Edgeworth price cycles in posted offer duopoly experiments reported on in Isaac and Smith (1985, p. 339).

3.3. *Mixed Strategy Nash Equilibrium (NE) in Prices*

The cycling pattern described by Edgeworth may be interpreted as the failure of existence of a pure strategy NE in prices (for the single period, complete information game). For the environments we consider, pure strategy NE in prices do not exist. Total capacity of sellers exceeds monopoly output and is less than the capacity that would generate the marginal cost-pricing Bertrand result for each capacity level treatment.

In Appendix II, we develop a computational procedure for finding the symmetric mixed strategy NE for the symmetric, four seller game. This procedure is applied to the parameters for each capacity level. The mixed strategy NE cumulative distribution functions for the three capacity levels are illustrated in Figure 2. In each case the lower bound of the price support for the equilibrium mixed strategy is within one peso of the corresponding competitive price. Also, each distribution is very steep at its lower bound, with more than 80 percent of price draws predicted to be within one peso of the lower bound. Median predicted prices for the mixed strategy NE are 5.48, 6.16, and 7.24 pesos, for the HIGH, MEDIUM, and LOW capacity environments, respectively.

The mixed strategy NE is derived in the context of a one-shot game model. One way to test this prediction would be to gather data from many single period experiments with a different set of seller subjects in each experiment. For example, this might be done by rotating a large pool of subjects in and out of groups with four sellers per group, so that each seller faces new rivals in each period. We are interested in a different issue. Oligopolistic pricing rivalry in naturally occurring markets usually involves a fixed group of sellers making repeated price decisions. We are interested in whether the mixed strategy NE can provide useful price predictions in repeated trial environments with a fixed group of sellers. Clearly, the NE mixed strategy is also an equilibrium for an environment with repeated play over a sequence of periods, such as our experimental environment. (A repeated play environment may admit additional Nash equilibria—this issue is addressed in our discussion of tacit collusion.) We interpret the symmetric NE mixed pricing strategies as providing predictions of frequency distributions of sellers' prices. A frequency distribution of prices for a seller in an experiment can be constructed from data gathered over a sequence of market periods. A repeated play environment also permits a richer set of alternative hypotheses (Edgeworth price cycles, tacit collusion, etc.) than one shot experiments.

A literal interpretation of the mixed strategy NE is that it applies to a one-shot game in which each player has complete information about the payoffs of all players. We ran our MEDIUM capacity experiments for three types of information conditions: PRIVATE, MIXED, and PUBLIC. Experimental evidence described in Section 2 suggests that the NE for the one-shot complete information game may provide good predictions for repeated trial experiments in which subjects have limited payoff information (as in our PRIVATE and MIXED information experiments).

3.4. *Tacit Collusion*

There are no opportunities for explicit communication between seller subjects in our experiments. However, subjects may be able to achieve high prices and profits through some type of tacitly collusive price signalling behavior. The highest total profit for a group of sellers is achieved at the monopoly price of $p^m = 38$ pesos for each experiment (see Figure 1). Demand and cost parameters were chosen so that there is a large separation (in percentage terms) between competitive and monopoly prices for each experiment. This feature of the experimental design yields a large support for mixed strategy NE prices and helps to separate the Edgeworth cycle and mixed strategy NE predictions.

Our experimental design involves substantial excess capacity at the monopoly price. The ratio of excess capacity at the monopoly price to total market capacity ranges from 87 to 91 percent in our experiments. This means that if sellers set a common price equal to the monopoly price and one seller undercuts the monopoly price, then that seller will experience a four-fold gain in sales and profits. Tacit collusion that involves monopoly pricing would be unlikely if subjects believe the experiment may end soon, because of the large gains from undercutting the monopoly price.

Tacit collusion may involve prices and profits that are below monopoly levels but above noncooperative levels. Subjects in our experiments interact over a long sequence of market periods with an unknown stopping time. Suppose that the subjects in an experiment share a common, subjective probability equal to $1-\delta$ that the experiment will stop after the current period. The theory of repeated games indicates that if the continuation probability δ is not too small, then a variety of tacitly collusive outcomes can be supported as noncooperative Nash equilibria of the repeated game. For example, Benoit and Krishna (1987) analyze a repeated game of seller price choice in which sellers have fixed capacity constraints.[12] One type of equilibrium they consider is a stationary perfect equilibrium, in which sellers charge constant prices along the equilibrium path. This pricing outcome is supported as a perfect equilibrium with trigger strategies that specify reversion to mixed strategy NE pricing if deviations from the stationary path are observed. The continuation probability δ must be high enough so that no seller has an incentive to cheat by undercutting the stationary price, if stationary prices are to be an equilibrium outcome.

For our experiments there is a minimum subjective continuation probability that would be required to support some level of tacit collusion with stationary pricing (i.e., stationary pricing that yields profit per seller above the corresponding mixed strategy NE profit). This minimum probability varies with the level of capacity.[13] For LOW Capacity experiments, δ must exceed 0.64. For MEDIUM Capacity experiments, δ must exceed 0.56. For HIGH Capacity experiments δ must exceed 0.48. These values for δ indicate that subjects would not need to have high subjective continuation probabilities in order to sustain some level of tacit collusion. The minimum subjective continuation probabilities required to sustain monopoly pricing are higher, because the gains from defection are greatest when all sellers set the monopoly price. The minimum continuation probabilities for monopoly pricing are as follows: $\delta > .85$ for LOW Capacity, $\delta > .81$ for MEDIUM Capacity, and $\delta > .78$ for HIGH Capacity.

Prior pricing experiments with this type of repeated interaction have sometimes yielded results consistent with tacit collusion; recall Alger's (1987) experiments with 2 or 3 sellers. However, the attainment of tacitly collusive prices by sellers who are not permitted to communicate with one another involves a

[12] Benoit and Krishna use surplus maximizing buyer rationing rather than the random buyer rationing rule that is used in our experiments. Thus, their results, such as Proposition 4 on stationary price paths, do not apply directly to our model. Benoit and Krishna also consider the choices of investment in production capacities by sellers.

