Capacity Choices and Price Competition in Experimental Markets*

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Abstract

In the heterogeneous experimental oligopoly markets of this paper, sellers first choose capacities and then prices. In equilibrium, capacities should correspond to the Cournot prediction. In the experimental data, given capacities, observed price setting behavior is in general consistent with the theory. Capacities converge above the Cournot level. Sellers rarely manage to cooperate.

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1. Introduction

The Cournot (1838) model is among the most prominent models in economic theory. An often raised critique against this model is that, without special institutions like an auctioneer who sets the price, quantity competition lacks realism. Against this critique, an innovative justification of Cournot competition was demonstrated by Kreps and Scheinkman (1983). They show that the Cournot solution may indeed be justified as the equilibrium outcome of a two-stage game in which sellers first choose capacities and then, knowing the vector of capacities, sellers set prices.

Given the importance of the Kreps and Scheinkman model in justifying quantity competition, an empirical evaluation seems warranted. Two recent experimental studies analyze capacity choices followed by price choices.[1] More precisely, Davis (1999) analyzes posted–offer markets with three sellers and with advance production. In Muren's (2000) paper, three sellers have to make a quantity precommitment before deciding about prices.

The experimental data support the Kreps and Scheinkman prediction only weakly. Firstly, capacities are significantly above the Cournot level in both studies. Secondly, the experimental markets did not converge. The data indicate that subjects persistently made inconsistent choices, leading to instable markets. In Davis (1999), stable Cournot outcomes were not observed as play never converged with advance production. Similar results were obtained by Muren (2000): Markets were only stable with experienced participants who did the experiment twice. Then the discrepancy between prediction and experimental outcome was somewhat reduced, though not completely. Finally, price choices for a given capacity were neither in line with the theoretical prediction in both papers. This was also observed by Brown–Kruse et al. (1994). Their experiment was designed to test the prediction for the distribution of prices; there were no capacity choices. Price choices were inconsistent with the mixed strategy equilibrium distribution. Taken

[1] Field studies (Rosenbaum, 1989; Rees, 1993) of markets in which price competition is constrained by capacities usually test for the collusive effects of excess capacities (see Phlips, 1995, for a survey).

together, the problem with the evidence from the experimental studies is not that they simply reject the theoretical prediction, but rather the erratic choices of the subjects in general.

Why does the Kreps and Scheinkman theory fail in experimental markets? One possible explanation could be the analytical difficulty of the intricate two-stage model. For example, Muren (2000, p. 154) mentions that even "in the experienced markets ... sellers did not seem to be entirely certain about the way the rationing mechanism worked". Such uncertainties and misunderstandings may suggest that the Kreps and Scheinkman model is too demanding. Davis (1999, p. 72) has an alternative explanation. He conjectures that "the added complexity is not the primary explanation for the continued instability. ... The instability of the advance production environment is not due to the failure of the institutional framework to induce Cournot incentives, but rather to the instability of Cournot incentives themselves".

In the light of these statements, it is interesting to recall that the Kreps and Scheinkman theory itself provoked criticism because of technical details. The main problem of their model is that no pure–strategy equilibrium in prices exists for generic ranges of capacity choices. The non–existence problem is caused by two discontinuities of the model. The first discontinuity results from the effect of product homogeneity on the residual demand function. The second discontinuity is that, beyond the capacity constraint, production costs are infinitely high. This might lead to situations where the profit functions are not quasi concave. Because of these features of the model, Kreps and Scheinkman have to make an assumption of how demand is rationed when prices differ and the low-price firm cannot meet market demand. Kreps and Scheinkman apply the above mentioned efficient rationing. The efficient rationing rule implies that the low-price seller serves the buyers with the highest reservation values. This assumption is crucial for the results, in particular when analyzing endogenously chosen capacities. Other rationing rules lead to different pricing behavior and thus to different endogenous capacities (see Davidson and Deneckere, 1986). In any event, the two discontinuities make the solution of the model technically very demanding.

Recent theoretical papers have modified and generalized the Kreps and Scheinkman model, in particular with respect to these technical problems. Yin and Ng (1997) and Martin (1999) analyze capacity precommitment and price competition when products are differentiated. Boccard and Wauthy (2000) and Güth and Güth (2000) analyze models with homogenous product competition, but capacities can be extended at a finite extra cost. All these approaches confirm the Kreps and Scheinkman result in the sense that the market equilibrium is à la Cournot.

In this experiment, we follow the line of these theoretical extensions. We will use a market model which assumes that goods are heterogenous and that capacities can be extended at a finite extra cost. In this way, we avoid problems with the non–existence of pure–strategy equilibria and somewhat arbitrary rationing rules. The capacity constraint is no longer an absolute upper limit on production, rather firms serve full market demand but at high costs. In this model, no matter how the distribution of capacities is, a (unique) pure–strategy in price is subgame perfect. Moreover, the unique Nash equilibrium in prices and capacities is according to the Cournot prediction.[2]

We address the same problem as Davis (1999) and Muren (2000), namely the viability of the Cournot prediction in experimental markets with self–selected capacities, followed by price competition. We thought that it might be worth reducing the complexity of the game. Therefore, the major deviation from Davis (1999) and Muren (2000) is that we use the different market model just mentioned. A second difference in the experimental design is that capacity is fixed for several periods in our experiment. This allows subjects to learn optimal pricing strategies within each capacity constrained subgame. Thirdly, we start the experiment with exogenously fixed capacities. Again, the idea is that subjects should first get an idea of how to choose prices. Our conjecture is that in the simplified environment the data might give a clearer picture about the Cournot-type results in Bertrand–Edgeworth markets.

[2] Similar models were proposed by Güth (1995) and Maggi (1996). Güth (1995) discusses how to view homogeneity as a limiting case of heterogenous products. Maggi (1996) shows how the equilibrium outcome ranges from Bertrand to Cournot as capacity constraints become more important. For a very comprehensive analysis, see Martin (2000).

Our results are as follows. In contrast to Davis (1999) and Muren (2000), we found that price choices are in general consistent with the subgame perfect prediction, and that capacity choices are stable. However, capacity choices were often above the Cournot prediction. While we are able to rationalize the capacity-setting behavior, it is remarkable that hardly any cooperation occurs in our duopoly markets.

