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To Commit or Not to Commit: Endogenous Timing in Experimental Duopoly Markets[1]

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In this paper we experimentally investigate the extended game with action commitment of Hamilton and Slutsky (1990, *Games Econ. Behavior* **2**, 29–46). In their duopoly game firms can choose their quantities in one of two periods before the market clears. If a firm commits to a quantity in period 1, it does not know whether the other firm also commits early. By waiting until period 2, a firm can observe the other firm's period-1 action. Hamilton and Slutsky predicted the emergence of endogenous Stackelberg leadership. Our data, however, do not confirm the theory. While Stackelberg equilibria are extremely rare, we often observe endogenous Cournot outcomes and sometimes collusive play. This is partly driven by the fact that endogenous Stackelberg followers learn to behave in a reciprocal fashion over time, i.e., they learn to reward cooperation and to punish exploitation. *Journal of Economic Literature* Classification Numbers: C72, C92, D43. © 2002 Elsevier Science

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1. INTRODUCTION

Starting with papers by Saloner (1987), Hamilton and Slutsky (1990), and Robson (1990), there has been a growing literature studying models of endogenous timing in oligopoly. These papers analyze extended timing games which establish conditions under which firms are likely to play either a simultaneous-move game or a sequential-move game. The order of output or price decisions is not exogenously specified. Rather, it is derived from firms' decisions about timing. Results from this literature may indicate whether models of simultaneous output or price decisions (Cournot, Bertrand) or sequential decisions (Stackelberg, price leadership) are preferable.

The games used to determine endogenous timing have, in principle, a simple structure. In Hamilton and Slutsky's (1990) (henceforth HS) extended game with action commitment, two firms may choose their action in one of two periods. A firm may move first by committing to an action or it may wait until the second period and observe the other firm's first period action. This extended timing game allows, a priori, for simultaneous-move outcomes as well as for sequential-move outcomes.

What are the equilibrium predictions of the extended game with action commitment? HS showed that—if equilibria in weakly dominated strategies are dismissed—only sequential-move structures emerge endogenously. With price competition, this result is not surprising as the outcome of the sequential-move price leader game Pareto dominates the outcome of the simultaneous-move Bertrand game. However, the same result also holds with quantity competition where the Stackelberg leader is better off than a firm in Cournot equilibrium while the Stackelberg follower is worse off compared to Cournot. There are two endogenous Stackelberg equilibria with either firm as the Stackelberg leader.[3] While there exists a simultaneous-move Cournot equilibrium in pure strategies, this equilibrium is in weakly dominated strategies.

In closely related timing games with Cournot competition, Ellingsen (1995) (extending Saloner's (1987) model) and Robson (1990) came to the same conclusion in the sense that only Stackelberg equilibria emerge endogenously.[4] Ellingsen (1995, p. 87) argued that "only Stackelberg

[3]Matsumura (1999) showed that this general conclusion does not hold in Cournot oligopolies with more than two firms and with more than two production periods. In an n-firm oligopoly playing HS's game with action commitment, at least $n-1$ firms choose the first production period endogenously. The generalized Stackelberg equilibrium in which each firm chooses a different production period never occurs except in duopoly.

[4]In Saloner's model, firms may produce their quantities in *both* periods. Robson's analysis is restricted to linear demand and cost. Moreover, he has an interest rate on production in the first period.

points survive." Similarly, Robson (1990, p. 70) concluded that an "argument in favor of Stackelberg at the expense of Cournot can be made forcefully." While firms are symmetric in these models, Stackelberg equilibria also emerge endogenously when firms are asymmetrically informed: again, only Stackelberg equilibria with either the informed or the uninformed firm moving first emerge (see Mailath, 1993, and Normann, 1997). Note that, in all the papers mentioned, the general theoretical support for Stackelberg equilibria crucially depends on equilibrium selection arguments. Simultaneous-move Cournot equilibria in pure strategies typically exist[5]—however, they do not survive the application of equilibrium refinements.

In this paper, we report on an experiment designed to test the HS model with action commitment. We analyze a market with two symmetric firms and with quantity competition. In particular, we check whether there is experimental evidence for endogenous Stackelberg equilibria—or whether some other (if any) equilibrium is selected by subjects.

There are two reasons to assume that the general theoretical evidence for Stackelberg equilibria is not likely to find definite support in experimental markets. First, most of the literature has ignored the coordination problem firms face in a duopoly with endogenous timing.[6] There exist *two* Stackelberg equilibria, and either firm may emerge as the Stackelberg leader. A priori, there is no reason why one equilibrium is preferable to the other. In an experimental market, severe coordination problems may arise.

The second reason makes the first one more forceful. Since firms are symmetric it is, from a behavioral perspective, difficult to see how players should always coordinate on an asymmetric equilibrium with large payoff differences. It is well known from the ultimatum bargaining literature (Güth *et al.*, 1982) that many subjects exhibit an aversion to disadvantageous inequality in experiments. On top of the coordination problem, this inequality aversion might render the Stackelberg equilibria unappealing candidates for convergence in an experiment.

In a companion paper (Huck *et al.*, 2001; henceforth HMN), we studied Stackelberg duopoly with exogenous Stackelberg leader and follower roles. We found that followers often punish Stackelberg leaders who try to exploit their first-mover advantage. Given the empirical response function of the followers (which differs substantially from the prediction), Stackelberg

[5] A simultaneous move Cournot equilibrium also exists in Robson (1990) if the interest rate on first-period production is equal to zero.

[6] A notable exception is van Damme and Hurkens (1999), who analyzed the HS extended game with action commitment in the presence of cost differences. Also their model has two pure strategy Stackelberg equilibria. However, by applying the tracing procedure (Harsanyi and Selten, 1988), a unique Stackelberg equilibrium with the efficient firm as the Stackelberg leader is selected.

leaders would be much better off producing less than prescribed by the subgame-perfect equilibrium. The parameters of the model and the experimental design underlying the experiment to be reported in this paper are the same as in HMN. The experiments in HMN also include some sessions with simultaneous-move Cournot duopolies. We shall therefore sometimes compare the results of HMN with Stackelberg and Cournot competition to the present study of endogenous timing.

The remainder of the paper is organized as follows. Section 2 discusses the theoretical background and introduces the market used in the experiment. Section 3 illustrates the experimental procedures. Sections 4 and 5 present the experimental results, and Section 6 concludes.

2. THEORETICAL BACKGROUND

Let us repeat the setup of HS's extended game with action commitment. This game modifies the standard duopoly model by allowing for two production periods before the market clears. Firms can choose their quantities in one of the two periods, $t = 1, 2$. A firm can move in period 1 by committing itself to a quantity—without knowing what its competitor is doing. By waiting until period 2, a firm can observe the other firm's period-1 quantity (or its decision to wait). It is assumed that the market for the homogeneous good exists only at period 2 and that production costs do not depend on the production period.