[13] This minimum probability is found as follows. First the "no cheating" condition is $\delta > (\bar{\pi}_d - \bar{\pi})/(\bar{\pi}_d - \pi^0)$, where $\bar{\pi}$ is the payoff per period from stationary pricing in a tacitly collusive outcome, $\bar{\pi}_d$ is the maximum payoff from defection from $\bar{\pi}$, and π^0 is expected payoff in the mixed strategy NE. Second, find the minimum δ that satisfies the no cheating condition for each value of $\bar{\pi}$ between π^0 and one firm's share of monopoly payoffs. Third, search for the smallest subjective probability δ over all of the δ-values that were identified in step 2. Recall that each δ-value identified in step 2 has a corresponding average collusive payoff per seller and a defection payoff.

difficult coordination problem. In practice, this coordination problem may be substantially more difficult when there are four sellers than when 2 or 3 sellers serve the market.

If tacit collusion does occur we would expect it to involve a relatively simple pricing pattern, such as constant equal prices for all sellers or some type of price rotation scheme (e.g., two pairs of sellers take turns being the low price sellers in alternating periods). Complex pricing patterns that yield tacitly collusive profit levels are possible in principle and it may be possible to support them as noncooperative NE of the repeated game. However, it would be extremely difficult for sellers to coordinate a complex pricing pattern without communicating with one another because of difficulties in interpreting defections from the tacitly collusive path.

The likelihood that collusive prices are observed should depend on both the information and capacity-level treatments. The provision of more information about demand and sellers' costs should aid sellers' pricing coordination and raise the likelihood of successful tacit collusion. Thus, the tacit collusion hypothesis yields the prediction that average market prices rise as we go from PRIVATE to MIXED to PUBLIC information conditions.

The level of capacity may also influence the stability of (tacitly) collusive agreements. The standard view is that more excess capacity weakens a collusive agreement. The argument for this is that if firms carry substantial excess capacity, then each firm has a strong incentive to cheat because it can greatly expand its sales with a small price cut.

An alternative view is advanced by Davidson and Deneckere (1990) in their analysis of the Benoit-Krishna model. They argue that one should also consider how excess capacity affects the ability of sellers to retaliate against cheating. While greater capacity may increase the short run gain from cutting price, it also permits rival sellers to retaliate more effectively and impose greater long run losses on any seller that cheats. Thus, higher capacity levels raise the likelihood of successful tacit collusion. This argument is the basis for conditions that are required to sustain monopoly pricing as a perfect equilibrium in our experimental set up. Lower capacity levels require a higher minimum subjective continuation probability in order to sustain monopoly pricing.

4. EXPERIMENTAL RESULTS

Summary statistics for prices (mean, median, sample variance around the mean, trend) for 20 experiments appear in Table II.[14] Statistics are computed for three intervals (beginning, middle, and ending periods) and for all periods of each experiment. Two primary conclusions can be drawn from the summary statistics and from observation of the raw price data.

1. All of the experiments exhibit a pattern of downward movement of prices over the first 20 to 25 periods. The trend growth rate of mean seller price is negative for the first 20 periods of every experiment. This pattern is broadly

[14] The raw price data for all 20 experiments are available from the authors by request.

TABLE II

SUMMARY STATISTICS FOR PRICE DATA

Experiment	Periods	Mean Price	Median Price	Sample Variance	Trend Growth
MRI1	1–60	8.64	8.12	36.35	−2.5
	1–20	10.53	9.11	103.64	−6.2
	21–40	8.26	8.13	0.17	−0.7
	41–60	7.12	7.05	0.06	−0.7
MRI2	1–60	9.45	7.25	46.01	−2.1
	1–20	13.96	9.75	107.41	−6.1
	21–40	7.46	7.35	0.47	0.4
	41–60	6.94	6.88	0.29	−0.8
MRE1	1–60	7.15	6.78	9.92	0.5
	1–20	7.58	6.96	19.50	−0.5
	21–40	6.67	6.03	4.72	0.8
	41–60	7.20	6.68	5.36	1.2
MRE2	1–60	7.82	7.53	8.53	−2.1
	1–20	8.98	8.07	22.32	−5.6
	21–40	7.33	7.18	1.00	−0.5
	41–60	7.13	7.19	0.38	−0.4
LMI1	1–60	10.89	8.25	125.07	−0.9
	1–20	9.07	8.57	1.85	−2.3
	21–40	13.79	8.00	255.08	5.9
	41–60	9.80	8.00	180.37	−6.3
LMI2	1–60	8.13	8.15	0.18	−0.2
	1–20	8.29	8.35	0.47	−0.1
	21–40	8.17	8.16	0.01	−0.1
	41–60	7.94	7.96	0.02	−0.3
LME1	1–60	7.59	6.98	36.26	−2.4
	1–20	9.01	7.73	106.57	−6.9
	21–40	6.99	6.98	0.03	−0.3
	41–60	6.76	6.75	0.05	−0.1
LME2	1–60	8.23	7.89	2.16	−0.7
	1–20	8.42	8.22	1.00	−2.0
	21–40	8.36	7.82	3.46	0.0
	41–60	7.91	7.70	1.93	−0.1
MMI1	1–54	7.78	6.99	41.19	2.4
	1–20	6.79	6.50	0.54	−1.3
	21–40	7.06	6.80	0.43	0.8
	41–54	10.22	8.51	151.32	9.2
MMI2	1–60	9.32	6.75	149.45	2.4
	1–20	7.30	6.99	1.31	−1.6
	21–40	6.73	6.54	0.57	−0.5
	41–60	13.93	6.75	417.82	9.2
MME1	1–60	6.95	6.10	37.69	−2.6
	1–20	7.75	6.15	110.33	−8.1
	21–40	6.45	6.10	1.00	1.2
	41–60	6.63	6.10	1.70	−1.2
MME2	1–60	7.40	7.00	1.13	−0.7
	1–20	7.68	7.20	1.72	−2.1
	21–40	7.30	7.10	0.74	−0.3
	41–60	7.23	6.90	0.85	0.1