In Section 2 we introduce the market environment and derive the equilibrium. Our experimental design is described in Section 3. Section 4 discusses the experimental results. We conclude in Section 5.

2. Market model

Our experiment assumes a heterogeneous oligopoly market with n sellers whose demand functions are given by

$$x_i(p) = \alpha - \beta p_i + \gamma \left(\sum_{j \neq i} \frac{p_j}{n-1} - p_i \right) \text{ for } i = 1, ..., n, \tag{2.1}$$

provided that all quantities are positive. Here $p = (p_1, ..., p_n)$ denotes the vector of individual sales prices p_j and $x_i(p)$ is seller i's demand level as depending on p. The positive parameters α and β describe how demand depends on prices when all prices are equal, i.e. when $p_i = \sum_{j \neq i} p_j / (n-1)$ for $i = 1, ..., n$. The positive parameter γ measures the degree of heterogeneity on the market. By $\gamma \to 0$, we could approach the situation where all n sellers are essentially monopolists, by $\gamma \to \infty$ a homogeneous market since small deviations from the average price would induce dramatic spill–overs of demand (what would rule out prices differences).

Production requires investments in capacities $\overline{x}$. We assume that capacity costs

$$K_i(\overline{x}_i) = c\overline{x}_i, \text{ for } i = 1, ..., n, \tag{2.2}$$

are linear in seller i's capacity $\overline{x}_i$. Production costs $C_i(x_i, \overline{x}_i)$ are (piecewise) linear

$$C_i(x_i, \overline{x}_i) = d \ \max\{0, x_i - \overline{x}_i\}, \text{ for } i = 1, ..., n. \tag{2.3}$$

According to equation (2.3) the capacity $\overline{x}_i$ is no rigorous upper bound for seller i's sales level x_i. A capacity $\overline{x}_i$ just represents a production target which does not preclude larger sales in the sense of $x_i > \overline{x}_i$, but only imposes positive extra costs $d(x_i - \overline{x}_i)$, $d > c$, for positive excess demands $x_i - \overline{x}_i$.

Due to market clearing, i.e.,

$$x_i = x_i(p) \text{ for } i = 1, ..., n, \tag{2.4}$$

the actual sales level x_i is determined by the vector p of chosen sales prices. The profits per period resulting from these choices are

$$\Pi_i(p, \overline{x}) = p_i x_i(p) - K_i(\overline{x}_i) - C_i(x_i(p), \overline{x}_i), \text{ for } i = 1, ..., n, \tag{2.5}$$

where $\overline{x}$ denotes the vector $(\overline{x}_1, ..., \overline{x}_n)$ of individual capacities.

Firms play a two-stage game. They first choose capacities and then, knowing the vector of capacity choices, they choose their prices. In order to derive equilibrium behavior, consider the last stage first. Given the capacities $\overline{x}$, there are three possible segments of the price reaction functions: One for the case of idle capacity, one where capacity is fully utilized, and one when there is excess demand (see Appendix A). If all firms' demand is equal to capacity, we can express price reaction functions solely in terms of capacities.[3] We get

$$p_i^*(\overline{x}) = \frac{(\alpha - \overline{x}_i)[\beta(n-1) + \gamma] + \gamma \sum_{j \neq i} (\alpha - \overline{x}_j)}{\beta[\beta(n-1) + n\gamma]} \tag{2.6}$$

as subgame perfect prices.

Then consider the first stage. We state three solutions of this model as benchmarks for the experiment (see Appendix A for the derivation). Consider first the joint-profit maximizing solution as a benchmark. We get

$$\overline{x}_i^c = \frac{\alpha - \beta c}{2} \text{ for } i = 1, ..., n, \tag{2.7}$$

[3] Though capacity choices up to 200 were allowed by design, in the experiment, all capacity choices were in the range where demand should equal capacity. That is, subgame perfect prices would have always yielded production up to capacity. Collusive pricing also almost always implies production up to capacity. The reason is that leaving idle capacities maximizes the joint profits only if capacities are very large. As such cases are very rare in our experimental data, we refrain from deriving the solution for collusive prices.

as the efficient and collusive capacity choices x_i^c of all sellers, and

$$p_i^c = \frac{\alpha + \beta c}{2\beta} \text{ for } i = 1, ..., n, \tag{2.8}$$

as optimal prices.

The second theoretical benchmark is the Cournot-Nash solution in which the players rationally recognize the influence of their capacity choice on the competitors' pricing behavior. The solution of the corresponding two-stage game is readily computed:

$$\overline{x}_i^n = \frac{\left[\beta\left(n-1\right) + n\gamma\right]\left(\alpha - \beta c\right)}{2\left(n-1\right)\beta + \left(n+1\right)\gamma} \text{ for } i = 1, ..., n. \tag{2.9}$$

Since equilibrium capacities are symmetric, prices are simply

$$p_i^n = \frac{\alpha - \overline{x}_i^n}{\beta} \text{ for } i = 1, ..., n. \tag{2.10}$$

in equilibrium.

The third theoretical benchmark is a competitive solution in which the players ignore the oligopolistic price mechanism. Of course, price setting strategies are not compatible with the standard notion of a competitive allocation, but we can easily replace this by a scenario of monopolistic competition in which the players take the prices of the competitors as given and maximize the resulting profit function. Note that in this case firms play a one-shot game. As the solution, we get

$$\overline{x}_i^w = \frac{\left[\beta + \gamma\right]\left(\alpha - \beta c\right)}{2\beta + \gamma}, i = 1, ..., n, \tag{2.11}$$

and

$$p_i^w = \frac{\alpha + c(\beta + \gamma)}{2\beta + \gamma}. \tag{2.12}$$

3. Experimental setup

In order to make the market as simple as possible, we decided to employ $n = 2$ firms in the market. The other parameters were as follows. The parameters $\alpha = 120$, $\beta = 1$ and $\gamma = 2$ describe the demand functions such that (2.1) becomes

$$x_i\left(p\right) = 120 - p_i + 2\left(p_{-i} - p_i\right) \text{ for } i = 1, 2, \tag{3.1}$$

given that $x_i(p) > 0$, $i = 1, 2$. If one firm sets a high price such that $x_i(p) < 0$, we made sure that the demand function for the remaining "active" firm is adjusted.[4]

[4] One gets $x_i < 0$ if $p_i > (120 + 2p_j)/3$. Hence, if $x_i < 0$, we set $x_i = 0$, $p_i = (120 + 2p_j)/3$ and therefore $x_j = 200 - 5/3p_j$ in the computer program of the experiment.

