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DUOPOLY BEHAVIOR IN ASYMMETRIC MARKETS: AN EXPERIMENTAL EVALUATION

Charles F. Mason, Owen R. Phillips, and Clifford Nowell*

Abstract—Experimental duopolies are analyzed to answer two questions: Are asymmetric duopolies less likely to collude than symmetric duopolies? Is the time it takes to reach an equilibrium affected by asymmetry? In a repeated game where output is the choice, we have data for 19 (respectively, 21) subject pairs where both agents are low-cost (respectively, high-cost) and 25 subject pairs where one agent is high-cost and one is low-cost. Subjects make choices for at least 35 periods. Results indicate that asymmetric markets are less cooperative and take longer to reach equilibrium than symmetric markets.

I. Introduction

A wealth of evidence indicates that most industries are comprised of different-sized firms, firms with different cost conditions, or firms facing different demand conditions. "Survivor principle" analyses commonly observe asymmetries (Saving, 1961; Shepherd, 1967; Stigler, 1958; Weiss, 1964). Porter (1985) describes a number of industry cases where a low-cost producer has a significant advantage over its high-cost rivals. Given their prevalence, an increased understanding of oligopoly can come from the continued study of asymmetric market structures.[1] It is unreasonable to believe that the behavior of asymmetric oligopoly can be predicted by a simple extension of symmetric market theory (Jacquemin, 1987; Schmalansee, 1987).

This paper empirically investigates asymmetric duopoly behavior using experimental methods. By using experimental markets, we can control for basic market conditions and exactly measure the relevant variables. This facilitates analysis of the effects of changes in cost conditions. In particular, by comparing observed behavior in experimental duopolies with identical payoffs against behavior when payoffs are not identical, we are able to assess the effect of asymmetries. While several experimental analyses of duopoly behavior have been previously conducted, experimental analysis of asymmetric markets has been given little or no attention. (For a survey of this literature, see Plott (1982).)

The experiments construct a repeated game in which there are two classes of quantity-choosing agents, distinguished by different payoff tables. Payoff differences can be equally ascribed to costs or demand, but for purposes of exposition we relate them to costs. Thus, we term an agent with higher (respectively, lower) payoffs a "low-cost" (respectively, "high-cost") producer. We consider three combinations of subject pairs: two symmetric ("low-low" and "high-high") and one asymmetric ("low-high").

We find two significant results. First, asymmetric duopolies tend to entail market outputs which are a significantly larger proportion of the monopoly output than choices in symmetric duopolies. Indeed, experiments with asymmetric agents tend towards outputs very close to the Cournot level. Second, subjects take significantly longer to reach an equilibrium in asymmetric markets than in symmetric ones. These findings provide robust evidence on the impact of asymmetries and are important because they suggest that the often-obtained result of a tendency towards collusion in experimental markets (see, e.g., Fouraker and Siegel, 1963; Friedman, 1967; Dolbear et al., 1968; Plott, 1982; Selten and Stoecker, 1986) is very sensitive to the imposition of sym-

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[1] It is widely agreed the "... more cost functions differ from firm to firm, the more trouble the firms will have maintaining a common price policy, and the less likely joint profit maximization is" (Scherer (1970) p. 192). In general, empirical evidence on this point is meager. Scherer (1970, pp. 136–145) surveys the early literature on studies of asymmetric duopoly behavior. An updated survey in Scherer and Ross (1990, pp. 279–294) cites several case studies where various asymmetries impede collusion. Asch and Seneca (1975) find that tight oligopolies in producer-goods industries are more profitable than tight oligopolies in consumer-goods industries, and conclude that this provides some evidence that product heterogeneity impedes collusion.

metry. On a policy level, our results show that asymmetry discourages cooperative behavior. Collusion might be more sensitive to asymmetry than previously thought. Mergers resulting in increased symmetry have an anti-competitive effect distinct from the increase in concentration.

II. Asymmetric Duopoly in Theory

Consider a market with two firms, indexed as 1 and 2. For purposes of exposition, we restrict our attention to a model where both firms face a linear inverse demand curve; each firm i has constant marginal cost c_i. Asymmetry is characterized by differing costs; without loss of generality we take $c_1 < c_2$. This generalizes easily to a model where the firms face different demand schedules. We write firm i's period t output as $q_i(t)$ and the market price as $P(q_1 + q_2)$.