Concerning the basic market game, HS rely on a number of rather general assumptions. They assume that there is, under both simultaneous and sequential play, a unique equilibrium in pure strategies and that these two equilibria differ from each other. Further, they assume that the strategy sets are compact, convex intervals of $\mathbb{R}^+$.

A strategy of firm i in the game can be described by the triple $(q_i^1, f_i(q_j^1), q_i^2)$, where q_i^1 either specifies an output for period 1 or indicates that the firm waits, i.e., $q_i^1 \in Q \cup \{W\}$ with Q being the set of possible outputs and W indicating the decision to wait. The function $f(q_j^1)$ is a mapping $Q \rightarrow Q$ specifying the firm's reaction in case it has decided to wait while the other firm has chosen $q_j^1 \neq W$. Finally, q_i^2 specifies firm i's quantity decision for the case where both firms have decided to wait.

The analysis of the extended game focuses on subgame-perfect equilibria. Subgame perfection requires that $f_i(q_j^1)$ is the standard best-reply function of a firm i facing firm j's quantity q_j^1 on the basic market. Furthermore, subgame perfection requires that q_i^2 be the Cournot-equilibrium quantity of the basic market game. In the following, we will often simplify notation and we will characterize equilibria only by the actions taken.

HS identify three (subgame-perfect) equilibria in pure strategies: the two Stackelberg equilibria in which one firm commits in period 1 to its Stackelberg leader quantity and the other firm waits and reacts with the Stackelberg follower quantity. The third equilibrium has both firms producing the simultaneous play Cournot equilibrium quantities in period 1.

In our experiment we used the linear inverse demand function

$$p(q_1 + q_2) = \max\{30 - (q_1 + q_2), 0\}. \tag{1}$$

Linear costs of production in both periods were given by

$$C_i(q_i) = 6q_i, \qquad i = 1, 2. \tag{2}$$

For this specification, the HS predictions are as follows. In the two Stackelberg equilibria the Stackelberg leader chooses $q_i^L = 12$ in period 1, whereas the Stackelberg follower chooses $q_j^F = 6$ in period 2. This implies payoffs of $\Pi_i^L = 72$ and $\Pi_j^F = 36$ ($i, j = 1, 2$; $i \neq j$) respectively.[7] The simultaneous-move Cournot equilibrium actions are $q_i = 8$ resulting in payoffs of $\Pi_i = 64$ ($i = 1, 2$), whereas the symmetric joint profit maximizing outputs are $q_i = 6$, implying payoffs of $\Pi_i = 72$ ($i = 1, 2$).

In our experiment subjects had to choose their quantities from a truncated and discretized strategy space, yielding a standard payoff bimatrix. We had two versions—one with a large payoff matrix where subjects had to choose integer quantities between 3 and 15 and one with a smaller strategy space. In the second version subjects could only choose among the quantities 6, 8, and 12. We refer to the first version as the one with a "large payoff matrix" and to the second as the one with a "small payoff matrix." For the rest of this section, we shall only discuss the large matrix. We will come back to the theoretical predictions for the sessions with the small matrix in Section 5.

The truncated and discretized strategy space is an important difference compared to HS's modelling assumptions. First, discretized Cournot matrix games derived from linear demand and cost may exhibit multiple Nash equilibria (see Holt, 1985). To avoid such multiplicity of equilibria, the entries in the payoff table differed slightly from those implied by Eqs. (1) and (2) (see Appendix Table A.I).[8] As a consequence, best replies are unique in the basic game and there is one simultaneous-move Cournot equilibrium and two sequential-move Stackelberg equilibria in the extended game, namely the equilibria mentioned above.

[7]As pointed out by Bagwell (1995), the theoretical prediction of the Stackelberg outcome crucially depends on the perfect observability of the Stackelberg leader's action. For experimental evidence on this point see Huck and Müller (2000).

[8]We subtracted 1 profit unit (Taler) in 14 of the $2 \times 169 = 338$ entries to ensure uniqueness of the best replies.

TABLE I
Truncation of the Extended Game (Large Matrix)

	10	11	12	W
10	40 40	33 30	24 20	49 70
11	30 33	22 22	12 11	42 66
12	20 24	11 12	0 0	36 72
W	70 49	66 42	72 36	64 64

The discretized strategy space has a second consequence: there exists a variety of mixed strategy equilibria for the setup we have chosen.[9] As HS require equilibria not to be in weakly dominated strategies, we focus on mixed equilibria with this property. More specifically, we analyze the truncation of the extended game, in which the function f_i denotes standard best-response functions and in which q_i^2 is the Cournot equilibrium quantity 8 (see above). In this truncated game (in which the strategy sets are simply given by $\{3, 4, \ldots, 14, 15, W\}$) the strategies 3, 4, 5, 13, 14, and 15 are strictly dominated. Among the remaining strategies, the quantities 6, 7, 8, and 9 are weakly dominated by the wait strategy W. This leaves us with the set $\{10, 11, 12, W\}$. Thus, we can focus on the 4×4 game depicted in Table I. It is easy to verify that this 4×4 game has only one symmetric mixed equilibrium in which both players choose to wait with probability 3/5 and produce quantity 10 with the complimentary probability 2/5. We refer to this equilibrium as the mixed Stackelberg equilibrium.

Summarizing, there are three Stackelberg equilibria in undominated strategies in our experiment: the two asymmetric Stackelberg equilibria in pure strategies and the symmetric mixed equilibrium in which firms commit themselves to $q = 10$ with probability $p = 2/5$ and wait with probability $1 - p = 3/5$. Furthermore, there is one pure equilibrium in weakly dominated strategies, namely the Cournot equilibrium in which both players choose quantity 8 in period 1, and there is also a variety of mixed strategy equilibria in weakly dominated strategies.

[9]With linear demand and cost, and with a continuous action space, no mixed equilibrium exists in which firms mix over committing to exactly one quantity in $t = 1$ and waiting. See HS and van Damme and Hurkens (1999).

3. EXPERIMENTAL PROCEDURES

The computerized experiment[10] was conducted at Humboldt University in November 1998. Ten subjects participated in the three sessions with the large matrix, each consisting of 30 rounds.[11] Additionally, we ran four 10-round sessions using the small payoff matrix. In each of these sessions there were also 10 participants. Thus, altogether 70 subjects participated in the experiment. They were students from various fields, mainly from economics, business administration, and law.[12] The sessions with the large matrix lasted about 90 minutes; the sessions with the small matrix lasted about 50 minutes.