Cost parameters were $c = 40$ for the capacity costs and $d = 80$ for the production costs of every unit exceeding the capacity. Equation (2.6) becomes

$$p_i^*(\overline{x}) = \frac{600 - 3\overline{x}_i - 2\overline{x}_{-i}}{5}, \ i = 1, 2.$$

Further, we introduced a fixed cost of 600 in order to get a relatively larger and reasonable difference between cooperative and non-cooperative profits.

With these parameters, the symmetric collusive solution requires

$$\overline{x}_i^c = 40 \text{ and } p_i^c = 80 \text{ for } i = 1, 2. \tag{3.2}$$

The non-cooperative Nash equilibrium implies

$$\overline{x}_i^n = 50 \text{ and } p_i^n = 70 \text{ for } i = 1, 2. \tag{3.3}$$

Finally, the competitive benchmark is

$$\overline{x}_i^w = 60 \text{ and } p_i^w = 60 \text{ for } i = 1, 2. \tag{3.4}$$

Profits resulting from these capacities and prices are 1000 at the symmetric collusive solution, 900 at the non-cooperative equilibrium and 600 at the competitive solution.

The sellers interact repeatedly on this market in periods $t = 1, 2, ..., 60$, i.e. within a given and known finite time horizon. Our setup also allows for cooperative outcomes to occur. There is ample evidence (Selten and Stöcker, 1986) of stable cooperation (except for a rather short end phase) even in the case of a known finite horizon, excluding so-called Folk Theorems.

Capacity was to be chosen every tenth period while the price was to be set in every period. A change in restructuring is seen as a major restructuring of the firm whereas prices can be more easily and frequently adjusted. In order to give participants an occasion to learn about the market, capacities are first exogenously given from $t = 1$ to 10 and anew from $t = 11$ to 20 respectively.[5] The decision process assuming that all former choices are commonly known is as follows.

[5] In a pilot session, the design of the experiment was without such initial exogenous capacities. It turned out that such a setup was too complicated. Subjects incurred substantial losses before converging to reasonable capacities so that they only broke even after 60 periods.

Stage 1: (in $t = 21, 31, 41, 51$): Sellers $i = 1, 2$ choose their capacities $\overline{x}_i$.

Stage 2: (in $t = 1, 2, ..., 60$): Sellers $i = 1, 2$ choose their sales prices p_i,

The initial capacity vectors $\overline{x} = (\overline{x}_1, \overline{x}_2)$ for $t = 1$ and $t = 11$ were

$$\overline{x} = \begin{cases} (50, 40) \text{ for } t = 1, ..., 10, \\ (45, 65) \text{ for } t = 11, ..., 20. \end{cases} \tag{3.5}$$

The corresponding equilibrium price vectors $p^* = (p_1^*, p_2^*)$ are

$$p^* = \begin{cases} (74, 76) \text{ for } t = 1, ..., 10, \\ (67, 63) \text{ for } t = 11, ..., 20. \end{cases} \tag{3.6}$$

Information was given to subjects in the following way. The cost parameters (40 for each capacity unit, and 80 for each unit in excess of capacity), the number of firms (two), the number of periods (60), and the exchange rate of experimental earnings into real currency (see below) were explicitly mentioned in the instructions (see Appendix B). Experiments were computerized.[6] This enabled us to give more information on the computer screen. After each period, subjects learned the price choice of the rival firm and the resulting profit for their own firm. Similarly, they learned the choice of the rival firm whenever capacities were chosen.

Moreover, subjects had access to a "profit calculator". When considering their decisions, subjects could enter trial prices and capacities (numbers between 0 and 200 with two decimal points) in this calculator. The profit calculator gave a subject the sales and profits of his or her own firm which would occur with these decisions. Once actual capacity choices were made, they remained fixed in the profit calculator and subjects could only experiment with prices. Subjects could experiment with the profit calculator as intensively as they wished. With the device of the profit calculator, the demand conditions could quickly be learned. Note that a profit calculator gives qualitatively the same information as a profit table. Such tables are often provided in market experiments of this kind (e.g. Holt, 1985). They allow, however, only for a small and discrete action space. The

[6] We used the software "z-Tree" (Fischbacher, 1999).

profit calculator allows for many actions. As we had two decimal points for the capacity and price decisions, continuous actions were approximated. This has the advantage that multiple Nash equilibria due to the discretization of the action space (see Holt, 1985) can be avoided. An alternative design would have been to provide the functional form of the demand function to subjects (Davis, 1999; Muren, 2000). However, since our design with product differentiation requires more complicated functional forms, this does not seem to be practible. Compared to the provision of functional forms, the profit calculator might help to avoid a bias due to limited computational capabilities of subjects. Generally, it seems possible that the use of a profit calculator reduces the "noise" in the data that results from subjects making random noises.

The experiments were conducted in the computer lab of the Humboldt University. We conducted three sessions, each consisting of six duopoly pairs. That makes a total of 36 subjects which were recruited via telephone and email from a list of participants of previous experiments. Each subject participated only once and no subject had participated an experiment similar to ours before. Subjects were randomly allocated to separated cubicles in the lab. They were not able to infer with whom they were interacting.

Sessions lasted between one hour and 45 minutes and two hours and 15 minutes. For 1,000 "points" earned in the experiment, DM 1 was paid. An initial capital of $15,000$ points was given since subjects could have made losses, particularly so in the beginning. Average earnings were DM 50.99 (which is roughly $27).

4. Results

We start by reporting the results for pricing behavior. As mentioned, in periods $t = 1, ..., 20$ capacities were exogenously fixed. In Figure 1 we have graphically illustrated the average price choices for the first 20 rounds (the solid lines indicating subgame perfect prices $(74, 76)$ and $(67, 63)$ respectively). Prices are often below the predicted level, however, this deviation is rather small. Prices move towards the equilibrium prices. For the first set of capacities prices are, after some time of coordination, quite close to the prediction, and very close for the second exogenously given capacity vector.