We assume there are an indefinite number of periods in which these firms make simultaneous output choices, i.e., they are participating in a repeated game. Firm i's period t profits can be expressed as

$$\pi_i(t) = \left[P(q_1(t) + q_2(t)) - c_i\right]q_i(t). \qquad (1)$$

Firm i selects its output in each period t so as to maximize its expected discounted value of future payoffs.

It is well known that potential equilibria in a repeated game are numerous, arising from various combinations of trigger strategies (Friedman, 1983; Fudenberg and Tirole, 1989; Kreps, 1990; Rasmusen, 1989). This is a result of the indefinite or infinite duration of the game, which precludes backwards induction arguments commonly applied to establish a unique equilibrium in a finite game of known duration. At one extreme, repeated play of the static Cournot outputs is an equilibrium; this yields firm i Cournot profits π_i^c in each period. At the other extreme, collusion can often be sustained as a stationary equilibrium path (Abreu, 1986); this yields firm i profits π_i^* in each period. The possible outputs in a collusive regime are defined by the locus of tangencies of the two firms' static isoprofit contours that satisfy an incentive constraint for each firm. This constraint requires that neither firm can increase its profit flow by a unilateral defection, i.e., that the collusive profit flow exceeds the sum of one-time defection profits plus the discounted flow of punishment profits (cf. equation (5.26) in Friedman (1983) and Phillips and Mason (1992)).

Kreps (1990) argues that Nash equilibria in non-cooperative games are interesting to the extent that they strike the participants as the "self-evident way to play." Further, bounded rationality may limit the pace at which agents learn about a rival's behavior and a corresponding self-evident strategy. Self-evident strategies may be cooperative, if the subject is patient or optimistic about the chances a rival will respond cooperatively. We submit that in either case it is easier to make deductions concerning self-evident strategies in symmetric games than in asymmetric games. We therefore expect subjects to be more cooperative and reach equilibrium more rapidly in symmetric games.

III. Experimental Markets and Data

Our experimental markets are set up as two-person repeated games with static inverse demand function

$$P(q_1, q_2) = 4 - (q_1 + q_2)/24. \qquad (2)$$

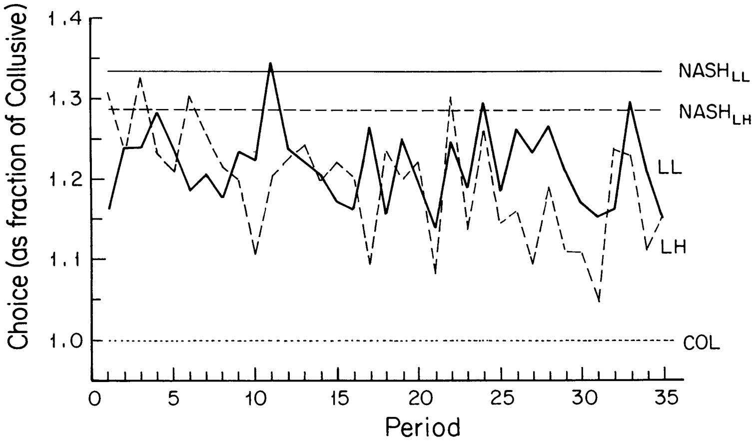
Marginal costs are 0 for low cost subjects and 1/2 for high cost subjects. Based on equations (1) and (2), static payoffs are

$$\pi_i = \begin{matrix} (4 - q_j/24)q_i - q_i^2/24, & i \in L; \\ (3.5 - q_j/24)q_i - q_i^2/24, & i \in H; \end{matrix} \qquad (3)$$

where L (respectively, H) is the set of low- (respectively, high-) cost subjects. These functions were presented to subjects in the form of payoff tables which show the dollar profit accruing from various output combinations. With this parameterization, the static non-cooperative Cournot/Nash equilibria in our three treatments are (32, 32) in the LL (low-low) design, (36, 24) in the LH design, and (28, 28) in the HH design. The static fully collusive equilibria entail combinations of output summing to 48, 45, and 42, respectively.[2]