In the instructions (see the Appendix) subjects were told that they would act as a firm which, together with another firm, serves one market, and that in each round both were to choose when and how much to produce. In all sessions subjects were informed that in each round pairs of participants would be randomly matched.[13] After having read the instructions participants could privately ask the experimenters questions.

Subjects were informed that, at the end of the experiment, 3 of the 30 rounds (large matrix) would be randomly selected to determine the actual monetary profit in German marks. The numbers given in the payoff tables were measured in a fictitious currency unit called Taler. The monetary payment was computed by using an exchange rate of 10:1 and adding a flat payment of DM 5.[14] (In the sessions with the small payoff matrix (see below) 2 out of 10 rounds were randomly selected to determine real payment.) Subjects' average earnings were DM 20.60 ($11.44 at the time) in the 30-round sessions and DM 17.22 ($9.57) in the 10-round sessions (including the flat payment).

In the sessions with the large payoff matrix, before the first round was started subjects were asked to answer two control questions (which were

[10]We are grateful to Urs Fischbacher for letting us use his software toolbox "z-Tree" (Fischbacher, 1999).

[11]In one of these sessions, only the results up to round 29 were saved. After the play of round 30 of this session the network broke down so that the results of the last round were not saved.

[12]Subjects were either randomly recruited from a pool of potential participants or invited by leaflets distributed around the university campus.

[13]We think that randomly matched duopoly pairs, rather than fixed pairs, are appropriate when testing the predictions of the HS model. In HMN (with exogenous timing), the sessions with fixed duopoly pairs were considerably collusive, particularly in the simultaneous-move treatment. Even when firms moved sequentially à la Stackelberg there was some collusion. It is doubtful whether, with fixed pairs and with endogenous timing, less collusion would be observed.

[14]This payment was made since subjects could have made losses in the game.

checked) to make sure that everybody had full understanding of the payoff table. After each round (with both small and large matrix) subjects got individual feedback about what happened in their market, i.e., the computer screen showed the production period, the quantity, and the profit of both duopolists.

4. EXPERIMENTAL RESULTS (LARGE MATRIX)

The results of sessions with the large matrix are reported in three subsections. Section 4.1 presents aggregate results. Group effects are examined in Section 4.2 and individual behavior is explored in Section 4.3. We will concentrate on preemptive commitments in the first period of a round, on the reaction of endogenous Stackelberg followers, on the behavior of two waiting firms deciding simultaneously in the second period, and on overall market outcomes. As mentioned in the introduction, in HMN we investigated Stackelberg and Cournot duopoly markets in which roles were exogenously fixed. In these experiments, 10 successive rounds were played using the same payoff matrix and the same experimental design—except that these experiments were run with pen and paper. Whenever useful we will compare the results of the current experiment with the results of HMN.

4.1. *Aggregate Data*

Table II presents a summary of experimental results on an aggregate level. Table II also shows the results of the Stackelberg and Cournot markets with random matching as observed in HMN. Inspection of Table II reveals that in the endogenous-timing sessions in 543 out of 890 cases (61%)

TABLE II
Aggregate Results

	In period 1	Explicit followers	Both firms in period 2	Total
Average quantity	9.15	8.39	8.40	17.70
Standard deviation	1.91	1.75	1.67	1.93
Number of observations	543	207	140	890
HMN average quantity	10.19[a]	8.32[a]	8.07[b]	18.51[a]/16.14[b]
Standard deviation	2.45	2.07	1.61	2.86/3.21
Number of observations	220	220	240	220/240

[a]Stackelberg market.
[b]Cournot market.

subjects committed themselves in period 1. In the remaining cases, subjects decided to wait.

When committing themselves in $t = 1$, subjects chose on average about one unit less than in the Stackelberg experiment with exogenous timing. Since subjects who endogenously got into the position of a Stackelberg follower chose about the same quantity as exogenous Stackelberg followers, the differences between total quantities in the two versions (17.70 vs. 18.51) seem to be entirely due to the fact that exogenous Stackelberg leaders committed to higher quantities. Note, furthermore, that the average quantity chosen in markets in which decisions were made simultaneously in the second period are slightly higher than in the Cournot duopolies in HMN (8.40 vs. 8.07).

Behavior in the First Period. To illustrate first-period behavior, Fig. 1 shows absolute frequencies (across all sessions) of quantities chosen in the first period of a round. In the left panel of Fig. 1 these frequencies are shown separately for the first (rounds 1–15) and the second half (rounds 16–30) of the experiment. The right panel of Fig. 1 shows absolute frequencies for all rounds of the experiment. First of all, recall that choosing quantities of 3, 4, 5, 13, 14, and 15 is a strictly dominated action in the two-stage quantity commitment game. According to Fig. 1, these quantities are rarely chosen in the first period. Altogether, choices in the first period are quite dispersed over the range of quantities from 6 to 12. The Stackelberg leader action, 12, was chosen in only 53 out of 543 cases (9.8%). Instead, we observe that the quantities 8 and 10 were chosen most often. This is true with respect to both the first and the second half of the experiment (#8 = 142 (26.2%); #10 = 139 (25.6%)). Moreover, whereas the absolute frequencies with which quantities 8, 10, and 12 were chosen remain rather constant over the two halves, this is not true for quantities 6, 7, 9, and 11. Here we observe that quantities of 9 and 11 were chosen less often in the second half, whereas quantities of 6 and 7 were chosen more often in the second half of the experiment. In fact, the frequency of choosing quantities 6 and 7 increases from 9.9% in the first half to 24.4% in the second. Thus behavior becomes more cooperative over time. Regarding the high frequency of $q = 10$, recall that playing this quantity in the first period is part of the symmetric mixed-strategy equilibrium in undominated strategies.