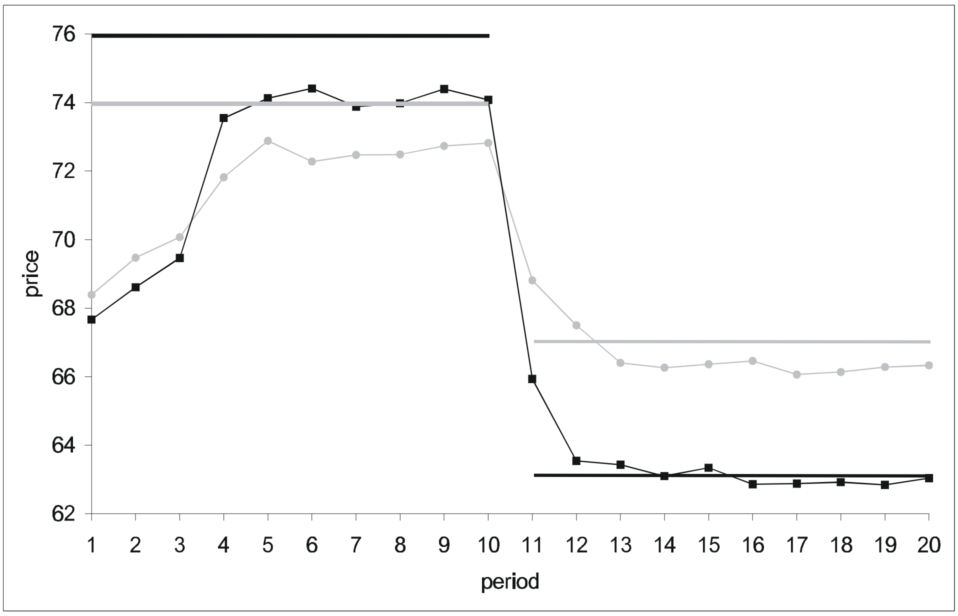

Figure 1: Average price choices for predetermined capacities in $t = 1, ..., 20$

How is pricing behavior when capacities are self-selected in later periods? In Table 1, we report the percentages of "hits", that is, the relative frequency of subgame perfect price choices. We distinguish exact hits and price choices which were within a 5% range of the subgame perfect prices. We report these results for the entire data set, separately for all thirds (periods $t = 1$ to 20, 21 to 40, and 41 to 60), and for the second halves of the ten-period interval with the same capacities (periods $t = 6$ to $10, 16$ to $20, ..., 56$ to 60.). The hypothesis behind this is that subjects make more accurate price choices over time. We also reports hits when capacity choices were symmetric. Here, the hypothesis was that subgame perfect prices are more easily found with equal capacities. Note that, for all observations, subgame perfect prices were such that demand would have equalled capacity, that is (2.6) was the appropriate price reaction function.

	exact	$\pm 5\%$
all observations (#2160)	33.47	85.83
$t = 1, ..., 20$ (#720)	28.75	77.63
$t = 21, ..., 40$ (#720)	36.81	86.53
$t = 41, ..., 60$ (#720)	34.86	93.33
$t = 6$ to $10, 16$ to $20, ..., 56$ to 60 (#1080)	35.37	91.02
symmetric capacities (#200)	72.00	99.50

Table 1: Relative frequency of subgame perfect price choices

In approximately one third of the cases, subjects played exactly the subgame perfect prices (recall that there were two decimal points). Almost all choices were roughly equal to the subgame perfect prices. Looking at the tables in Appendix C, it is remarkable how close prices p_i^* and actual average prices were. It appears that participants understood the price implications of capacity vectors well. From Table 1, the frequency of hits in later periods within a ten-period subgame increases. It also appears that $\pm 5\%$ hits increase over the course of the experiment. Moreover, symmetric capacities seem to facilitate hits.

In order to test for statistic significance of these effects, we ran the simple regression

$$h = \beta_0 + \beta_1 first + \beta_2 last + \beta_3 early + \beta_4 symm,$$

where we take into account that observations are independent across sessions but not neccesarily within sessions.[7] The number of "hits" (h, two at most) was the variable to be explained. The variable $first$ was equal to one if $t < 21$ and zero otherwise; similarly $last$ was equal to one if $t \in (40, 60]$ and zero otherwise; $early$ was equal to one in periods $t = 1$ to 5, 11 to 15,..., 51 to 55 and zero otherwise; $symm$ was equal to one if capacity choices were symmetric. (see Table 2).

All coefficients have the expected sign, except $last$ for exact hits. Subgame perfect prices are significantly more likely when capacities are symmetric. The variables $first$ and $last$ are not significant, while $early$ is. We interpret this as a confirmation of our design (few capacity choices, several price choices within subgames). There is learning going on within the ten period subgames, but prices do not become more accurate in the later periods of the experiment.

[7] We used the *cluster* option for linear regressions of the STATA package. See STATA Corp. (1999, vol. 3, pp.156-158).

	exact hit	$\pm 5\%$ hit
β_0	$+0.761^{**}$	$+1.817^{**}$
β_1	-0.067	-0.155
β_2	-0.086	$+0.125$
β_3	-0.239^{**}	-0.219^{**}
β_4	$+0.850^{*}$	$+0.208^{**}$

Table 2: Regression results for hit rates. Superscripts $^{**}(^{*})$ indicate significance at the 1(5)% level.

We summarize the results of the price setting stage as follows:

Observation 1: Participants quickly learn to rely on equilibrium prices p_i^* satisfying $x_i(p^*) = \overline{x}_i$ for $i = 1, 2$.

We now turn to the results of the capacity choices. In the tables in Appendix C, we list the four capacity vectors for all 18 markets. Since capacity choices are likely to depend on individual paths, we first report industry capacities, $\overline{x}_{1,2} = \overline{x}_1 + \overline{x}_2$, in Table 3. Recall that the predictions were 80 for the collusive market, 100 for the Cournot market and 120 for the competitive market.