[2] It is easy to verify that Cournot outputs for a model with inverse demand $P = A - BQ$ and marginal costs c_1, c_2, are $q_i = (A - 2c_i + c_j)/3B$, $j \neq i = 1, 2$. With $A = 4$ and $B = 1/24$, these outputs are: $q_1 = 32 = q_2$ if $c_1 = 0 = c_2$; $q_1 = 36$ and $q_2 = 24$ if $c_1 = 0, c_2 = 1/2$; and $q_1 = 28 = q_2$ if $c_1 = 1/2 = c_2$. In the symmetric designs, the fully collusive regime entails the firms' outputs summing to the monopoly output. With $c_1 = c_2 = c$, this gives $q_1 + q_2 = 12(4 - c)$ which equals 48 when $c = 0$ and 42 when $c = 1/2$. With equal costs, the natural division of output entails $q_1 = q_2$. In general, the collusive regime is described by the locus of iso-profit tangen-

FIGURE 1.—AVERAGE INDIVIDUAL CHOICE
LOW COST SUBJECTS



In each game two players simultaneously made output choices from rows in their respective payoff tables. Subjects played against the same opponent for the entire experiment, which entailed at least 35 choice periods; the identity of their opponent was never revealed. Along with their payoff table everyone had a copy of their rival's table. All participants knew that payoffs were common knowledge. The number of the periods and the exact time an experiment would run were not known by any of the participants during a session. Subjects were recruited for a length of time 30 to 45 minutes greater than an experiment actually ran. After the instructions (available on request) were read, a practice period was conducted. A monitor randomly chose the counterpart value while all subjects simultaneously selected their row value from a sample payoff table.[3]

Every subject was given a starting cash balance of \$5.00 to cover potential losses, and was told that if their balance went to zero they would be dismissed from the experiment with a \$2.00 participation fee. The remaining participant would then be allowed to operate as an unfettered monopolist. Although it was feasible for low-cost players to dispatch a high-cost opponent without suffering losses, such predatory behavior never occurred in any of our sessions; indeed, the lowest recorded cumulative earnings were near \$17.00. Some low-cost subjects earned as much as \$37.00 in a two-hour setting.

We analyze data from eight experimental sessions. In three *LL* sessions, a total of 38 subjects (19 pairs) made choices for 35 to 46 periods. In two *HH* experiments, 42 subjects (21 pairs) ran for 45 periods. Three *LH* sessions were conducted with 54 subjects (27 pairs), operating for 36 to 46 periods.

A graphic description of the data is given in figures 1 through 3. To facilitate comparisons between designs, we first adjust units so that *subject choices are represented as fractions of the respective collusive choices*. That is, a subject's choice in each period is divided by 24 in the *LL* markets and 21 in the *HH* markets; for the *LH* pairs, low-cost subject choices are divided by 28 and high-cost subject choices are divided by 17 (cf. footnote 2).

cies. With $A = 4$, $B = 1/24$, $c_1 = 0$ and $c_2 = 1/2$, and using equation (6) in Schmalansee (1987), this locus is given by

$$q_2 = 69 - q_1 - \left([729 - 6q_1]^{1/2}\right)/6.$$

As noted above, this is subject to the two constraints requiring each subject i's static collusive profits, π_i^*, to exceed his static Cournot profits, π_i^c. The resulting constrained locus of outputs yields a market output of 45, after rounding. This may be further refined to $q_1 = 28$ and $q_2 = 17$ (after rounding) by utilizing either the Nash bargaining solution (which chooses q_1 and q_2 to maximize $[\pi_1^* - \pi_1^c][\pi_2^* - \pi_2^c]$) or Friedman's (1983) concept of balanced temptation. Alternative collusive concepts are discussed in Schmalansee (1987). We note for reference below that Cournot outputs are 133% of collusive for individuals in the symmetric designs; for low- (high-) cost subjects Cournot output is 129% (141%) of collusive in the asymmetric design.

[3] This table was unrelated to the tables used in the experiments. There may be concern that the practice period generates an anchoring effect. In a similar experimental context, Mason et al. (1991) test for, and strongly reject, the hypothesis of an anchoring effect. This paper also elaborates on our experimental techniques.