Behavior of Endogenous Stackelberg Followers. Figure 2 shows best responses as well as average observed responses of endogenous Stackelberg followers. Additionally, it shows average responses of exogenous Stackelberg followers as observed in HMN. The empirical response function of exogenous Stackelberg followers virtually coincides with the theoretical best-response function as long as the Stackelberg leader's quantity is smaller

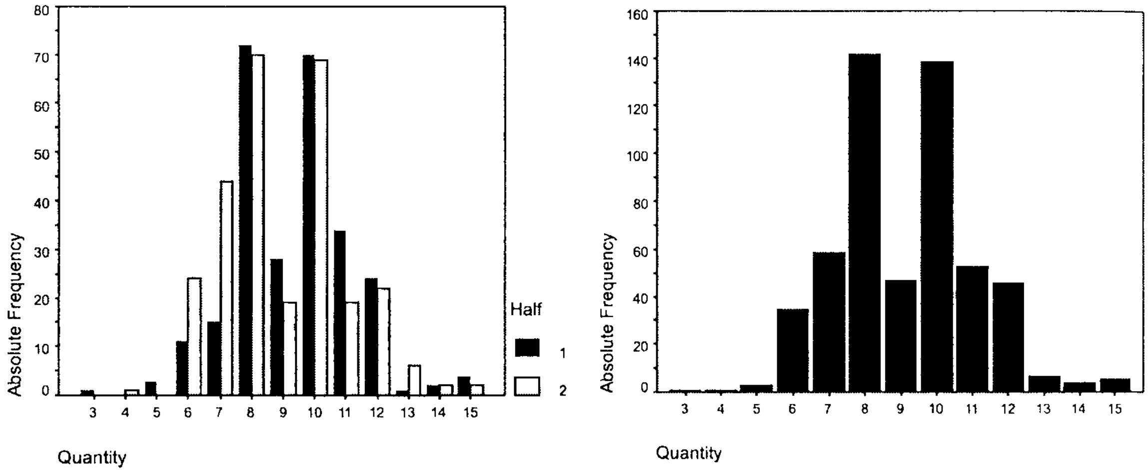

FIG. 1. Absolute frequencies of quantities chosen in the first period in the first (rounds 1–15) and second half (rounds 16–30) (left) and for all rounds (right).)

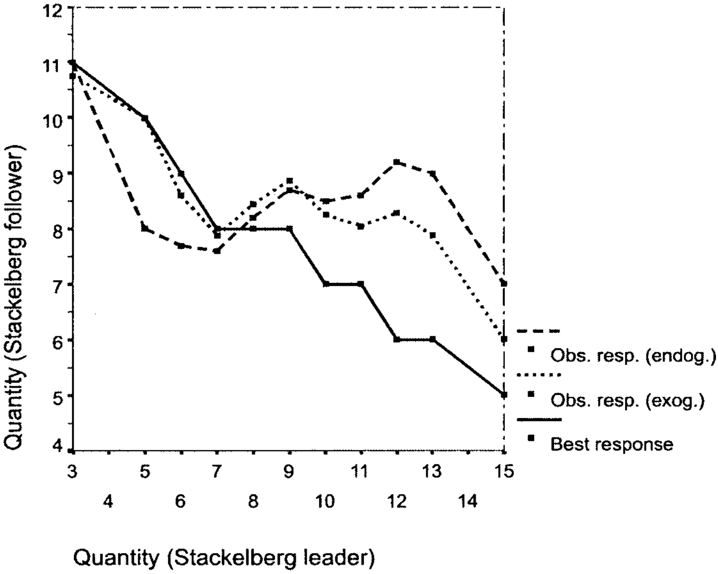

FIG. 2. Best- and observed response functions of Stackelberg followers.

than or equal to 7. However, exogenous Stackelberg followers as reported in HMN produce on average more than 1 unit more than prescribed by the best-response function if Stackelberg leaders produce more than 7 units. The endogenous Stackelberg followers in this experiment behaved according to the following empirical response function. We first observe that, for $q^L < 7$, the average responses are below the observed responses of exogenous followers. For $7 \leq q^L \leq 9$, the behavior of exogenous and endogenous Stackelberg followers almost coincides. Finally, for $q^L > 9$, endogenous Stackelberg followers produce actually more. Thus one clearly sees that (i) endogenous Stackelberg followers reward cooperation more often and (ii) endogenous Stackelberg followers punish harder than exogenous followers if Stackelberg leaders commit to high outputs.

The best-reply function is given by $q^F = 12 - 0.5q^L$ (for continuous actions).[15] Estimating the followers' actual response function by a simple linear regression model for the endogenous timing experiment, we get $q^F = 6.98 + 0.154q^L$ (for a more complex regression, see the next subsection). Surprisingly, the response function is upward sloping. It is even more interesting to look at the response function for the first half of the experiment and the second half of the experiment separately. For the first half

[15] A linear regression estimation of the best-reply function for the discretized game yields $q^F = 12.1 - 0.49q^L$.

(rounds 1–15) we get $q^F = 9.596 - 0.149q^L$, whereas for the second half (rounds 16–30) of the experiment we get $q^F = 4.59 + 0.442q^L$. The striking result is that, over time, the empirical response function clearly moves away from the best-response function. In the second half, the reward-for-cooperation-and-punishment-for-exploitation scheme that second movers apply becomes more pronounced, which probably explains the higher frequency of collusive choices taken in the first period (see above).

Behavior in Case of Simultaneous Decisions in the Second Period. When deciding simultaneously in the second period, subjects play a standard Cournot game. The average quantity chosen is 8.40 with a standard deviation of 1.67. This does not vary significantly across the first and second halves (8.30 (1.88) and 8.55 (1.91)). The average quantity is slightly larger than the observed average in the simultaneous-move Cournot duopolies of HMN.

Market Outcomes. We shall distinguish between *rational* outcomes and *boundedly rational* outcomes. Table III shows absolute and relative frequencies of outcomes classified along these lines. We define rational outcomes as outcomes which stem from strategies which are either part of one of the pure equilibria or part of the mixed equilibrium in undominated strategies (these are the quantities 8, 10, or 12 in $t = 1$ or opt to wait, and in which they play best replies in $t = 2$.) Playing rational strategies might lead to an equilibrium, but coordination failures can also occur, e.g., both firms could play Stackelberg leader (that is, engage in Stackelberg warfare) or one firm could play Cournot in $t = 1$ while the other plays Stackelberg leader. We refer to collusive strategies (i.e., to produce 6 or 7 in either period) and to punishment strategies of followers (i.e., to produce strictly more than

TABLE III
Number of Outcomes (Large Matrix)

Market outcome	Type	Number of cases	Number of cases incl. quant. 9 and 11
Cournot	Equilibrium	64 (14.4%)	93 (20.9%)
Stackelberg	Equilibrium	24 (5.4%)	33 (7.4%)
Stackelberg/Cournot	Coord. failure	27 (6.1%)	41 (9.2%)
Stackelberg warfare	Coord. failure	21 (4.7%)	30 (6.7%)
Stackelberg punished	Rational/bound.	43 (9.7%)	55 (12.4%)
Collusion (successful)	Boundedly rational	25 (5.6%)	25 (5.6%)
Collusion (exploited)	Bound./rational	19 (4.3%)	19 (4.3%)
Collusion (failed)	Bound./rational	34 (7.6%)	41 (9.2%)
Others		188 (42.2%)	108 (24.3%)
Sum		445 (100%)	445 (100%)

TABLE IV
Average Earnings of Actions in Period $t = 1$ (Large Matrix)

6	7	8	9	10	11	12	W
54.97	58.49	59.42	56.63	52.24	44.00	32.53	53.54

the best reply in $t = 2$) as boundedly rational strategies. Collusion may be successful, it may be exploited in $t = 2$, or it may fail when one firm plays 6 or 7 in $t = 1$ while the second firm plays Cournot or Stackelberg leader in $t = 1$. Among the remaining strategies (3, 4, 5, 9, 11, 13, 14, and 15), only 9 and 11 are chosen frequently. It is not very surprising that subjects choose 9 and 11 more often than, say, 3 or 14 since it seems reasonable to assume that subjects are more likely to choose nonequilibrium actions that are close to equilibrium actions (Simon and Stinchcombe, 1995). For this reason, we also report the results (in parentheses) when 9 and 11 are viewed as quasiequilibrium strategies. Somewhat arbitrarily, we count 9 as a Cournot action and 11 as a Stackelberg leader action.