	$\overline{x}_{1,2}$	$\sigma(\overline{x}_{1,2})$
$t = 21, ..., 30$	114.2	18.6
$t = 31, ..., 40$	110.0	16.1
$t = 41, ..., 50$	109.9	14.7
$t = 51, ..., 60$	109.5	14.9

Table 3: Average industry capacity

Out of 72 observations for industry capacity (see Appendix C), none was smaller than 80, 16 were smaller than 100, 37 were between 100 and 120, and 19 were larger than 120 with 153 being the maximum. Average industry capacity is 110.93 which is above the Cournot-Nash equilibrium value and below the monopolistic competition solution. The 95% confidence interval for industry capacity (again accounting for possible dependence of observations within groups) is $[103.89, 117.97]$ around the observed mean. Therefore, we have to reject the hypothesis that capacity choices coincide with the Cournot prediction, and we also have to reject the hypothesis that capacity choices are in line with monopolistic competition.

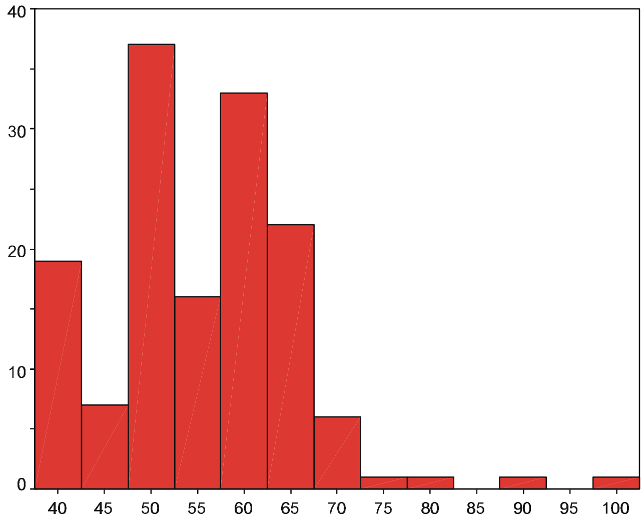

Figure 2: Histogram of the individual capacities

A look at the histogram of individual capacity choices in Figure 2 gives further insights. The Cournot equilibrium choice (50) is contained in the bracket which occurred most often. Ignoring the (somewhat arbitrary) brackets in Figure 2, we find that 50 is also the mode of all capacity choices. The monopolistic competition solution (60) is the second most frequent choice while the intermediate value (55) is chosen less often then the collusive capacity.[8] While there is some dispersion in capacity choices, these choices are relatively constant for individual industries (see Appendix C). Moreover, average capacity choices are, except for a slight (and insignificant) negative trend, stable over time.

Stable behavior which is more competitive than the Cournot solution was also found in Huck, Normann, an Oechssler (1999). In their quantity-setting homogenous-goods Cournot experiment, depending on the information revealed to subjects,

[8] The benchmark capacities $\overline{x}^c_{1,2}$, $\overline{x}^n_{1,2}$ and $\overline{x}^w_{1,2}$ were chosen simultaneously by both firms in 2, 4, and 1 of the 72 possible cases, respectively. Surprisingly, all price choices in all periods are optimal for these capacities in the sense that $x_i(p) = \overline{x}_i(p)$, $i = 1, 2$.

play converged close to the competitive equilibrium.[9] And even when structural information was granted as in our study, the results were quite competitive. These results were confirmed in experimental markets with quantity-setting firms and differentiated goods by Huck, Normann, an Oechssler (2000). However, in Huck, Normann, and Oechssler (1999, 2000), there were four firms and, in Davis (1999) and Muren (2000), there were three firms. Since we used duopoly markets, our results are surprising. In most standard Cournot duopoly experiments in which subjects are matched in fixed pairs, there is at least some cooperation and there are rarely choices beyond the Cournot level.[10] We conclude from this that repeated interaction over a long but finite horizon is no reliable reason for cooperating.

Observation 2: (i) Capacity choices are at a level above the Cournot prediction and below the competitive prediction. (ii) Despite the relatively long horizon, there is hardly any cooperation.

Since we have concentrated on $n = 2$ firms, our test seems to provide the most favorable conditions for cooperation (since cooperation on larger markets is more doubtful, see Selten, 1972, for a rigorous distinction of small, i.e. cooperative markets with few sellers). Thus game types inviting cooperation seem to be: not framed as markets[11], and relying on one-stage base games (or binary games). It seems interesting to explore which of these aspects is (more) reasonable for inducing cooperative outcomes, but this is beyond the scope of this study. It seems that the strong cooperative results for finitely repeated prisoners' dilemma and public good provision games are special results for certain game types which are cognitively perceived as cooperative exercises.

Another reason for more competitive results is that our design relies on quite realistic assumptions concerning the profitability of cooperation. Whereas, in

[9] For our market model this would require both, $\gamma \to \infty$ and $n \to \infty$, and thus $\overline{x}_i \to 80$ and $p_i \to 40$.

[10] Concerning this issue, see e.g. Dufwenberg and Gneezy (2000), or Keser (2000). Selten et al. (1997) show that, in tournaments, there is a particularly strong motivation to establish collusion.

[11] Experiments framed as markets seem to induce more competitive behavior. See Hoffman et al. (1994).

our experiment, cooperation leads to moderate increases in profits, mutual cooperation in most base games (of finitely repeated games with fixed matching) yields much larger, sometimes outrageous increases in profits (see, for example, the repeated prisoners' dilemma experiment of Cooper et al., 1996; or repeated interaction in trust games of Berg et al., 1995). It is quite possible that the usually claimed cooperation in finitely repeated games is mainly due to the dominance[12] of striving for efficiency when cooperation is highly profitable. This may surprise naive protagonists of cooperative behavior or efficiency. From an antitrust perspective, however, the result is most welcome since there might be competitive results even in narrow markets. It also allows to maintain the duopoly market as a standard case for illustrating the effects of competition.

5. Conclusion

In this experiment, we tested for the viability of the Cournot prediction in duopoly markets with capacity and price competition. We used a simplified environment which allowed subjects sufficient time for learning of frequently adjusted choices (prices) and rarely adjusted choices (capacities). In contrast to other experiments (Davis, 1999; Muren, 2000), we found subgame perfect price choices and stable capacity choices. Individual capacities converge at a level below the competitive prediction and above the Cournot prediction. That is, capacity choices were more competitive than pure non–cooperative behavior suggests. It is surprising that no cooperation occurs in our duopoly markets with the same firms interacting for 60 market periods.