FIGURE 2.—AVERAGE INDIVIDUAL CHOICE
HIGH COST SUBJECTS

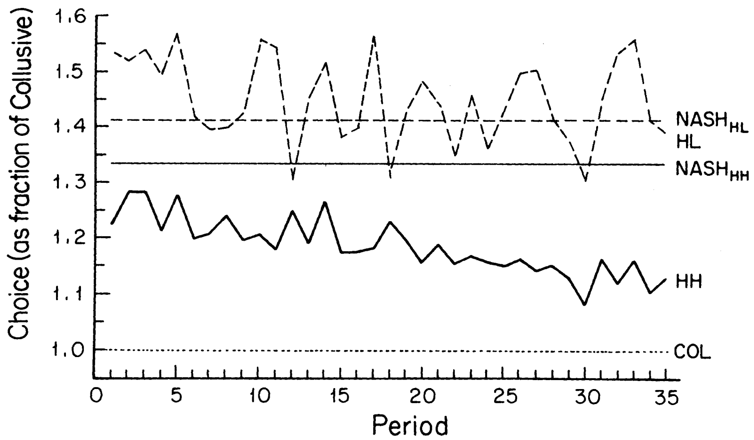


FIGURE 3.—AVERAGE PAIRED CHOICE
SYMMETRIC VS. ASYMMETRIC MARKETS

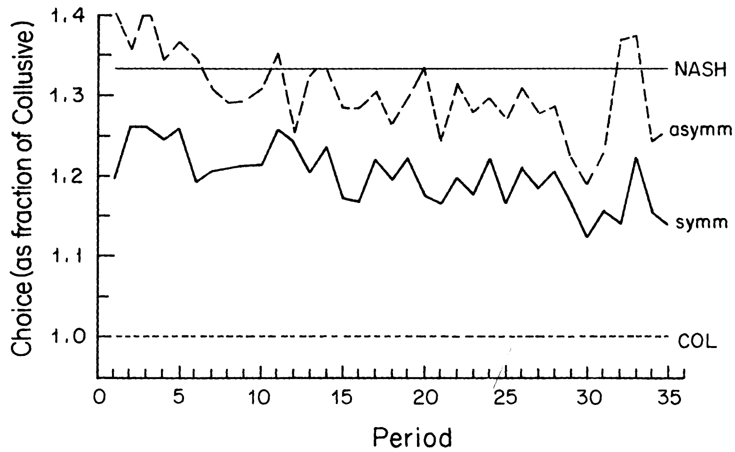


Figure 1 plots average low-cost subject choices as a fraction of the collusive output in the *LL* and *LH* treatments, for the first 35 periods. The solid time series, corresponding to the symmetric treatment, is labelled *LL*. The dashed time series, corresponding to the asymmetric treatment, is labelled *LH*. The dotted horizontal line at 1.00 labelled *COL* corresponds to the collusive regime, while the solid horizontal line at 1.33, labelled $NASH_{LL}$, corresponds to the Cournot *LL* regime. The low-cost component of a Cournot regime in the asymmetric treatment is represented by the dashed horizontal line at about 1.29, labelled $NASH_{LH}$ (cf. footnote 2). For almost every period the *LL* and *LH* plots lie between their respective collusive and Cournot equilibria, and lie close together. Indeed, it appears that, on average, low-cost subjects ultimately make similar output choices, as a fraction of the collusive level, when paired with either low- or high-cost opponents.

Figure 2 provides information on high-cost subjects. Again, the solid locus *HH* (respectively, dashed locus *HL*) corresponds to the symmetric (respectively, asymmetric) treatment. As in figure 1, the dotted line at 1.00 is associated with the collusive regime, and the solid line $NASH_{HH}$ represents the Cournot regime in *HH*. The dashed horizontal line $NASH_{HL}$ represents the high-cost agent's Cournot output in the asymmetric design. It is apparent that, on average, high-cost subjects are more cooperative in the symmetric experiments than in asymmetric experiments. While the *HL* plot varies about the Cournot level, the *HH* plot lies well below it. This suggests that low-cost agents are unable to induce high-cost agents to collude, and so speaks against various models of large firm price-leadership.