Out of 445 outcomes, 257 (337) can be classified in our scheme. The remaining 188 (108) outcomes involve the choice of a dominated strategy or a nonbest reply in $t = 2$ not punishing the Stackelberg leader. The most striking fact is that Stackelberg equilibria occur only rarely (24 (33) outcomes or 5.4% (7.4%)). A subject who commits itself in $t = 1$ faces the risk of a coordination failure (48 (71) cases) or of being punished (43 (55) cases). Even successful collusion occurs more often than a Stackelberg equilibrium. However, the collusive strategies are likely to be exploited or to fail coordination.

The Cournot equilibrium is the most frequent outcome (64 (93) cases). Playing Cournot is also (ex post) the most successful strategy across all sessions; in contrast to playing Stackelberg leader, it is not punished by followers in $t = 2$ and, when it clashes with a collusive firm in $t = 1$, it yields a profit at least as high as the (equilibrium) payoff of a Stackelberg leader. Table IV contains the average earnings certain actions chosen in the first period yield. Playing a Stackelberg leader action (10, (11), 12) yields a profit strictly worse than the collusive strategies. The fact that the wait strategy does worse than any quantity in $t = 1$ smaller than 10 is explained by the high costs Stackelberg followers inflicted on themselves by punishing Stackelberg leaders committed to high outputs.

4.2. *Group effects*

In this subsection we will briefly examine group effects by looking at the results for each of the sessions separately. Figure 3 shows absolute frequencies of quantities chosen in earlier and later rounds of each session. We also estimated, separately for the three sessions and for the pooled data,

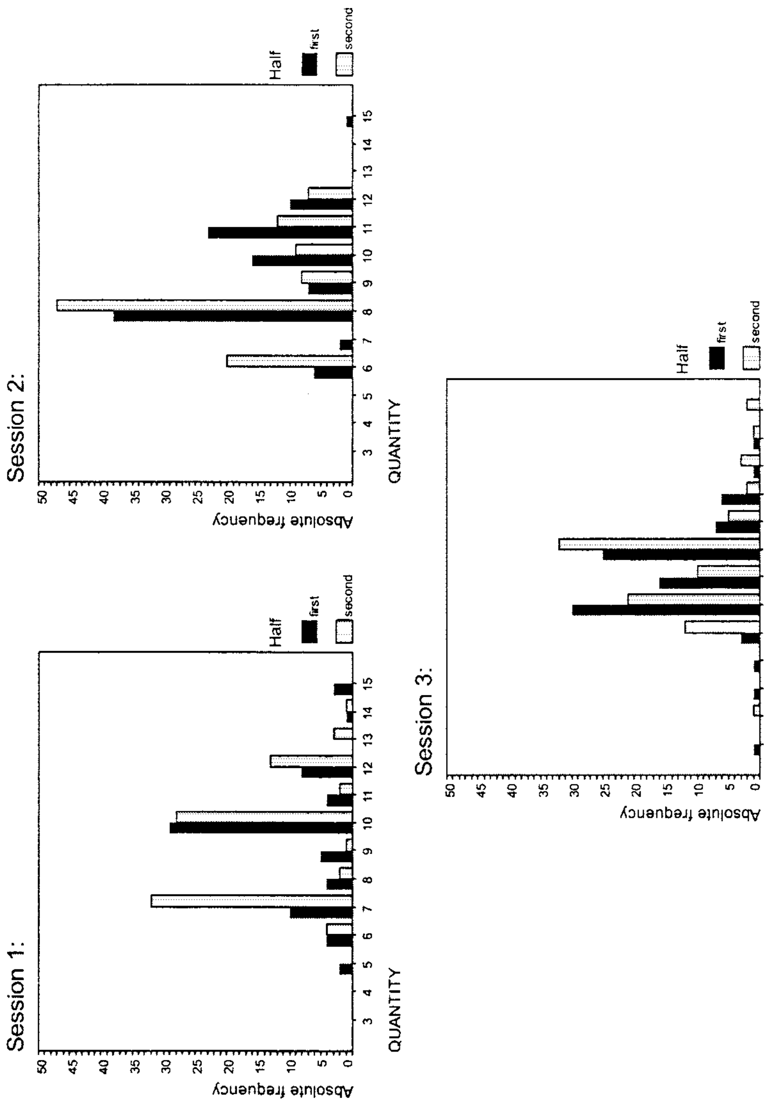

FIG. 3. Absolute frequencies of quantities chosen in the first period in the first and second halves for each session with large payoff matrix.

TABLE V
Regression Results (Estimating Equation: $q^F = \beta_0 + \beta_1 q^L + \beta_2 \text{Half} + \beta_3 \text{Half} * q^L + \epsilon$)

	β_0	β_1	β_2	β_3
Session 1	8.46**	−0.05	−5.52**	0.70**
	(6.89)	(−0.43)	(−3.31)	(3.93)
Session 2	8.41**	0.00	−5.57*	0.70**
	(4.11)	(−0.01)	(−2.21)	(2.62)
Session 3	11.73**	−0.38**	−3.38*	0.36*
	(10.27)	(−3.06)	(−2.04)	(2.00)
Pooled data	9.60**	−0.15	−5.01**	0.59**
	(11.63)	(1.72)	(4.48)	(4.95)

Note: ** and * denote significant at the 1% and 5% levels respectively. Absolute value of asymptotic t-statistics are given in parentheses.

the simple regression model given in Table V. The dependent variable in the equation given in Table V is the observed quantity, q^F, of followers. The two explanatory variables included are the quantity of Stackelberg leaders, q^L, and a dummy, Half, representing the first (respectively, second) half of the session. The dummy was introduced to control for experience effects. It turns out that behavior is quite different across sessions.

