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Experimentally observed imitation and cooperation in price competition on the circle

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Abstract

This paper reports an experiment on a location game, the so-called "Price competition on the circle." There are n symmetric firms equidistantly located on a circle. Consumers are uniformly distributed. Each consumer buys one unit from that firm whose price, including the cost of transportation, is the lowest, provided such a price is below a maximum willingness to pay. Experiments, extended over 200 periods, were run with 3, 4, and 5 participants. Subjects did not receive any information about the relationship between prices and profits, but they received feedback on prices and profits of two neighbors after each period. The evaluation compares predictions derived from imitation equilibrium and Cournot equilibrium, as well as symmetric joint-profit maximization. The results show that behavior is influenced by imitative tendencies and attempts to cooperate.

JEL classification: C72; C92; L13; R32

Keywords: Imitation; Cooperation; Location; Price competition; Market size; Experiments

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1. Introduction

It has often been proposed in the literature that competitors in an oligopolistic market may be guided by imitation rather than by profit calculations. Horst Todt (1970, 1972, 1975) has expressed this view in connection with his experiments on a locational oligopoly, involving investment and pricing decisions of hotels in three health resource towns. Later, the idea of imitation as a driving force of competition has been worked out by various contributors to evolutionary game theory (Vega-Redondo, 1997, 1999; Schlag, 1998, 1999; Rhode and Stegeman, 2001). In this literature processes of imitation are described which may not converged to Nash equilibrium but to other outcomes, e.g., the competitive equilibrium in the symmetric Cournot model.

In a paper by Selten and Ostmann (2001) the notion of imitation equilibrium is introduced. The imitation equilibrium is a behavioral static equilibrium concept, which can be compared to equilibrium points in pure strategies like the Nash equilibrium. Learning processes often involve several parameters which have to be estimated from the data. The concept of imitation equilibrium, however, does not involve any parameter and therefore permits a direct comparison with the static equilibrium point notion of non-cooperative game theory. In the paper by Selten and Ostmann, imitation equilibria have been determined for the symmetric Cournot model with constant average cost, for the asymmetric Cournot duopoly with constant average cost, and for a simple oligopolistic model of price competition on the circle. The experiments reported here concern the last of these three examples.

In the case of the oligopolistic model of price competition on the circle, imitation equilibrium predicts stronger competition for markets with three firms, than for those with four or five firms. This is a surprising theoretical result since usually one expects competition to get stronger with an increase in the number of competitors. It seemed to be an interesting research question to what extent the prediction of imitation equilibrium theory is supported by experimental data.

It is plausible to assume that imitation is favored by a lack of knowledge about the connection of prices and profits. Accordingly, in our experiments subjects did not get any information about how the profit depends on the prices. They were not informed about intervening variables like costs and sales, and they were not told that they were involved in a spatial competition situation. They were not even informed about the number of competitors in the market. They knew that they have to determine a price and that their profits would depend deterministically on all prices of the same period, and not on those on earlier periods. They got feedback about own price and profits, and the prices and profits of the left and right immediate neighbors, but they did not know anything beyond this. With these information conditions, we wanted to give the best chance to processes of imitation.

More than we expected it turned out that cooperation was often observed in the experiments. Probably, the frame of the experiment suggested the idea to subjects that a price increase by everyone may be good for everybody. Obviously, no knowledge of the functional relationship between profits and prices is necessary for being led to this conjecture. In our analysis of the results we try to disentangle the effects of imitation and cooperative behavior.

In the last section of this paper our results will be discussed in the light of the recent experimental literature on imitation (Huck et al., 1999, 2000; Offerman et al., 2002; Bosch-Domènech and Vriend, 2003; Apesteguia et al., 2004), and on the relation between collusion and market size (see, e.g., Dufwenberg and Gneezy, 2000; Abbink and Brandts, 2002a, 2002b).

2. The model

The experiment is based on a model of mill price competition on the circle (see Beckmann, 1968; see also Salop, 1979).[1] The model can be taken to represent a circular town around an insurmountable mountain. There are n identical firms, indexed by $i \in N = \{1, \dots, n\}$, equidistantly located on a circle with a distance of one unit between any two consecutive firms. Consumers are evenly located around the circle with a density of one. The individual demand amounts to one unit, and below a maximum price $\bar{p}$, demand is inelastic. Above $\bar{p}$ individual demand is zero. There are transportation costs of t per unit of distance. Consumers buy from the cheapest firm, including the transport costs. Denote by $v \in (0, n]$ the circle coordinate, and let $v = i$ be the location of firm i for all $i \in N$. Hence, we can represent the *local price* at any particular location v by

$$p(v) = \min\left\{\bar{p}, \min_{i=1,\dots,n}\left(p_i + t|v - i|\right)\right\},$$

where $p_i \in P \subset \Re_+$ denotes the price chosen by firm $i \in N$, and P is the price set. If two or more firms offer the same price at some segment on the circle, these firms equally share such a segment. Let L_{im} denote the total lengths of all segments served by i and $m - 1$ others. Then, the ith total demand L_i can be written as

$$L_i = \sum_{m=1}^{n} \frac{1}{m} L_{im} \quad \text{for all } i \in N.$$

Let c denote marginal costs, then the ith profits are represented by

$$H_i = (p_i - c)L_i \quad \text{for all } i \in N.$$

Figure 1 shows an example with $n = 4$. Location is represented by the horizontal axis, while prices are represented by the vertical axis. Note that the circle is represented as a horizontal line starting and ending at the value 4. The vertical distances at locations $i = 1, 2, 3$, and 4 represent the prices chosen by the firms. For all $v \in (0, 4]$ the local price $p(v)$ is represented by the fat line.