Figure 3 reports data on *subject pair* choices. Here, the market output is obtained for each subject pair, and then expressed as a fraction of collusive output for the pair. Thus, market output was divided by 48 for subjects in the *LL* treatment, 45 in the *LH* treatment, and 42 in the *HH* treatment. Then for each period, we calculate the average fraction for duopoly pairs in the symmetric and asymmetric treatments. The symmetric averages combine the *LL* and *HH* treatments. These averages are plotted against time, with schedules labelled by design: symmetric (symm) or asymmetric (asymm). As in figures 1 and 2, the dotted horizontal line corresponds to market collusive choices. The solid line labelled *NASH* corresponds to market choices at the Cournot level, equal to 133% of the collusive level in all cases. The striking feature in this diagram is that the mean paired outputs in the asymmetric treatment are further from the collusive level, while the mean paired outputs in the symmetric treatments lie closer to the collusive level.[4] This suggests that behavior is more collusive in symmetric markets than in asymmetric markets, on average. We now proceed to more rigorous analysis of paired choice behavior.

IV. Econometric Analysis

We use two distinct econometric models to evaluate the impact of asymmetries. Taking the perspective that market behavior is the relevant statistic, we analyze paired choices. In the first model, we interpret the data set as a pooled cross-section/time-series sample, where the dependent variable is subject pairs' choice. In the second model, we conduct a time-to-failure analysis; here the dependent variable is "failure" time, where "failure" is reaching an equilibrium. In both subsections the data set has at least 35 observations on 65 pairs.

[4] While it appears that the asymm plot stabilizes earlier than the symm plot, inferences on the amount of time it took our subject pairs to reach equilibrium cannot be drawn from these diagrams. This is because average choices can appear quite stable even as individual pairs' choices are fluctuating.

A. *Paired Choice as the Dependent Variable*

In this section we estimate the level of cooperative behavior achieved by subject pairs in symmetric and asymmetric markets and test for differences. Regarding our data set as a pooled cross-section/time-series sample requires an equal number of observations from each pair. Correspondingly, we consider the first 35 observations on each pair, giving us 2,275 data points for our estimation. The structural model we utilize is

$$Q_k(t) = \alpha_k + \epsilon_k(t), \tag{4}$$

where $Q_k(t)$ is pair k's period t choice as a fraction of the associated collusive output, α_k is the steady-state or equilibrium choice, and $\epsilon_k(t)$ is a residual capturing variations about the equilibrium. There are a host of reasons to expect serial correlation in this structure. Each subjects' choice in period t is likely to be linked to both subjects' choices in $t-1$ (Friedman, 1983). Any attempts at signalling a desire to collude hinge on an intertemporal connection (Shapiro, 1980). Similarly, any learning implies a connection between current and preceding choices. Taken together, these argue for a time-series structure in the $\epsilon_k(t)$, which is likely to be more complicated than an AR(1) process. Indeed, in a similar experimental setting Mason et al. (1991) argue this time series structure is best described by an AR(2) process. Assuming this to be the case

$$\epsilon_k(t) = \rho_{k1}\epsilon_k(t-1) + \rho_{k2}\epsilon_k(t-2) + \mu_k(t), \tag{5}$$

where the residual $\mu_k(t)$ is white noise (i.e., $E\mu_k(t) = 0$, $E\mu_k(t)\mu_k(s) = 0$ for $t \neq s$ and $E\mu_k(t)^2 = \sigma_k^2$). Equations (4) and (5) may be combined to yield:

$$Q_k(t) = \beta_k + \rho_{k1}Q_k(t-1) + \rho_{k2}Q_k(t-2) + \mu_k(t), \tag{6}$$

where $\beta_k = \alpha_k(1 - \rho_{k1} - \rho_{k2})$. Dynamic stability requires that $|\rho_{k1}| < 1$, $|\rho_{k2}| < 1$, and $|\rho_{k1} + \rho_{k2}| < 1$ (Fomby et al., 1988). This is a substantive concern, for dynamic stability allows us to interpret α_k as the steady state, or equilibrium, choice in equation (4). In turn, this indicates that α_k may be viewed as the natural parameter to focus on when asking questions about the equilibrium of the system.