[12] When one views decision making as the result of competing behavioral forces, it makes sense to assume that one can influence behavior by changing the relative strength of one motivation, e.g. by weakening the gains from cooperation.

Appendix

A. Derivation of the benchmark solutions

We first derive subgame perfect prices given the installed capacities. The reaction function of each firm has three different segments.

• Up to capacity, firm i can produce at zero marginal cost. That is, if $x_i < \overline{x_i}$ we get

$$\frac{\partial \Pi_i \left(p, \overline{x}\right)}{\partial p_i} = \alpha - 2(\beta + \gamma) p_i + \gamma \frac{\sum_{j \neq i} p_j}{n-1} = 0, \tag{A.1}$$

and therefore

$$p_i^* = \frac{\alpha + \gamma \frac{\sum_{j \neq i} p_j}{n-1}}{2(\beta + \gamma)}. \tag{A.2}$$

The first part of the reaction function is relevant if it is optimal to hold idle capacity. In that case, firm i chooses its prices such that marginal revenue is zero.

• The second segment of the reaction function is relevant if marginal revenue is between zero and d. Here, firm i chooses p_i such that $x_i = \overline{x_i}$:

$$\alpha - (\beta + \gamma) p_i + \gamma \frac{\sum_{j \neq i} p_j}{n-1} = \overline{x_i}, \tag{A.3}$$

that is,

$$p_i^* = \frac{\alpha + \gamma \frac{\sum_{j \neq i} p_j}{n-1} - \overline{x_i}}{\beta + \gamma}. \tag{A.4}$$

In this segment, capacity is fully utilized. If reaction functions of all firms intersect in this segment, we can use $\beta \sum_{j=1}^{n} p_j^* = \sum_{j=1}^{n} \left(\alpha - \overline{x}_j\right)$ to express p_i^* in terms of capacities only:

$$p_i^* \left(\overline{x}\right) = \frac{\left(\alpha - \overline{x}_i\right) \left[\beta \left(n-1\right) + \gamma\right] + \gamma \sum\limits_{j \neq i} \left(\alpha - \overline{x}_j\right)}{\beta \left[\beta \left(n-1\right) + n\gamma\right]}. \tag{A.5}$$

• In the third segment, firm i produces more than its capacity, at the extra cost d:

$$\frac{\partial \Pi_i \left(p, \overline{x}\right)}{\partial p_i} = \alpha - 2(\beta + \gamma) p_i + \gamma \frac{\sum_{j \neq i} p_j}{n-1} + (\beta + \gamma) d = 0, \tag{A.6}$$

and so

$$p_i^* = \frac{\alpha + \gamma \frac{\sum_{j \neq i} p_j}{n-1} + (\beta + \gamma) d}{2(\beta + \gamma)}. \tag{A.7}$$

Here, marginal revenue is larger than d and therefore it is rational to produce the excess demand units.

The slope of reaction function differs in the three segments: $\partial p_i^* / \partial p_j$ is larger in the second segment. It is easy to verify that $0 < \partial p_i^* / \partial p_j < 1/(n-1)$ in any segment, therefore a unique vector of prices exists for any combination of capacities.

Our first benchmark is the joint–profit maximum. Perfect collusion requires efficiency in the form of $x_i(p) = \overline{x}_i$ for all sellers $i = 1, ..., n$, and symmetry in the form of $\overline{x}_i = \overline{x}_j$ for all $i, j = 1, ..., n$. We can therefore set $\overline{x}_j = \overline{x}_i$ for all $j \neq i$ in equation (A.5) so that

$$p_i^*(\overline{x}_i) = \frac{[\beta(n-1) + n\gamma](\alpha - \overline{x}_i)}{\beta[\beta(n-1) + n\gamma]} = \frac{\alpha - \overline{x}_i}{\beta}. \tag{A.8}$$

The profit of all sellers $i = 1, ..., n$ is thus $\Pi_i(\overline{x}_i) = p_i^*(\overline{x}_i) \cdot \overline{x}_i - c\overline{x}_i$. From $\frac{\partial^2}{\partial \overline{x}_i^2} \Pi_i(\overline{x}_i) < 0$ and

$$\frac{\partial}{\partial \overline{x}_i} \Pi_i(\overline{x}_i) = p_i^*(\overline{x}_i) + \overline{x}_i \frac{\partial}{\partial \overline{x}_i} p_i^*(\overline{x}_i) - c = 0 \tag{A.9}$$

we derive

$$[\beta(n-1) + n\gamma](\alpha - \overline{x}_i^c) - \overline{x}_i^c [\beta(n-1) + n\gamma] = c\beta[\beta(n-1) + n\gamma] \tag{A.10}$$

or

$$\overline{x}_i^c = \frac{\alpha - \beta c}{2}, \text{ for } i = 1, ..., n, \tag{A.11}$$

as the efficient and collusive capacity choices x_i^c of all sellers. Collusive prices are immediate from (A.8): $p_i^*(\overline{x}) = (\alpha + \beta c)/2\beta$.

Then turn to our second benchmark, the Cournot–Nash equilibrium. We first show that, in equilibrium, firm i chooses $\overline{x_i}$ such that $x_i = \overline{x_i}$, that is, in equilibrium there is neither idle capacity, nor is output produced in excess of the capacity. Suppose that, by contrast, $x_i < \overline{x_i}$ in equilibrium. Then firm i could slightly reduce its capacity. This would save costs, but would not alter the price choices of other firms as p_j^* only depends on p_i^*, but not on $\overline{x_i}$. Suppose $x_i > \overline{x_i}$ in equilibrium. Then firm i could gain by increasing its capacity which, again, would save costs without changing behavior among the other firms. Therefore, in equilibrium, $x_i = \overline{x_i}$.