TABLE II—CONTINUED

Experiment	Periods	Mean Price	Median Price	Sample Variance	Trend Growth
HMI1	1–60	7.30	5.89	80.21	−0.6
	1–20	6.64	6.22	2.00	−2.6
	21–40	8.65	5.68	236.23	−0.2
	41–60	6.61	5.69	1.67	0.9
HMI2	1–60	8.10	6.87	40.38	−2.6
	1–20	9.39	7.49	76.96	−7.3
	21–40	6.65	6.62	0.21	−1.2
	41–60	8.28	5.99	41.16	0.6
HME1	1–60	7.28	5.89	48.06	−4.6
	1–20	7.93	6.25	115.58	−4.4
	21–40	6.29	5.68	12.02	4.5
	41–60	7.61	6.00	16.27	−4.5
HME2	1–60	6.51	5.35	39.31	−2.9
	1–20	8.69	7.13	111.26	−7.8
	21–40	5.55	5.30	0.30	−1.2
	41–60	5.28	5.33	0.12	0.0
MUI1	1–60	12.39	9.78	60.46	−2.6
	1–20	18.32	17.75	118.98	−6.2
	21–40	9.91	9.44	7.37	−1.6
	41–60	8.95	8.27	2.84	−0.3
MUI2	1–60	10.13	6.92	157.21	−1.5
	1–20	10.62	7.13	102.83	−5.2
	21–40	10.74	6.82	215.07	−0.3
	41–60	9.02	6.92	155.87	0.1
MUE1	1–60	7.21	6.75	36.61	−0.7
	1–20	7.14	6.84	1.18	−2.3
	21–40	6.81	6.75	0.09	−0.2
	41–60	7.67	6.50	109.28	0.3
MUE2	1–60	7.56	6.75	50.37	1.5
	1–20	7.75	6.58	109.09	−0.1
	21–40	6.92	6.55	1.65	0.2
	41–60	8.04	6.86	40.97	4.3

consistent with pricing data from prior posted offer experiments (see, e.g., Ketcham, Smith, and Williams (1984)). However, prices typically do not reach the competitive price level by the end of this initial phase of price cutting. For six of the experiments (LME1, LMI2, HME2, MRI1, MRE2, and MUI1) this downward price pattern continues for the duration of the experiment. Note that experience of subjects does not seem to play a role in determining whether or not prices continue to fall during an experiment. Out of the six experiments identified as having falling prices throughout, three involved inexperienced subjects and three involved experienced subjects.

2. The majority of the experiments exhibit a pattern of upward and downward price swings by two or more sellers that begins during the middle periods of the experiment. The sample variance of prices is relatively high in the middle third

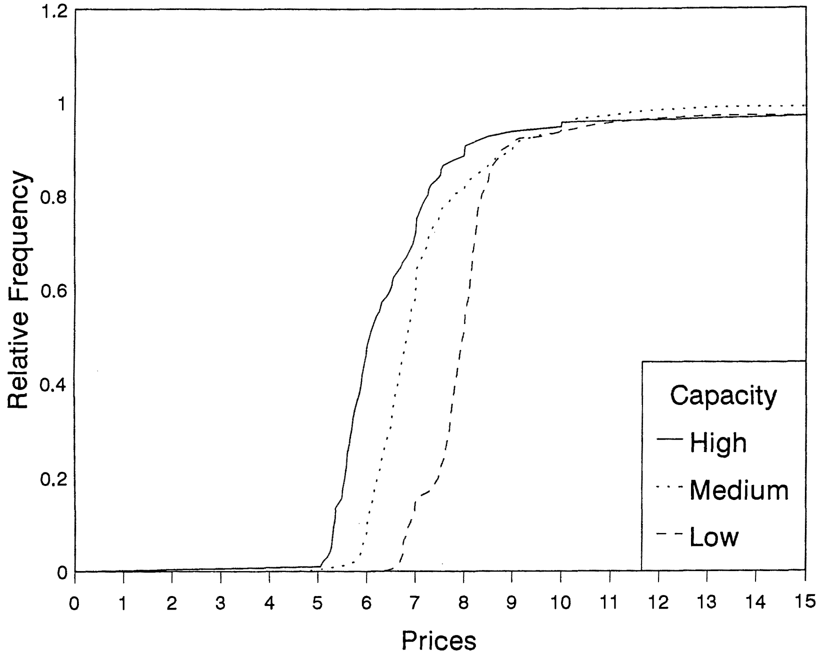

FIGURE 3.—Cumulative price distributions (MIXED Information).

or the final third of a number of experiments. In several cases, this pattern of price swings persists for the remainder of the experiment; that is, prices do not necessarily stabilize over time.

The impact of the amount of capacity held by sellers is illustrated in Figure 3. This figure shows the cumulative distributions of actual prices for HIGH, MEDIUM, and LOW capacity levels for prices in all MIXED information experiments. The distributions of prices for lower capacity experiments are to the right of distributions for higher capacity experiments, as one would expect.

We investigated the effects of all of the exogenous treatment conditions on prices by using an analysis of variance (ANOVA) procedure. The ANOVA statistics were calculated by running an OLS regression with price as the dependent variable and dummy variables specified to represent the experimental treatment conditions. The regression was run for all of the price data after trading period one collected in 20 experiments. Three capacity dummy variables span the space of capacity treatments. There are dummies for two of the information conditions: PRIVATE and PUBLIC. The MIXED information condition is the omitted category. In our analysis of the data we found that subject inexperience had effects that interacted with capacity and information conditions. We specified five dummy variables for subject inexperience, so that inexperience is interacted with the five possible combinations of capacity level and information provision in our experiments. These dummy variables are listed as INEXP followed by two letters; the first letter indicates capacity (L, M, or H)

TABLE III
OLS RESULTS FOR ANOVA PRICE REGRESSION

Variable	Coefficient Estimate (t statistic)
LOW Capacity	7.220 (24.15)
MEDIUM Capacity	6.472 (21.65)
HIGH Capacity	6.155 (20.59)
PRIVATE Information	0.436 (1.06)
PUBLIC Information	0.441 (1.07)
INEXP-LM	1.817 (4.42)
INEXP-MM	1.644 (3.95)
INEXP-HM	0.873 (2.12)
INEXP-MR	1.371 (3.34)
INEXP-MU	3.586 (8.72)
PERINV	7.308 (6.53)
4696 Observations; Adjusted $R^2 = 0.630$	

NOTE: Based on data beginning in period 2.

and the second letter indicates information (M, R, or U). Subject experience is the omitted category. PERINV is an explanatory variable equal to the inverse of the trading period.