In session 1, the quantities 7 and 10 were chosen most often, whereas the Cournot quantity of 8 was rarely chosen. Comparing behavior in the two halves of this session, the most striking result is that quantity 7 was chosen more than twice as often in the second half than in the first half. Thus there is a clear shift toward more cooperative behavior. Inspecting Table V, we find that followers chose a rather flat response function in the first half. They played more or less the Cournot quantity regardless of what Stackelberg leaders did. So, it seems that followers tried to induce Stackelberg leaders to play Cournot. (After all, the best reply to such a response strategy is playing Cournot!) In the second half, the response function is upward sloping and has a smaller intercept. As we have seen on the aggregate level, endogenous followers learn to behave in a reciprocal fashion. In turn, this is learned by endogenous Stackelberg leaders who choose more collusive actions in the second half.

Next, consider session 2. In contrast to session 1, we observe that the quantity 7 was chosen only twice whereas the Cournot quantity 8 is the one that was chosen most often. We also observe that the frequency with which quantity 6 was chosen clearly increases from the first to the second half. Note, furthermore, that quantities smaller than 6 or larger than 12 were virtually never chosen during the course of this session. Regarding followers' behavior, session 2 is virtually identical to session 1. As in session 1, followers start by playing Cournot (regardless of the Stackelberg leader's choice) and then shift to an upward sloping response function.

Finally, consider session 3. Whereas the collusive quantity 6 was chosen only once, we observe that quantities 8 and 10 were chosen most often. Interestingly, the number of choices of quantity 8 decreases whereas the number of choices of quantity 10 increases from the first to the second half of the experiment. With respect to followers, we find that they start with a response function very "close" to the rational one. However, they change their behavior in the second half where their response function is similar to those of followers in the first halves of sessions 1 and 2: it is more or less flat and prescribes the Cournot quantity. It would have been interesting to see whether this process would have continued if there had been more rounds of play. In any case, the more aggressive behavior of Stackelberg leaders in session 3 can be explained by the more rational response function of followers in the first half and the less reciprocal one in the second.

4.3. *Individual Behavior*

An interesting question is whether behavior converged on the individual level. Do some subjects always commit themselves? If so, which quantity do they play? Are there pure followers, possibly playing best reply? More specifically, we searched for subjects who had chosen the same production period in at least 25 of the 30 periods. There were not too many: Five subjects almost always committed themselves and three subjects almost always waited until $t = 2$. The behavior of these subjects is quite telling.

The five subjects almost always committing cannot generally be classified as pure Stackelberg leaders. One subject produced a quantity of 6 in 28 out of 30 rounds. This subject is thus a pure collusive player. A second subject produced a quantity of 8 in 22 out of 28 rounds in which he or she committed in $t = 1$ (average quantity produced in $t = 1$ was 8.23)—a Cournot player. A third subject must also be classified as a Cournot player (average quantity 8.38), though this person also experimented with the quantities 7 and 10. Another subject chose 12 in 15 out of 30 rounds and 8 in the remaining rounds. In accordance with our aggregate and group data, this person played 12 in the beginning and, apparently being discouraged, played exclusively 8 over the last 10 rounds. Only one subject may be classified as a Stackelberg leader (average quantity: 10.00), but even this subject occasionally produced 8 in $t = 1$. He or she started with producing 12, but then reduced the output to 10 or 8 over the last third of the experiment.

The behavior of the subjects who almost always waited is strikingly homogenous. Looking at the periods in which they actually became

Stackelberg followers, they played *tit-for-tat* to a very large extent. One subject strictly played *tit-for-tat*. That is, this person produced exactly the same quantity as the Stackelberg leader in every period except one. A second subject very often did so, though occasionally punishing Stackelberg leaders even more severely than plain tit-for-tat would have prescribed. The third subject played tit-for-tat in each of the last 14 rounds of the experiment (and occasionally earlier on).

4.4. *Discussion*

In this subsection we summarize the main results of the experiments with the large payoff matrix and discuss their implications. In view of the theory we embarked on testing, the most important result is the following:

Result 1. HS's prediction fails. Endogenous Stackelberg equilibria are extremely rare and their frequency does not increase with experience.

The next two results implicitly offer explanations for this.

Result 2. Subjects have problems in coordinating their actions. In roughly 25% of all cases, we find evidence of coordination failures.

Result 3. Endogenous Stackelberg followers exhibit an aversion to disadvantageous inequality. Over time they learn to employ reciprocal (upward sloping) response functions, rewarding cooperation and punishing exploitation.

As a consequence of this we find:

Result 4. The frequency of collusive outputs is increasing over time.

Finally, we note:

Result 5. Cournot equilibria are the most frequent outcomes.

In spite of these five results, it is difficult to offer a complete description of behavior. Although we can indicate some trends, we do not find convergence. Rather, behavior is quite dispersed, even when subjects have gained experience. Furthermore, it is not perfectly clear how to interpret some of the frequently chosen actions. For example, the choice of $q_i^1 = 10$ might be interpreted as a compromise between full exploitation of the theoretical first-mover advantage but it can also be seen as the outcome of mixed-equilibrium play. With strategies not in support of the equilibria we focused on, it is even harder to assess their precise meaning. As a consequence of this, we conducted four additional sessions with a smaller payoff matrix which are discussed in the following section.

TABLE VI
The Small Payoff Matrix

		Firm 2		
		6	8	12
Firm 1	6	72 (Firm 2: 72)	60 (Firm 2: 80)	36 (Firm 2: 72)
	8	80 (Firm 2: 60)	64 (Firm 2: 64)	32 (Firm 2: 48)
	12	72 (Firm 2: 36)	48 (Firm 2: 32)	0 (Firm 2: 0)

5. EXPERIMENTAL RESULTS (SMALL MATRIX)

In the sessions with the small payoff matrix, subjects had to choose their quantities from the set {6, 8, 12}. The reduced matrix in Table VI was the basis for these sessions.[16] The time horizon was reduced to 10 periods of which 2 periods were randomly selected to determine real payment. Everything else in the design remained unchanged. Concerning pure strategy equilibria, the equilibrium predictions with the small matrix are similar to those of the large matrix. However, there now exists a symmetric mixed equilibrium in which firms randomize over committing to 12 and waiting.[17] The equilibrium probability for a commitment is $p = 2/11$. As with the large matrix, the Cournot-like equilibria are in weakly dominated strategies.

Table VII presents a summary of experimental results at the aggregate level. We observe that, in 136 out of 400 cases (34%), subjects committed themselves in period 1. The proportion of committing firms is much smaller than that observed with the large matrix. Average outputs are slightly smaller compared to those observed with the large matrix.