From (A.5), we have

$$\frac{\partial}{\partial \overline{x}_i} p_i^*\left(\overline{x}\right) = -\frac{\beta\left(n-1\right)+\gamma}{\beta\left[\beta\left(n-1\right)+n\gamma\right]}, \tag{A.12}$$

so $\frac{\partial^2}{\partial \overline{x}_i^2}\Pi_i\left(\overline{x}\right) < 0$. The first order conditions

$$\frac{\partial}{\partial \overline{x}_i}\Pi_i\left(\overline{x}\right) = p_i^*\left(\overline{x}\right) + \overline{x}_i \frac{\partial}{\partial \overline{x}_i} p_i^*\left(\overline{x}\right) - c = 0 \tag{A.13}$$

for $i = 1, ..., n$ can be written as

$$\begin{aligned} & \left(\alpha - \overline{x}_i\right)\left[\beta\left(n-1\right)+\gamma\right] + \gamma\sum_{j\neq i}\left(\alpha - \overline{x}_j\right) - \left[\beta\left(n-1\right)+\gamma\right]\overline{x}_i \\ = \; & c\beta\left[\beta\left(n-1\right)+n\gamma\right] \end{aligned} \tag{A.14}$$

for $i = 1, ..., n$ whose unique symmetric solution is

$$\overline{x}_i^n = \frac{\left[\beta\left(n-1\right)+n\gamma\right]\left(\alpha-\beta c\right)}{2\left(n-1\right)\beta+\left(n+1\right)\gamma} \text{ for } i = 1, ..., n. \tag{A.15}$$

From $\overline{x}_i^n = x_i^n$ we obtain

$$\frac{\partial \Pi_i\left(p, \overline{x}\right)}{\partial p_i} = \overline{x}_i^n - (\beta+\gamma)p_i^n + (\beta+\gamma)d > 0,$$

and therefore $d > p_i^n - \overline{x}_i^n/(\beta+\gamma)$ as a necessary condition for the equilibrium. Equation (A.15) and (A.5) describe the non-cooperative equilibrium behavior of the market. Note that approximating homogeneous markets via $\gamma \to \infty$ implies

$$\overline{x}_i^n \to \frac{n(\alpha-\beta c)}{n+1}, \tag{A.16}$$

which is the usual homogenous goods Cournot prediction for quantity setting oligopoly (note that there are n markets). By contrast, $\overline{x}_i^c$ does not depend at all on the degree γ of heterogeneity.

The third theoretical benchmark is the monopolistic competition solution. Players take the prices of the competitors as given and maximize the resulting profit function $\Pi_i = (p_i - c) \cdot x_i(p)$ assuming that $x_i(p)$ is produced with the cost minimizing capacity $\overline{x}_i = x_i(p)$.[13] The resulting one-stage game yields the following first order conditions for the best reply functions

$$\alpha - \beta p_i + \gamma(\Sigma p_j/(n-1) - p_i) - (p_i - c)(\beta + \gamma) = 0. \tag{A.17}$$

Using symmetry this immediately gives the (unique) equilibrium at

$$p_i^w = \frac{\alpha + c(\beta + \gamma)}{2\beta + \gamma}. \tag{A.18}$$

The corresponding capacity, $\overline{x}^w$, is easily derived from $\overline{x}_i = x_i(p)$.

B. Instructions

Welcome to our experiment. Please read first carefully the following instructions. In the next one or two hours you have to make various decisions. Doing so, you can earn some real money. One thing is important in the beginning: Please, keep calm during the entire experiment. If you have a question, please raise your hand and somebody will help you.

You will receive your **payment** individually and discrete right after the experiment. We guarantee full anonymity against all other participants. Also, we do only save the decision data, in an anonymous way. All money in the experiment is given in **points**. In the beginning you get a capital of 15,000 points. In the end of the experiment your payment will be transformed where 1,000 points = 1 DM.

Now we explain the **rules** of the experiment. You are representing a firm, producing or distributing a certain product. Besides your firm there is another firm producing or distributing a similar product. You have to make two different kinds of decisions for your firm. On the one hand you have to decide about the capacity for your firm, on the other hand you have to decide about the price of the product.

[13] Since $x_i(p)$ is learned after choosing all prices, this somewhat reverses the order of moves. It nevertheless seems possible that participants engage in cognitive deliberations whose dynamics justify this assumption.

First, consider the **capacity decision**. In the first 20 rounds your capacity is given. More precisely, you produce in round 1 to 10 with a given capacity and in round 11 to 20 with a different given capacity. Beginning with round 21 you have to decide yourself about the capacity. This decision also holds for 10 rounds. The entire experiment lasts for 60 rounds. This means you have to decide about the capacity in the 21^{st}, 31^{st}, 41^{st}, and 51^{st} round. Capacity causes costs of 40 points per unit. Your capacity has the following meaning: up to the capacity limit, you can produce without additional costs. Production exceeding the capacity limit is possible, but causes higher costs of 80 points per unit.

The **price decision** has to be made every round. The price determines how much of the product you will sell in every round. There is one important rule: The higher the price, the lower is the quantity you sell. From a certain price on, the quantity you sell will be zero. In addition it holds that the lower the price of the other firm is, the lower is your quantity. Your sales quantity can be above or below your capacity. If the quantity is higher, you have to pay extra costs, as mentioned above. If your quantity is lower than your capacity, you have idle capacity. An example: Suppose your capacity is 50. If prices are such that you sell 60 units, then your costs are $50 * 40 + 10 * 80 = 2,800$ points. If your price is such that you sell 45 units, your costs are $50 * 40 = 2,000$ points. In addition you have to pay fixed costs of 600 points every period.

If you want to know which profit a certain capacity and price combination yields, you can access a special **profit calculator**. The profit calculator works as follows: In rounds where you have to choose your capacity, by the way of trial you can (as often as you want to) enter a capacity for your and the other firm. Furthermore you have to enter a trial price for your and the other firm. The profit calculator will give you the expected profit for these values. In rounds where you only have to decide about the price, the capacities for your and the other firm are fixed in the profit calculator. The profit calculator enables you to calculate different combinations of prices.

Before the experiment starts you will have enough time to get familiar with the profit calculator directly at the computer. In advance, you get a printout of the computer screen with a detailed description.

The profit calculator uses the following abbreviations

C1	Own capacity
C2	Other capacity
Q1	Own quantity
Q2	Other quantity
P1	Own price
P2	Other price
Eink. 1	Own income
Eink. 2	Other income

All the things we described here are not only valid for you but also for the other firm. In all of the 60 rounds you will interact with the same partner. All of you read the same instructions. Have fun!