The ANOVA regression results are reported in Table III.[15] The positive and significant coefficient on PERINV is consistent with our earlier observation that there is a downward trend in prices for the early periods of all twenty experiments. The coefficients on the capacity dummy variables are all statistically significant. The hypothesis that these three coefficients are equal can be rejected at the one percent level in favor of the alternative hypothesis that they are ordered so that higher capacity is associated with a lower coefficient.

The coefficient for PRIVATE is positive but not statistically significant. This means that PRIVATE information experiments had prices that were higher, but not significantly higher, than MIXED information experiments. PUBLIC information raises prices by 0.44 pesos on average, compared to the MIXED information condition. However, this effect is not statistically significant.

[15] The ANOVA regression explains only part of the observed price variability. This is not surprising given the pricing instability predicted by the Edgeworth cycle and mixed strategy NE theories for this environment.

The coefficients on the five subject inexperience dummy variables are all positive. This means that experiments with experienced subjects had *lower* prices than experiments with inexperienced subjects. Prior experience with this posted pricing environment did not enable subjects to achieve higher prices. All of the coefficients for inexperience were significantly greater than zero (at the five percent level).

We also checked for the presence of experiment-specific (or, cohort) effects in the data. A regression equation was specified that included all of the independent variables listed in Table III plus a set of dummy variables that represented individual experiments. We ran an F test for the hypothesis that the coefficients of these experiment-specific dummy variables are all zero. This hypothesis is rejected at the one percent significance level. This indicates the presence of cohort effects in the data. We also ran an ANOVA regression for price data using the average price for the first five periods in an experiment as an additional explanatory variable. We wanted to see if the cohort effects could be explained on the basis of the average price that a cohort began with. Cohort effects were diminished with this specification but were still present; the F test was significant at the one percent level.

We now examine how well the competing hypotheses of price formation stack up against the data. The competitive model provides, at best, a very incomplete explanation of the price data. There are two experiments (LME1 and HME2) in which prices converge to the competitive equilibrium price from above. In the other 18 experiments prices remain above the competitive price.

Edgeworth price predictions are derived by calculating a seller's profit maximizing price given the expectation that rival sellers maintain their prices from the previous period. This approach permits us to compute predicted Edgeworth prices after period one for each seller in each experiment. To assess the extent to which actual prices adjusted to predicted Edgeworth prices, we first estimated a linear equation for each seller in which the dependent variable was the current period price minus the previous period price and the independent variables were the current predicted Edgeworth price minus the actual previous period price and the lagged value of this independent variable. The form of the estimating equation captures the case of complete and immediate adjustment to the predicted Edgeworth price (for some coefficients) as well as cases of partial or zero adjustment to the predicted Edgeworth price. We then performed tests of significance for the coefficients that characterize adjustment to predicted Edgeworth prices. The estimating equation and a summary of results of significance tests are reported in Table IV.

The first test reported in Table IV measures the significance of both explanatory variables in accounting for a seller's price adjustments. For 63 out of 80 sellers, the explanatory variables (which are based on current and lagged predicted Edgeworth prices) do have a significant effect (at the .05 level) on actual price adjustments. The null hypothesis of the second test is that the actual price adjusts completely and immediately to the predicted Edgeworth price. This null hypothesis is rejected for 70 out of 80 sellers.

TABLE IV

RESULTS OF OLS REGRESSIONS FOR ADJUSTMENT TO PREDICTED EDGEWORTH PRICES

Estimating Equation:

$$P_{it} - P_{i,t-1} = \beta_0 + \beta_1(P_{it}^E - P_{i,t-1}) + \beta_2(P_{i,t-1}^E - P_{i,t-2})^{a}$$

Results for Subject-Specific Regressions:

Null Hypothesis	Number of subjects whose behavior allows rejection of the null hypothesis at the .05 level (out of 80 subjects)
(1) $\beta_1 = \beta_2 = 0$	63
(2) $\beta_0 = 0; \beta_1 = 1; \beta_2 = 0$	70
(3) $\beta_1 = 0^{b}$	55
(4) $\beta_2 = 0^{b}$	12

Coefficient Estimates When All Subjects Are Pooled:[c]

β_0	−0.572
	(0.112)
β_1	0.291
	(0.010)
β_2	−0.174
	(0.010)

Adj. $R^2 = .158$; 4616 observations

[a] P_{it} is the price set by seller i in period t. P_{it}^E is the Edgeworth predicted price for i in t, based on rivals' prices in period $t-1$.

[b] The alternative hypothesis is that the coefficient is positive.

[c] Standard errors are in parentheses.

The null hypothesis of the third test is that the first adjustment coefficient is zero. This hypothesis is rejected for 55 out of the 80 seller subjects in favor of the one-sided alternative that the coefficient is positive. The large number of rejections for the second test shows that few sellers adjusted their prices completely and immediately to the predicted Edgeworth price. The results of the third test show that most subjects did adjust their prices partially in response to the current predicted adjustment to Edgeworth prices. The null hypothesis of the fourth test is that the coefficient for lagged predicted adjustment is zero. This can be rejected for only 12 out of 80 subjects. That is, the once-lagged predicted Edgeworth adjustment does not have a significant effect on current price adjustment for most subjects.