TABLE 1.—ESTIMATION RESULTS, SUBJECT PAIRS' CHOICES
(as fractions of collusive outputs)

Parameter Estimate	Treatment		
	LL [627]	*LH* [825]	*HH* [693]
b_p	0.555	0.651	0.199
	(0.063)	(0.048)	(0.028)
r_{p1}	0.2547	0.2858	0.4520
	(0.0396)	(0.0331)	(0.0326)
r_{p2}	0.2694	0.2168	0.3650
	(0.0396)	(0.0320)	(0.0318)
a_p	1.165	1.308	1.083
	(0.036)	(0.009)	(0.033)
SSE	0.258	0.398	0.375
R^2	0.976	0.993	0.993

Note: Number of observations in square brackets; SSE = summed squared errors.

Our approach to estimating the parameters in equation (6) is to regard the residuals $\mu_k(t)$ as generated from a multi-variate distribution. Estimation then follows standard techniques for analyzing pooled cross-section/time-series data, once the covariance structure is specified. We shall allow for different variances across subject pairs, and assume that no cross-equation covariance exists: $E[\mu_k(t)\mu_h(s)] = 0$, for $k \neq h$.

We are primarily interested in the difference between steady-state behavior of subjects in asymmetric and symmetric environments. To focus on this issue we assume that α_k, ρ_{k1}, and ρ_{k2} are the same for all subject pairs in a given design, and that any variation across pairs is captured by the respective residual terms. Precisely, the parameter vector estimated is $(\alpha_L, \rho_{L1}, \rho_{L2})$ for $k \in LL$; $(\alpha_M, \rho_{M1}, \rho_{M2})$ for $k \in LH$; and $(\alpha_H, \rho_{H1}, \rho_{H2})$ for $k \in HH$.

Our estimation problem is now fully specified, with 35 observations on each of 65 equations. This system may be efficiently estimated by feasible generalized least squares, yielding the efficient estimator vector (b_p, r_{p1}, r_{p2}) for $(\beta_p, \rho_{p1}, \rho_{p2})$, $p = LL, LH, HH$. We may then consistently estimate α_p by

$$a_p = b_p/(1 - r_{p1} - r_{p2}). \tag{7}$$

Under plausible assumptions, a_p may be regarded as the maximum likelihood estimator.[5] The results of this estimation procedure are given in table 1. We report for each experimental design the estimates b_p, r_{p1}, r_{p2}, and a_p. Standard errors are given in parentheses.

We observe that in each design, the conditions for dynamic stability are met. Further, the estimated equilibrium choice is a larger fraction of the collusive level in the asymmetric experiments than in the symmetric experiments. The relative estimated equilibrium value is smallest in the *HH* group. The estimated value a_{LH} is close to 1.3, implying the asymmetric equilibrium is near the Cournot level. Note too that the estimated values a_{LL} and a_{HH} are each statistically different from both the Cournot and collusive levels (1.33 and 1, respectively).

The hypotheses of interest are that the steady-state values of paired choices are the same for symmetric and asymmetric designs, or equivalently that $\alpha_{LH} - \alpha_{LL} = 0$ and $\alpha_{LH} - \alpha_{HH} = 0$. These hypotheses can be analyzed by t-tests, using the information in table 1.[6] For the comparison between *LH* and *LL* treatments, we obtain the test statistic 3.836. For the comparison between *LH* and *HH* treatments, the test-statistic is 4.387. Both are statistically significant and so we reject the hypothesis that subject behavior is identical for symmetric and asymmetric designs. Specifically, subjects in our asymmetric experi-

[5] With standard assumptions on the joint distribution of the $\mu_k(t)$, Slutsky's theorem implies that a_k is asymptotically equivalent to the maximum likelihood estimator of α_k. The asymptotic variance of a_k can be calculated using Corollary 4.2.2 in Fomby et al. (1988, p. 58).

[6] Our computations are facilitated by the observation that the data set can be partitioned into the three subsets *LL*, *LH*, and *HH*, and each of the three estimates a_p is based only on the corresponding subset. This implies zero covariance between the estimates a_{LL}, a_{LH}, and a_{HH}, and so the variance of each difference just equals the sum of variances.