C. Capacities choices and average price implications

No./t	$\overline{x}_1$	$\overline{x}_2$	$\overline{x}_{1,2}$	p_1^*	p_2^*	$\emptyset p_1$	$\emptyset p_2$	σp_1	σp_2
1/21	50	65	115	64	61	64.9	61.9	0.316	0.316
1/31	50	65	115	64	61	63.6	62.0	2.951	0.000
1/41	50	65	115	64	61	63.6	62.0	2.951	0.000
1/51	50	70	120	62	58	63.8	61.0	0.632	0.000
2/21	50	55	115	68	67	67.3	66.6	1.096	0.810
2/31	52.5	60	112.5	64.5	63	65.3	63.5	1.318	0.726
2/41	62.5	55	117.5	60.5	62	61.3	62.9	1.161	0.637
2/51	65	55	120	59	61	59.2	61.3	0.483	0.235
3/21	60	55	115	62	63	62.1	63.2	0.316	0.330
3/31	65	55	120	59	61	59.2	61.3	0.483	0.235
3/41	60	50	110	64	66	64.0	66.0	0.000	0.000
3/51	60	50	110	64	66	64.0	66.0	0.000	0.000
4/21	50	50	100	70	70	70.0	70.0	0.000	0.000
4/31	40	50	90	76	74	74.2	73.6	2.898	1.265
4/41	40	50	90	76	74	73.0	73.2	3.162	1.687
4/51	50	50	100	70	70	70.0	70.0	0.000	0.000
5/21	60	65	125	58	57	58.6	58.2	0.843	2.469
5/31	60	65	125	58	57	58.0	57.0	0.000	0.000
5/41	60	65	125	58	57	58.0	57.0	0.000	0.000
5/51	63	65	128	56.2	55.8	56.8	56.3	0.486	0.422
6/21	61	60	121	59	60	61.2	60.5	3.000	1.091
6/31	61	61	122	59	59	59.5	59.3	0.290	0.210
6/41	61	61	122	59	59	59.2	59.1	0.136	0.087
6/51	61	64	125	57.8	57.2	57.4	57.3	0.584	0.805
7/21	53	65	118	62.2	59.8	62.6	60.4	0.578	0.971
7/31	58	57	115	62.4	62.6	62.3	62.4	0.215	0.246
7/41	58	60	118	61.2	60.8	61.9	61.2	0.248	0.318
7/51	59	59	118	61	61	61.1	60.9	0.626	0.221
8/21	40	62	102	71.2	66.8	71.1	66.8	0.544	0.680
8/31	50	52	102	69.2	68.8	69.5	69.1	0.201	0.110
8/41	50	40	90	74	76	72.1	74.6	1.584	1.115
8/51	55	40	95	71	74	71.0	73.5	0.000	1.078
9/21	50	50	90	70	70	70.0	70.0	0.000	0.000
9/31	50	40	90	74	76	74.0	76.0	0.000	0.000
9/41	40	50	90	76	74	76.0	74.0	0.000	0.000
9/51	40	40	80	80	80	80.0	80.0	0.000	0.000

No./t	$\overline{x}_1$	$\overline{x}_2$	$\overline{x}_{1,2}$	p_1^*	p_2^*	$\emptyset p_1$	$\emptyset p_2$	σ_{p_1}	σ_{p_2}
10/21	40	45	85	78	77	76.5	76.2	0.972	1.107
10/31	50	45	95	72	73	72.6	73.6	1.174	1.506
10/41	55	47	102	68.2	69.8	69.3	69.9	3.199	2.183
10/51	52	45	97	70.8	72.2	69.8	70.2	1.476	1.476
11/21	50	50	100	70	70	70.0	68.0	0.000	6.325
11/31	50	40	90	74	76	72.2	74.4	1.125	0.842
11/41	52.01	50	102.01	68.8	69.2	68.7	69.1	0.610	0.175
11/51	52.14	50	102.14	68.7	69.1	67.9	67.8	0.790	1.414
12/21	40	55	95	74	71	74.3	70.1	0.443	2.006
12/31	45	60	105	69	66	68.7	66.7	0.769	1.733
12/41	50	55	105	68	67	68.1	66.9	0.212	0.669
12/51	50	70	120	62	58	62.1	59.6	0.183	2.386
13/21	50	70	120	62	58	62.0	58.5	0.000	1.581
13/31	50	57	107	67.2	65.8	55.7	54.5	0.699	1.838
13/41	50	66	116	63.6	60.4	63.8	61.0	0.422	0.816
13/51	55	63	118	61.8	60.2	61.9	60.6	0.316	1.265
14/21	60	65	125	58	57	59.3	58.1	0.823	2.601
14/31	65	75	140	51	49	62.9	62.9	3.268	3.100
14/41	65	70	135	53	52	56.8	55.1	3.521	2.846
14/51	50	64	114	64.4	61.6	64.4	61.1	1.350	0.994
15/21	100	53	153	38.8	42.2	40.2	49.1	2.300	1.101
15/31	60	55	115	62	63	57.4	59.1	0.876	0.876
15/41	60	62	122	59.2	58.8	59.8	59.7	1.398	1.337
15/51	60	60	120	60	60	60.0	60.0	0.000	0.000
16/21	90	60	150	42	48	49.7	53.9	3.690	3.777
16/31	70	60	130	54	56	57.4	59.1	4.136	0.589
16/41	65	40	105	65	70	62.8	68.3	4.341	1.578
16/51	60	40	100	68	72	68.2	73.1	3.705	0.032
17/21	80	52	132	51.2	56.8	54.9	61.7	4.040	2.983
17/31	70	62	132	53.2	54.8	54.4	56.6	1.776	1.647
17/41	65	64	129	55.4	55.6	55.5	57.3	0.972	1.829
17/51	63	62	125	57.4	57.6	57.2	57.9	0.632	0.568
18/21	40	55	95	74	71	73.6	71.1	3.134	0.738
18/31	40	45	85	78	77	78.0	77.0	0.000	0.000
18/41	40	45	85	78	77	75.7	77.0	4.900	0.000
18/51	40	40	80	80	80	80.0	80.0	0.000	0.000

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