We also estimated the Edgeworth adjustment equation specified in Table IV for the pooled sample with all subjects. The estimated coefficients (see Table IV) illustrate the response to predicted Edgeworth prices averaged over all subjects in all periods. The results are consistent with the idea of partial adjustment that emerged from the subject-specific regressions. A representative subject would be predicted to adjust their price by an amount equal to 29 percent of the difference between the Edgeworth prediction and their current price. The extent of a subject's adjustment would diminish somewhat over time if the Edgeworth prediction stays fixed, because the estimated β_2 is negative.

Our interpretation of the mixed strategy NE prediction is that each seller's price is drawn from a common distribution, ϕ^*, in each period; that is, predicted prices are independent, identically distributed random variables. We ran a vector autoregression for each experiment in order to test the hypothesis that mean prices in a period are independent of prices in previous periods. A VAR(2) specification was used with current period prices for the four sellers as a vector of dependent variables and once and twice lagged price vectors as independent variables. The results of the VAR's indicate that actual prices are not realizations of independent, identically distributed random variables. By using F tests, we reject the hypothesis that mean prices in a period are independent of prices in previous periods for each experiment; i.e., lagged prices do contribute to the explanatory power of the VAR for each experiment.[16] We also checked whether this failure of independence was due to a dependence only on own lagged prices or whether it was due to dependence upon both own lagged prices and lagged prices of rivals. By running Chi-squared tests, we reject the hypothesis that current prices depend only on own lagged prices, for each experiment (at the .05 level). Lagged prices of rivals do contribute to the explanatory power of the VAR for each experiment. This is consistent with the results from the Edgeworth regressions, in which we found that most subjects adjusted at least partially to the predicted Edgeworth price, which is based on lagged prices of rival sellers.

The results from the VAR's suggest that actual prices do not conform to period-by-period draws from the mixed strategy NE distribution. Actual prices depend on past prices in some way that is not captured by the static NE theory. However, we were still interested in whether the mixed strategy NE distribution captured qualitative features of the aggregate price data. A comparison of the (symmetric) mixed strategy NE distributions in Figure 2 and the price frequency distributions in Figure 3 indicates some similarities between the aggregate price frequencies and the mixed strategy NE predictions.[17] In most experiments a high percentage of prices are in an interval that begins within about a peso above p^c and ends 3 to 4 pesos above p^c. This is the price interval where the mixed strategy NE distribution places the greatest probability weight. However, the aggregate frequency distributions for price data tend to lie to the right of the corresponding mixed strategy NE distributions, indicating that actual prices tended to be higher than predicted mixed strategy NE prices.

[16] We also ran the VAR(2) regressions with an explanatory variable equal to the inverse of the trading period. These regressions permit us to test for independence from past prices after taking into account a time trend in the data. We reject the hypothesis that mean prices in a period are independent of lagged prices for each experiment, based on these regressions.

[17] The Kolmogorov-Smirnov Test provides a statistical test of the hypothesis that a sample of observations comes from a particular continuous theoretical cdf. This test requires that data represent independent draws from some common distribution. The VAR(2) tests suggest that the independent draws assumption is violated. Nevertheless, we ran a KS test of the hypothesis that prices are drawn from the mixed NE distribution for each subject in our experiments. The hypothesis that prices are drawn from the mixed strategy NE distribution is rejected for all subjects in our experiments.

TABLE V

PROFIT COMPARISONS

Information: Capacity:	PRIVATE MEDIUM	MIXED LOW	MIXED MEDIUM	MIXED HIGH	PUBLIC MEDIUM
Benchmark Profit per Seller:					
CE	65.2	234.2	65.2	0.0	65.2
Expected Static NE	199.8	310.3	199.8	97.2	199.8
Monopoly Pricing	640.9	640.9	640.9	640.9	640.9
Actual Average Profit per Seller:[a]					
Inexperienced subjects	332.7	366.0	265.0	207.4	362.6
Experienced subjects	312.9	316.4	236.6	157.6	263.7
All subjects	322.8	341.2	250.8	182.3	313.1

[a] Average profit in pesos per seller per period. Actual dollar payoffs to subjects were determined by an exchange rate that was fixed at the beginning of the experiment.

The experimental results are clearly inconsistent with monopoly pricing. The summary statistics in Table II show mean and median prices that are far below the monopoly price of 38.3 pesos for all experiments. Given the very high levels of excess capacity when sellers choose the monopoly price, this result is not too surprising.

The results appear to support a type of tacit collusion that yields prices and profits that are above the noncooperative level and below the monopoly level. The median price for the last twenty periods exceeds the noncooperative NE median price in 17 out of 20 experiments (see Table II). Table V reports profit comparisons. Average profit per seller exceeds the corresponding noncooperative static NE profit for each of the treatment categories reported in Table V. If one looks at the last one-half of each experiment, average profit per seller exceeded the noncooperative static NE profit in 18 out of 20 experiments.

The impact of capacity levels on prices is consistent with the standard view of how excess capacity effects tacit collusion. The ANOVA regression results indicate that higher capacity levels are associated with lower prices (see also Figure 3). The data are inconsistent with the Davidson and Deneckere (1990) prediction that greater excess capacity makes collusive pricing more likely. This prediction relies on the ability of sellers to find a joint profit maximizing level for prices and to sustain this price level by punishments of low pricing. Sellers occasionally set high prices in our experiments, but there were no episodes of sustained monopoly pricing by all sellers.

The tacit collusion theory predicts that greater provision of information to sellers will raise prices. The ANOVA results offer little support for this. Prices in PUBLIC information experiments were higher, but not significantly higher than prices in MIXED information experiments.

While the price and profit results described above are supportive of the tacit collusion hypothesis in some respects, it is less clear that tacit collusion provides a good explanation for the observed results. Tacitly collusive behavior is based on the idea that sellers recognize their mutual interdependence and mutual interest in high prices. This recognition would motivate each seller to avoid price cuts that would lead to further price cuts by rivals. Price cuts would be utilized only to punish "cheaters."

There was little evidence that sellers set stable high prices (i.e., above the median noncooperative price) in the experiments. While all four sellers did set high prices in a trading period for some experiments, these high prices were quickly followed by successive rounds of price cuts. There was also no evidence of simple price rotation schemes designed to achieve high profits.