TABLE 2.—DURATION DATA

(1) Duration by Period Intervals	(2) Number of Pairs Reaching Equilibrium	(3) Number of Pairs That Have Not Yet Achieved Equilibrium	(4) Number of Pairs Censored	(5) Survival Rate	(6) Hazard Rate
0–4	2	65	0	1.000	0.008
4–8	0	63	0	0.969	0.000
8–12	2	63	0	0.969	0.008
12–16	4	61	0	0.938	0.017
16–20	0	57	0	0.877	0.000
20–24	3	57	0	0.877	0.013
24–28	4	54	0	0.831	0.019
28–32	10	50	0	0.769	0.056
32–36	8	32	16	0.615	0.071
36–40	1	8	15	0.461	0.031

ments were significantly less cooperative than subjects in our symmetric experiments.[7]

B. *Time as a Dependent Variable*

Recently, an extensive literature has arisen addressing estimation problems where time is the dependent variable and unique applications of these problems have appeared in the economics literature (Atkinson, Sandler and Tschirhart, 1987; Atkinson and Tschirhart, 1986; Kiefer, 1988). In our application, we take the failure time to be the period when a subject pair reaches an equilibrium.[8]

Table 2 summarizes the relevant information for failure-time analysis. Most of the columns in this table are self-explanatory; two deserve comment. With respect to column four, some pairs were censored during the last two intervals tabulated because their session was terminated prior to these pairs achieving equilibrium. Column six lists the hazard rate, the probability of a pair achieving equilibrium in the interval given they have not yet done so.

Statistical analysis of failure-times proceeds by modelling the hazard rate as a function of a set of explanatory variables. Using an ordinary least squares regression to examine the time to equilibrium yields the most efficient estimates if the distribution of failure times is normal; otherwise an alternative approach is typically more efficient. Two alternative approaches to analyze failure times have been commonly utilized in the literature. The first assumes the distribution of failure times follows a Weibull density function, which implies the hazard rate changes monotonically over time.[9] The second uses a non-parametric proportional hazards model. While the proportional hazards model does not require the hazard function to be monotone, it can result in substantial efficiency losses (Lawless, 1982). Using a chi-square goodness-of-fit test we reject the hypothesis of normality distributed failure times in our database with a high degree of confidence. We report results based on both the Weibull regression model and the non-parametric regression approach in tables 3a and 3b.

For both models, the explanatory variables used to explain the length of time required to reach

[7] The reader may wonder if behavior in our asymmetric markets is influenced by equity concerns. If so, a design where agents know their costs, and not their rivals, would yield qualitatively different behavior. In a longer version of this paper, available on request, we show that the asymmetric behavior we report here is virtually unaffected by the absence of information.

[8] We say equilibrium has occurred in the period when, for all subsequent periods and including the last three periods of the experiment, the subject pairs' choices do not vary by more than two units. Experiments were terminated after two hours. In some cases this resulted in 35 periods, in the remaining cases data through period 40 are analyzed in the duration analysis.

[9] The Weibull model subsumes a third alternative, the exponential time-to-failure model. The exponential model is appropriate when the hazard rate is constant. This may be tested by comparing the shape parameter σ, discussed below, with 1. As the estimated value of σ in table 3b is significantly less than 1, we conclude that the exponential model is inappropriate.

TABLE 3.—TIME-TO-FAILURE REGRESSIONS

A. NON-PARAMETRIC PROPORTIONAL HAZARDS MODEL

Variable	Estimated Coefficient	Standard Error
LL	0.063	0.474
HH	0.910	0.406

$n = 65$ with 31 censored
chi-square significance level = 0.045

B. WEIBULL TIME-TO-FAILURE MODEL

Variable	Estimated Coefficient	Standard Error
ONE	−3.994	0.170
LL	0.055	0.253
HH	0.492	0.224
σ	0.514	0.053

$n = 65$ with 31 censored
chi-square significance level = 0.040.

equilibrium include *LL* and *HH*, dummy variables that equal 1 if the subject pair was in the associated treatment, and 0 otherwise. The Weibull model also includes a constant and a shape parameter, listed respectively as "one" and "σ" in table 3b.

An estimated coefficient which is significantly greater than zero indicates that increases in the associated explanatory variable lead to a greater probability of equilibrium in any period given equilibrium has not already occurred. The estimated coefficients on the variables *LL* and *HH* are positive in both regression models, indicating a greater hazard of equilibrium in the symmetric treatment than in the asymmetric treatment. The estimated value of σ in table 3b is 0.51, and is significantly less than one at the 0.01 level, indicating that the hazard rate is increasing over time.