Quantity choices are summarized in Table VIII, where behavior of the first 5 rounds is shown in the top row, rounds 6–10 are shown in the middle row, and all 10 rounds are at the bottom of the table. The table consists

[16] In the instructions, we actually labelled the strategies 6, 8, and 12 by 1, 2, and 3. The labels 6, 8, and 12 are meaningless for the subjects (recall that they did not know the demand and cost parameters of the model). Moreover, the difference between 8 and 12 is larger than the difference between 6 and 8. So the action 12 might appear to be a rather extreme choice to subjects and, hence, they might be biased against this action. To avoid confusion, here in the paper, we refer to quantities 6, 8, and 12.

[17] There exists also a continuum of mixed equilibria (in weakly dominated strategies) in which firms randomize over committing to quantity 8 in period 1 and the wait strategy.

TABLE VII
Aggregate Results

	In period 1	Explicit followers	Simult. dec. in period 2	Total
Average quantity	8.65	7.89	7.60	16.05
Standard deviation	2.24	1.22	1.21	1.64
Number of observations	136	94	170	200

of several 3×3 matrices. The left matrix shows quantity decisions for the case where both firms produce in period 1, the middle matrix shows output decisions in the case of endogenous Stackelberg leaders and followers, and the right matrix shows output combinations for the case where both

TABLE VIII
Summary of Experimental Results (Small Matrix)

First half (rounds 1–5)

$t = 1$ \ $t = 1$	6	8	12
6	1	1	2
8	—	2	4
12	—	—	0

$t = 1$ \ $t = 2$	6	8	12
6	1	11	1
8	1	17	0
12	6	6	0

$t = 2$ \ $t = 2$	6	8	12
6	6	20	0
8	—	18	3
12	—	—	0

Second half (rounds 6–10)

$t = 1$ \ $t = 1$	6	8	12
6	0	5	0
8	—	1	5
12	—	—	0

$t = 1$ \ $t = 2$	6	8	12
6	1	8	0
8	2	24	1
12	4	8	3

$t = 2$ \ $t = 2$	6	8	12
6	1	8	0
8	—	28	1
12	—	—	0

All rounds

$t = 1$ \ $t = 1$	6	8	12
6	1	6	2
8	—	3	9
12	—	—	0

$t = 1$ \ $t = 2$	6	8	12
6	2	19	1
8	3	41	1
12	10	14	3

$t = 2$ \ $t = 2$	6	8	12
6	7	28	0
8	—	46	4
12	—	—	0

Numbers of outcomes in the case of simultaneous decisions in period 1 (left), in the case of sequential decisions (middle), and in the case of simultaneous decision in period 2 (right).

TABLE IX
Number of Outcomes (Small Matrix)

Market outcome	Type	Frequency
Cournot	Equilibrium	90 (45%)
Stackelberg	Equilibrium	10 (5%)
Stackelberg/Cournot	Coord. failure	9 (4.5%)
Stackelberg warfare	Coord. failure	0 (0%)
Stackelberg Punished	Rational/bound.	17 (8.5%)
Collusion (succesful)	Boundedly rational	10 (5%)
Collusion (exploited)	Bound./rational	19 (9.5%)
Collusion (failed)	Bound./rational	36 (18%)
Others		9 (4.5%)
Sum		200 (100%)

firms produce in the second period. We find that endogenous Stackelberg followers punish harder in the second half of the experiment than in the first. However, in contrast to the results with the large matrix, positive reciprocity does not increase, i.e., followers almost always play best replies as long as endogenous Stackelberg leaders commit to quantities of 6 or 8. The best reply to both actions is to choose a quantity of 8. Average responses are fairly homogeneous across the two halves.

Table IX classifies the market outcomes according to the scheme we developed above. Note that, with the small payoff matrix, the classification of market outcomes is unique, since there are no actions which are close to the collusive, Cournot, or Stackelberg leader actions. With respect to our main question, the result is clear-cut. Endogenous Stackelberg equilibria occur even less frequently (5%) than with the large matrix. When players commit themselves in the first period, they choose the Cournot or the collusive action rather than the Stackelberg leader action. Thus, HS's prediction fails again, although the game is considerably less complex than before. The increased simplicity of the game has further effects: unclassifiable (not even boundedly rational) outcomes virtually disappear and coordination failure becomes less of an issue (4.5% vs. 15.8%). At the same time, Cournot outcomes become much more frequent (45% vs. 20.9%). The frequencies of successful and unsuccessful collusion are roughly similar to those in the large-matrix version.

We conclude the discussion of aggregate results with a look at ex post realized payoffs. The best first-period choice was to wait with an average ex post payoff of 62.62. The other actions 6, 8, and 12 yielded average payoffs of 59.25, 61.33, and 51.79, respectively. This explains why commitment in the first period is much rarer in the sessions with the small matrix than in the sessions discussed above (34.5% vs. 61%) where commitment paid more than waiting.

Behavior across the four sessions was quite homogenous in the treatment with the small matrix as there were only few significant group effects. Regarding choices made in the first period, average quantities chosen rise from the first to the second half in three of the four sessions (from 7.5 to 8.1 in session 1, from 8.0 to 8.9 in session 2, and from 8.9 to 9.1 in session 4)—although the groups started from different levels. Only in session 3, in which subjects commit to high quantities in the first half, does the average quantity decrease in the course of the experiment (from 10.1 to 9.2). Follower behavior is also quite homogenous. Average responses to quantities of 6 or 8 in each half of the four sessions deviate from 8, if at all, by at most 0.5 units. The only differences worth mentioning are due to reactions to the Stackelberg leader quantity of 12, to which the best response is to choose an output of 6. In sessions 1 and 2 endogenous Stackelberg leaders committing to quantity 12 in the first period are punished in both halves of these sessions (average response is 8.0). However, endogenous Stackelberg followers in sessions 3 and 4 react rather gently in the first half (6.7 vs. 7.0) whereas they punish much harder in the second half of the experiment (8.5 vs. 8.7).

We finally take a look at individual behavior. We selected subjects who either committed or waited in at least 9 of the 10 rounds. As the total number of commitments in $t = 1$ is smaller than with the large matrix, it is not surprising that we found fewer subjects almost always committing (3 out of 40) and more subjects almost always waiting (9). As with the large matrix, the subjects who committed themselves in $t = 1$ are by no means Stackelberg leaders. Instead, they have to be classified as Cournot players. One subject chose the Cournot quantity in $t = 1$ in 10 out of 10 rounds. A second subject chose a quantity of 8 in 8 of 10 rounds while attempting to collude in 2 rounds. The third subject produced the Stackelberg leader quantity in $t = 1$ twice, but, in 6 out of 9 commitments, he or she played Cournot, particularly over the second half of the experiment (average quantity 8.60). The behavior of the subjects who waited does not yield much insight because of the large proportion of Cournot outcomes at the aggregated level (45%). Occasionally, a Stackelberg leader was punished or an attempt to collude was exploited by these subjects. But most of the time, Cournot was answered by Cournot.