There were efforts by sellers in some experiments to signal rivals by setting high prices. For example, seller 3 set the following sequence of prices in the middle periods of experiment LMI1: {25, 50, 75, 50, 50, 50}. This sequence of high prices set by seller 3 appears to be a signal for rivals to raise their prices. The last five prices in this sequence were well above seller 3's myopic best responses, so seller 3 was foregoing profitable opportunities to cut his price. However, this signalling by seller 3 did not help the group of sellers achieve stable, high prices. While one rival seller did raise his price to 50 pesos during this sequence, the other sellers raised their prices only partially to this level, and prices unravelled several periods later so that all prices fell below 9 pesos.

The appearance of profit levels above the noncooperative profit benchmark may be a result of a disequilibrium adjustment process, rather than a result of tacit collusion. In order to illustrate this point, suppose four sellers each set prices according to the estimating equation for adjustment to predicted Edgeworth prices in Table IV. We chose parameter values $\beta_0 = -0.572$, $\beta_1 = 0.291$, $\beta_2 = -0.174$, and an error term with standard deviation of 3 pesos, for each seller's price adjustment (these are the parameter values estimated from the pooled sample). We ran a simulation of price adjustment for 60 periods for the MEDIUM capacity case, with initial prices set equal to marginal cost for each seller. Average profit per seller in the simulation was 529.1 pesos per period. This profit level is well above the noncooperative profit benchmark of 199.8 pesos per period.[18] This simulation is not advanced as an accurate description of individual seller behavior in the experiments. Rather, it is intended to illustrate how a myopic partial adjustment process that responds to past prices of rivals can lead to profits that are substantially higher than noncooperative profits in this environment.

The impact of subject experience provides indirect evidence against the tacit collusion hypothesis. The ANOVA results indicate that prices were higher for inexperienced subjects than for experienced subjects. Subjects with no prior experience in this price-setting environment would have difficulty in tacitly coordinating their decisions to achieve high prices. If successful tacit collusion was the basis for observed prices and profits, then we would expect groups of experienced subjects to achieve higher profits and prices than inexperienced groups. Experienced subjects should have a better understanding of the advan-

[18] These average profit results are robust with respect to changes in initial prices and to minor adjustment parameter changes.

tages of high prices and a better understanding of how to achieve tacit coordination.[19]

5. SUMMARY AND CONCLUSIONS

The Bertrand-Edgeworth model describes competition among a group of price setting sellers, each of whom faces a production capacity constraint. We report on a series of twenty experiments that were designed so as to capture essential features of BE competition. These experiments permit us to evaluate the predictive power of four different theories of BE competition: Competitive equilibrium (CE) pricing, Edgeworth cycles in prices, mixed strategy Nash equilibrium (NE) in prices, and tacit collusion. Our experimental results indicate that each of the four theories helps to explain some aspects of the data. However, none of these theories are completely consistent with the experimental data.

Average seller price is decreasing over time for the first 20 periods of each experiment. However, with the exception of two experiments, prices do not converge to the CE over time.

Observed pricing did not conform to our interpretation of the Edgeworth cycle theory. The hypothesis of complete adjustment to predicted Edgeworth prices was rejected for 70 out of 80 sellers. However, the hypothesis of partial adjustment to predicted Edgeworth prices was not rejected for a majority of subjects. In addition many of the experiments exhibit upward and downward price swings of the sort predicted by the Edgeworth cycle theory.

Pricing was not consistent with the mixed strategy NE distribution. Observed pricing violated intertemporal independence and tended to exceed predicted mixed strategy NE prices. The qualitative nature of price dispersion for aggregate data is similar to the dispersion predicted by the mixed strategy NE; most prices are in a fairly small interval above the CE price, with a "tail" extending to the monopoly price.

Observed price and profit levels were consistent with tacit collusion. Median prices and average profit were above the corresponding (static) mixed strategy NE predictions in each experiment. However, the observed patterns of pricing within individual experiments are less supportive of the hypothesis that behavior was tacitly collusive. There was neither evidence of sustained high prices by all sellers within an experiment nor evidence of simple price rotation schemes to achieve tacit collusion. Whenever a group of sellers did manage to achieve high prices, this was quickly followed by a price cutting episode.

[19] The cohort effects that we reported in our ANOVA results and the variety of pricing patterns observed in the experiments are supportive of the presence of repeated game effects in the data. The folk theorem for repeated games tells us that many different pricing patterns can be sustained as noncooperative equilibrium play if subjects possess a high subjective continuation probability. Equilibrium play of this type requires that sellers understand the strategies employed by rival sellers and that deviations from equilibrium play are met by a series of punishment actions that are part of equilibrium strategies. While repeated game effects may be the explanation for the cohort effects in the data, we think it is at least as likely that diesequilibrium adjustments that vary across experiments are behind the cohort effects. The results on subject experience argue against an explanation based on sophisticated equilibrium play.

None of the four theories that we considered provides a single, comprehensive explanation of the experimental price data. This points to a need for the development of theory that is capable of explaining the variety of pricing patterns that were observed. The observed pricing results seem most consistent with some type of disequilibrium process of price adjustment. The Edgeworth cycle theory, which posits a disequilibrium adjustment process, is the only one of the four theories that we considered that predicts the sort of time dependence and price cycles that appear in the data. Our regression results indicate that while few subjects adjusted their prices completely to predicted Edgeworth prices, most subjects adjusted their prices by a positive fraction of the predicted Edgeworth price change.

A modified version of the Edgeworth cycle theory may provide a good model of disequilibrium price formation. Modifications that may prove to be useful include changes in the specification of expectations of rivals' prices, adding price inertia or partial adjustment to optimal price choices, and adding "experimentation" in price choices or "noisy" price adjustment.

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APPENDIX I

Instructions for Subjects—on Plato Computer System

This is an experiment dealing with market decision making. Funds for this experiment have been provided by a research grant. If you consider your alternatives carefully and make effective decisions you may earn a CONSIDERABLE AMOUNT of MONEY which will be paid to you IN CASH at the end of this experiment.