The hypothesis of interest is that no significant differences in the time it takes subjects to reach equilibrium exist between the symmetric and asymmetric experiments. This may be tested using a likelihood-ratio test, comparing the unconstrained maximum likelihood value to the likelihood value which is induced by constraining the coefficients on both *LL* and *HH* to equal zero. For both regression models, the probability that both slope coefficients equal zero is less than 5%, and so we reject the null hypothesis. The conclusion is that asymmetric duopoly markets take longer to achieve an equilibrium than do symmetric markets in our experimental setting.

V. Concluding Remarks

The results of our experiments suggest that subjects in asymmetric experiments are significantly less cooperative than subjects in symmetric experiments. Since our subjects knew their opponents' outputs and the profits they could earn at various combinations, this result cannot be attributed to difficulties in identifying shirking on implicit agreements, as in Stigler (1964). Subjects in the asymmetric experiments simply found it more difficult to reach a cooperative equilibrium.

Our results provide two policy implications relevant to tightly-held oligopolies. First, markets whose firms have different cost or demand conditions are less likely to engender collusion than are markets whose firms face very similar demand or cost conditions; these asymmetries need not be large.[10] Second, welfare losses do not necessarily follow from variations in firm size: disparities between subjects' outputs were five to six units larger in the asymmetric experiments than in the symmetric experiments, on average, yet surplus was larger. This has implications for the interpretation of concentration, since it indicates that variations in firm size need not lead larger firms to ruthlessly exploit any power this connotes.[11]

While it is widely recognized that horizontal mergers increase concentration, which can facilitate cooperation, we argue that horizontal mergers can have anticompetitive consequences for other reasons. Our experimental results indicate that horizontal mergers which foster symmetry may also increase the likelihood of cooperation.

[10] One may easily calculate the Herfindahl index at the Cournot equilibrium as 5200 for the asymmetric design; in the symmetric design the corresponding value is 5000. Interestingly, over the final 5 choice periods the average value of the Herfindahl index was 5189 for the asymmetric sessions, and 5031 for the symmetric sessions.

[11] In comparing surplus between designs, one must also bear in mind that industry costs increase as one or both subjects are confronted with the high-cost payoff table. One way to account for this is to compare the surplus in our sessions to the potential maximum surplus which would obtain at the non-cooperative level. But this is of course equivalent to identifying the design whose market output is the largest fraction of the Cournot output, and in our experiments this is the asymmetric design. Correspondingly, one might argue that relative to its potential, asymmetric markets are more efficient than symmetric markets. We argue that our results support a conjecture that asymmetries do not lead to inefficiencies.

Asymmetry is currently regarded as a positive but highly subjective attribute of market structures by the Department of Justice (DOJ) and Federal Trade Commission. The DOJ's 1984 Merger Guidelines recognize that as products become more heterogeneous collusion becomes "more complex." But market asymmetry does not play a concrete role in merger decisions because "there is neither an objective index of product variation nor an empirical basis for its use ...".[12] The Herfindahl Index (the sum of squared market shares) is the prominent measure of concentration used in markets where merger requests are made, and this index tends to penalize asymmetry. Consider a hypothetical triopoly, whose firms have market shares of 50%, 25%, and 25%. The Herfindahl index is 3750. The first firm could be larger because it has a cost advantage. If there are multi-plant economies of scale, and one of the smaller firms should merge with the largest, the index would rise by 67% to 6250, a substantial increase in concentration. Suppose instead that the two smaller firms proposed a merger; the Herfindahl would increase by 33% to 5000, indicating less of an increase in concentration. Some economists may even be in favor of such a merger because it gives the dominant firm a more forcible rival. But in our view the decreased asymmetry, combined with the increased concentration, works to increase cooperation in the market. Our results indicate that asymmetry is a powerful control on cooperative behavior in highly concentrated markets which should be preserved whenever possible.

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[12] See "Merger Guidelines Issued by Justice Department, June 14, 1984, and Accompanying Policy Statement," p. 5–6, Bureau of National Affairs (BNA) Daily Report to Executives, Special Supplement, June 16, 1984. We are grateful to an anonymous referee for pointing this reference out to us.

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