What can we conclude from these results? In our view, the most important aspect of the small-matrix data is that the failure of HS's theoretical predictions which we observed in the large game is not due to its complexity. Given the small amount of unclassifiable outcomes in the small-matrix game we can be sure that subjects understood the game well. Nevertheless, they did not play Stackelberg games. Furthermore, the failure of the theory cannot be exclusively attributed to the coordination problem. With the small matrix coordination failures are rare. Rather, it seems that subjects prefer symmetric Cournot outcomes to asymmetric outcomes.

6. CONCLUSION

Recent theoretical contributions have made forceful arguments supporting endogenous Stackelberg equilibria. The data of our experimental test show, however, that endogenous Stackelberg leadership does not occur to the degree theory predicts. The theoretical criterion to prefer pure-strategy equilibria in undominated strategies over other equilibria turns out to be of little behavioral importance. Rather, we see the emergence of Cournot outcomes and, sometimes, collusive outcomes.

An important driving force for this result is the behavior of endogenous Stackelberg followers who learn to behave in a reciprocal fashion over time. In games with an exogenous first-mover advantage, it is sometimes claimed that nonrational response functions of second movers are likely to disappear (or, at least, to become "more rational" when subjects have the opportunity to learn). Our data show that, when timing decisions are endogenous, the opposite may happen. To this extent the framework we studied here offers some hints about why the behavioral rule of reciprocity may have evolved. In our case, it helps subjects to resurrect initial symmetry.

Although our data refute HS's predictions, this does not imply that endogenous Stackelberg leadership is generally unlikely to arise. In all our sessions we focused on symmetric firms and introducing cost asymmetries (van Damme and Hurkens, 1999) could change the picture. However, an examination of this hypothesis requires a full-fledged study of its own. There are more options for future research. For example, we pointed out in the Introduction that endogenous price leadership might be more likely to be observed in a laboratory than endogenous Stackelberg leadership, as sequential decisions may increase the payoffs of both firms when their actions are prices.[18] This is an interesting hypothesis, to be tested in experimental research.

APPENDIX: LARGE-MATRIX EXPERIMENT

A.1. *Translated Instructions*

Welcome to our experiment! Please read these instructions carefully! Do not talk to your neighbors and keep quiet during the entire experiment. If you have any questions, give notice. We will answer them privately.

[18] For experimental evidence on sequential price competition in duopoly markets (with exogenous role assignment), see Kübler and Müller (2000).

TABLE A.1.
Payoff Table

	3	4	5	6	7	8	9	10	11	12	13	14	15
3	54 54	51 68	48 80	45 90	42 98	39 104	36 108	33 109	30 110	27 108	24 104	21 98	18 90
4	68 51	64 64	60 75	56 84	52 91	48 96	44 99	40 100	36 99	32 96	28 91	24 84	19 75
5	80 48	75 60	70 70	65 78	60 84	55 88	50 89	45 90	40 88	35 84	29 78	25 70	20 60
6	90 45	84 56	78 65	72 72	66 77	60 80	54 81	48 80	41 77	36 72	30 65	24 56	18 45
7	98 42	91 52	84 60	77 66	70 70	63 72	55 71	49 70	42 66	35 60	28 52	21 42	14 30
8	104 39	96 48	88 55	80 60	72 63	64 64	56 63	48 60	40 55	32 48	24 39	16 28	8 15
9	108 36	99 44	89 50	81 54	71 55	63 56	54 54	45 50	36 44	27 36	18 26	9 14	0 0
10	109 33	100 40	90 45	80 48	70 49	60 48	50 45	40 40	30 33	20 24	10 13	0 0	−10 −15
11	110 30	99 36	88 40	77 41	66 42	55 40	44 36	33 30	22 22	11 12	0 0	−11 −14	−22 −30
12	108 27	96 32	84 35	72 36	60 35	48 32	36 27	24 20	12 11	0 0	−12 −13	−24 −28	−36 −45
13	104 24	91 28	78 29	65 30	52 28	39 24	26 18	13 10	0 0	−13 −12	−26 −26	−39 −42	−52 −60
14	98 21	84 24	70 25	56 24	42 21	28 16	14 9	0 0	−14 −11	−28 −24	−42 −39	−56 −56	−70 −75
15	90 18	75 19	60 20	45 18	30 14	15 8	0 0	−15 −10	−30 −22	−45 −36	−60 −52	−75 −70	−90 −90

The head of the row represents one firm’s quantity and the head of the column represents the quantity of the other firm. Inside the box at which row and column intersect, one firm’s profit matching this combination of quantities stands up to the left and the other firm’s profit stands down to the right.

In our experiment you can earn different amounts of money, depending on your behavior and that of other participants matched with you. All participants read identical instructions.

You have the role of a firm which produces the same product as a second firm in the market. First you have to decide, at which time you want to produce. There are two possibilities: the first and the second production periods. Afterward, you decide on the quantity you want to produce.

If you choose the first production period, you decide about your production quantity immediately afterward. At this point in time you will not know how the other firm has decided about its production period. If the other firm has chosen the second production period, it will be informed about the amount you have chosen before it decides about its own quantity.

If you choose the second production period, you get the following information before you decide on your quantity: If the other firm has made a decision about its quantity on the first period of production, you will be informed about this quantity. If the other firm has also chosen the second production period, you will be informed about this.

Note that the profit in each round depends only on the chosen quantities, not on the choice of production periods.

In the accompanying payoff table (Table A.I), you can see the resulting profits of both firms for all possible choices of quantity.

The table is read as follows: At the head of a row the quantity of your firm is indicated and at the head of a column the quantity of the other firm is stated. In the cell at which row and column intersect, your profit is noted in the upper left and the other firm's profit is stated in the lower right. All profits are expressed in a fictional currency, which we call Taler.

The experiment consists of 30 rounds. After each round, you will be informed about the period of production, the quantity, and the profit of the other firm. You do not know with which participant you serve the same market. You will be randomly matched with a participant each round. The decisions are made at the computer.

Anonymity is kept among participants and instructors, as your decisions will only be identified with your code number. You will discreetly receive your payment by showing your code number at the end of the experiment.

Concerning the payment note the following: At the end of the experiment 3 out of the 30 rounds will be randomly drawn to determine your payment. The sum of your profits in "Taler" of (exclusively) these 3 rounds determines your payment in deutsche marks. For 10 "Taler" you will receive DM 1. In addition to this money, you will receive DM 5 independently of your profit during the 30 rounds.

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