From this point on, all references to money will be in terms of "Plato pesos." At the conclusion of this experiment you will be paid in cash at the rate of $1.00 U.S. for every 1000 Plato pesos you have earned during the experiment. Note that you will maximize your cash payment at the end of the experiment by earning as many Plato pesos as you can. During the experiment your accumulated wealth in pesos will be displayed.

Press -NEXT- to continue

To aid in conducting this experiment and distributing the profits at its end, please type in your NAME at the arrow, and then press the -NEXT- key. (If you make a mistake, press the -ERASE- key to erase one character at a time, or press the -EDIT- key to erase an entire entry.)

Stephen Rassenti

Stephen Rassenti, you will be known as seller #4 during this experiment.

Press -NEXT- to continue

The experiment which follows will be conducted for a sequence of many periods. During each period sellers are able to produce and market a fictitious good which buyers may then choose to purchase.

In this experiment the buyers will be simulated by a computer. Each period these simulated buyers—some rich and some poor—will be placed in a queue (lined up) in random order. In that order, buyers will make purchases from sellers based on price and availability of the good. In other words, when a given buyer's turn comes up, this buyer will purchase from the seller that has available capacity at the lowest price.

Press -NEXT- to continue

Although sellers are free to post whatever selling price they choose, they provide the good to the buyers through a single, jointly owned, production facility. As a seller, you incur a cost of producing and selling the good. Your production cost is based on the number of units purchased from you. Your production cost during this entire experiment is 5 pesos PER UNIT. You will have the capacity to produce a maximum of 145 units of the good in each period.

The sequence of events in each period is:

1. Submit your selling price for the good. (You may use a decimal point to submit fractional prices... e.g., 11.61 pesos.)
2. Sellers' prices are displayed to buyers.
3. Buyers take turns purchasing the good.
4. Your Plato record displays the following:
   (a) how many units you sold;
   (b) your revenue, cost, and profit;
   (c) your accumulated wealth;
   (d) all other sellers' prices;
   (e) the total trade in the market.
5. The next period begins.

We are waiting for 1 subjects to finish the instructions. Please be patient!

P25	P26	P27	P28	P29	P30	P31	Seller #1
145 8.21	145 8.17	145 8.18	145 8.16	145 8.16	145 8.17	145	k = Capacity p = Unit Price
15 123	145 1185	17 139	145 1183	145 1183	145 1185		u = Units Sold r = Revenue
75	725	85	725	725	725		pc = Prod. Cost
48	460	54	458	458	460		Period Profit
8447	8907	8961	9419	9877	10337		Wealth
							Other Sellers
145 8.20	145 8.19	145 8.17	145 8.16	145 8.20	145 8.17	145	Capacity (2) Unit Price (2)
145 8.18	145 8.17	145 8.16	145 8.16	145 8.15	145 8.16	145	Capacity (3) Unit Price (3)
145 8.19	145 8.18	145 8.17	145 8.25	145 8.25	145 8.20	145	Capacity (4) Unit Price (4)
450	448	452	453	449	452		Total Trade

Type in your unit price for period 31 >

APPENDIX II

Computing Mixed Strategies for a Symmetric, Four-Seller Game

Let $\pi(p; \phi)$ be the expected profit to a seller who charges a price p when each of his three rivals plays the mixed strategy cumulative distribution function ϕ. The support of ϕ is $[p^0, p^m]$ where $p^0 \geqslant p^c$.

$$\text{(A1)} \quad \pi(p;\phi) = (p-c)\min\{K, D(p)\}(1-\phi(p))^3$$
$$+3(p-c)(1-\phi(p))^2$$
$$\times \int_{p^0}^{p} \min\left\{K, \max\left\{0, D(p)\left(1-\frac{K}{D(q)}\right)\right\}\right\}\phi'(q)\,dq$$
$$+3(p-c)(1-\phi(p))$$
$$\times \int_{p^0}^{p}\int_{p^0}^{p} \min\left\{K, \max\left\{0, D(p)\left(1-\frac{K}{D(q)}-\frac{K}{D(r)}\right)\right\}\right\}\phi'(q)\,dq\,\phi'(r)\,dr$$
$$+(p-c)\int_{p^0}^{p}\int_{p^0}^{p}\int_{p^0}^{p} \max\left\{0, D(p)\left(1-\frac{K}{D(q)}-\frac{K}{D(r)}-\frac{K}{D(s)}\right)\right\}$$
$$\times \phi'(q)\,dq\,\phi'(r)\,dr\,\phi'(s)\,ds.$$

This expected profit is the sum of four terms. The first term is the profit to this seller if p is the lowest price times the probability that the other three sellers all set a higher price. The second term is expected profit to this seller when p is the second lowest price. Note that $(1-K/D(q))$ is the fraction of buyers allocated to this seller when the lowest price is $q<p$. The third term is expected profit when p is the third lowest price. Finally, the fourth term is expected profit for this seller when p is the highest price.

Equation (A1) may be rewritten as follows:

$$\text{(A2)} \quad \frac{\pi(p;\phi)}{(p-c)D(p)}$$
$$= \min\left\{1, \frac{K}{D(p)}\right\}(1-\phi(p))^3$$
$$+3(1-\phi(p))^2$$
$$\times \int_{p^0}^{p} \min\left\{\frac{K}{D(p)}, \max\left\{0, 1-\frac{K}{D(q)}\right\}\right\}\phi(q)\,dq$$
$$+3(1-\phi(p))$$
$$\times \int_{p^0}^{p}\int_{p^0}^{p} \min\left\{\frac{K}{D(p)}, \max\left\{0, 1-\frac{K}{D(q)}-\frac{K}{D(r)}\right\}\right\}\phi'(q)\,dq\,\phi'(r)\,dr$$
$$+\int_{p^0}^{p}\int_{p^0}^{p}\int_{p^0}^{p} \max\left\{0, 1-\frac{K}{D(q)}-\frac{K}{D(r)}-\frac{K}{D(s)}\right\}\phi'(q)\,dq\,\phi'(r)\,dr\,\phi'(s)\,ds.$$

If ϕ is a Nash equilibrium strategy, then π must be constant for all p in $[p^0, p^m]$. Let p_3 be the price that is implicitly defined by $D(p_3)=3K$. If $p^0<p_3$, then equation (A2) may be rewritten as follows for $p \in (p^0, p_3)$:

$$\text{(A3)} \quad \frac{(p^0-c)K}{(p-c)D(p)} = \frac{K}{D(p)}\{(1-\phi(p))^3 + 3\phi(p)(1-\phi(p))^2$$
$$+3\phi(p)^2(1-\phi(p))\}$$
$$+\int_{p^0}^{p}\int_{p^0}^{p}\int_{p^0}^{p}\left(1-\frac{K}{D(q)}-\frac{K}{D(r)}-\frac{K}{D(s)}\right)\phi'(q)\,dq\,\phi'(r)\,dr\,\phi'(s)\,ds.$$

The constant profit level in (A2) is equal to $(p^0-c)K$. After integrating the expression on the right-hand side of (A3) and rearranging terms we have the following equation for $p \in (p^0, p_3)$:

$$\text{(A4)} \qquad \int_{p^0}^{p} \frac{\phi'(q)}{D(q)}\, dp = \frac{\left(\dfrac{p-p^0}{p-c}\right) + \left(\dfrac{D(p)-K}{K}\right)\phi(p)^3}{3D(p)\phi(p)^2}.$$

Now differentiate both sides of (A4) with respect to p. After simplifying the expressions that result from this differentiation, the following ordinary differential equation (ODE) emerges:

$$\text{(A5)} \qquad \phi'(p) = \frac{\dfrac{(p^0-c)}{(p-c)^2} + \dfrac{D'(p)\phi(p)^3}{K} - \dfrac{D'(p)(p-p^0)}{D(p)(p-c)} - \left(\dfrac{D'(p)\phi(p)^3}{D(p)}\right)\left(\dfrac{D(p)-K}{K}\right)}{\phi(p)^2\left(4 - \dfrac{D(p)}{K}\right) + \dfrac{2(p-p^0)}{\phi(p)(p-c)}}.$$

This ODE defines the Nash equilibrium mixed strategy ϕ over the interval (p^0, p_3), as long as $p^0 < p_3$.

The mixed strategy ϕ is defined over the remainder of the price support as follows. Differentiating (A2) with respect to p and holding π constant provides a necessary condition that ϕ must satisfy over all of its support. (If ϕ is piecewise differentiable, then this differentiation is admissible except on a set of points of measure zero. The other functions of p on the right-hand side of (A2) are continuous and piecewise differentiable in p.)

$$\begin{aligned}
\text{(A6)} \qquad -(p^0-c)KZ(p) &= (1-\phi(p))^3 Y'(p) - 3\phi'(p)(1-\phi(p))^2 Y(p) \\
&\quad + 3\phi'(p)(1-\phi(p))^2 Z_2(p,p) \\
&\quad + 3(1-\phi(p))^2 \int_{p^0}^{p} \frac{\partial Z_2(p,q)}{\partial p}\phi'(q)\, dq - 6\phi'(p)(1-\phi(p)) \\
&\quad \times \int_{p^0}^{p} Z_2(p,q)\phi'(q)\, dq \\
&\quad - 3\phi'(p)\int_{p^0}^{p}\int_{p^0}^{p} Z_3(p,q,r)\phi'(q)\, dq\, \phi'(r)\, dr + 3(1-\phi(p)) \\
&\quad \times \int_{p^0}^{p}\int_{p^0}^{p} \frac{\partial Z_3(p,q,r)}{\partial p}\phi'(q) dq\, \phi'(r)\, dr \\
&\quad + 6\phi'(p)(1-\phi(p))\int_{p^0}^{p} Z_3(p,q,p)\phi'(q)\, dq + 3\phi'(p) \\
&\quad \times \int_{p^0}^{p}\int_{p^0}^{p} Z_4(p,q,r)\phi'(q)\, dq\, \phi'(r)\, dr,
\end{aligned}$$

where

$$\begin{aligned}
&Z(p) = (D(p) + (p-c)D'(p))/((p-c)D(p))^2, \\
&Y(p) = \min\{1, K/D(p)\}, \\
&Z_2(p,q) = \min\{K/D(p), \max\{0, 1-K/D(q)\}\}, \\
&Z_3(p,q,r) = \min\{K/D(p), \max\{0, 1-K/D(q)-K/D(r)\}\}, \\
&Z_4(q,r,s) = \max\{0, 1-K/D(q)-K/D(r)-K/D(s)\}.
\end{aligned}$$

An equilibrium distribution function $\phi(p)$ must satisfy the integro-differential equation (A6) and the boundary conditions, $\phi(p^0)=0$, $\phi(p^m)=1$.

We have developed a computational procedure that permits numerical approximation of the symmetric, Nash equilibrium mixed strategy function ϕ. First, choose a value for p^0 between p^c and p_3. Second, approximate ϕ over the interval $[p^0, p_3]$ by solving the ODE of (A5). Third, divide the interval $[p_3, p^m]$ into a large number of subintervals and solve for $\phi'(p)$ at the right-hand edge of each subinterval by using (A6). The solution for ϕ' at the right-hand edge of a subinterval provides an approximation of ϕ over the next subinterval. This iterative process is repeated until a value for $\phi(p^m)$ is found. If $\phi(p^m)$ is equal to one then the procedure is finished. If $\phi(p^m)$ is less than one, then a smaller value for p^0 is selected and steps 1–3 above are repeated. If $\phi(p^m)$ exceeds one then a larger value for p^0 is selected and steps 1–3 are repeated.

This computational procedure was utilized for each of the three capacity levels in our experimental design. In each case the value for p^0 that was selected was between p^c and p_3. The computed value of $\phi(p^3)$ exceeded 80 percent for each capacity level. That is, over 80 percent of the mixed strategy cdf was calculated using the ODE defined in equation (A5).

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[Footnotes]

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