Note that in Fig. 1 there is a segment between firms 2 and 3 that is unserved. That is, since in such a segment prices plus transportation costs are above $\bar{p}$, the demand of consumers located there is zero. Furthermore, note also that since $p_4 + t = p_3$, firms 4 and 3 share the segment served immediately at the left of firm 3.

Table 1 shows the values of the parameters used in the experiment.

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[1] There is an evolutionary literature on local interaction. See, e.g., Ellison (1993, 2000) and Eshel et al. (1998). Interestingly enough, Eshel et al. (1998) analyses the evolutionary dynamics emerging from a particular type of imitation.

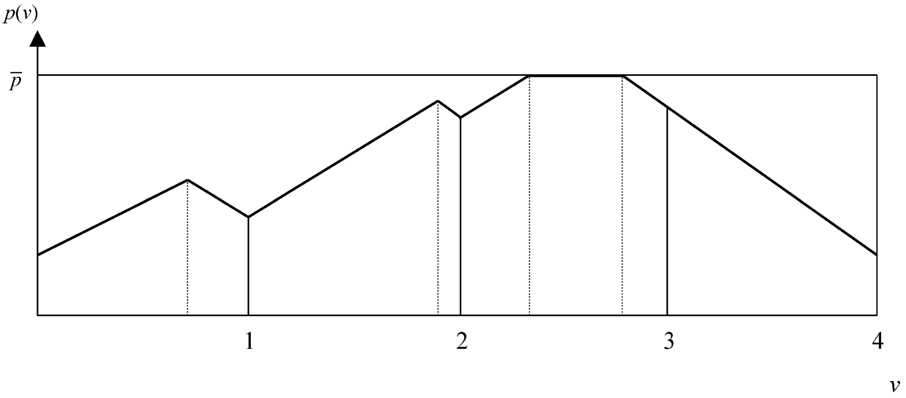

Fig. 1. An example with $n = 4$.

Table 1
Values of the parameters used in the experiment

Price set	Transportation cost	Marginal cost	Reservation price	Number of firms
$p_i \in [0, 500]$	$t = 120$	$c = 107$	$\bar{p} = 400$	$n = 3, 4, 5$

3. Theoretical benchmarks

Throughout this paper we focus our analysis on the Cournot–Nash equilibrium, imitation equilibrium, and joint-profit maximization outcome.

3.1. Cournot–Nash equilibrium

Given that the reservation price is large enough, the unique Cournot–Nash equilibrium of the price competition on the circle model is the strategy combination

$$p^C = (t + c, \dots, t + c) \quad \text{for } n = 2, 3, \dots$$

That is, the Cournot equilibrium of the model is unique, symmetric, and independent of the number of firms (see Beckmann, 1968; see also Selten and Ostmann, 2001).

3.2. Imitation equilibrium

This section presents a simplified version of imitation equilibrium theory for games in which all players have the same strategy set. For the complete formulation of the theory we refer to Selten and Ostmann (2001).

We start by introducing a number of definitions needed to introduce the notion of imitation equilibrium. Then, we will present its predictions for the price competition on the circle model. The *reference group* of a player $i \in N$ is the set of players $j \neq i$, $j \in N$, whose strategies and payoffs are observed by i. Denote this set by $R(i)$. In our experimental analysis the reference group of any i is formed by the left and right immediate neighbors. We say that i is a *success leader* at $s = (s_1, \dots, s_n)$ if i's payoff is at least as high as the highest payoff of a member of i's reference group. That is, i is a success leader at s if $H_i(s) \geqslant \max_{j\in R(i)} H_j(s)$. Assume that i is not a success leader at s. Then, a player j in i's reference group is a *success example* for i, if j has the highest payoff in i's reference group, greater than the highest payoff by somebody in the reference group of i who use the same strategy than i, and $s_i \neq s_j$ holds. That is, denote by $C_i(s)$ the set of players $k \in R(i)$ with $s_k = s_i$. Then, a success example for i at s is a player $j \in R(i)$ with $H_j(s) = \max_{k\in R(i)\cup\{i\}} H_k(s) > \max_{k\in C_i(s)} H_k(s)$. We say that i has an *imitation opportunity* at s if i is not a success leader and there is at least one success example for i.[2] We define a *destination* as a strategy combination without imitation opportunities.

An *imitation path* is a sequence of strategy combinations with the following properties:

(1) Each member of the sequence, except the first one, results from the immediately preceding one by all players with imitation opportunities taking one of them.
(2) The sequence is continued as long as there are imitation opportunities.

Note that implicit in the argument is that players do not anticipate the course of the imitation path. They simply react by taking one imitation opportunity, if there is one.

An imitation path may be infinite or may stop at a destination. Since a player may have more than one imitation opportunity, there are maybe many imitation paths starting at the same state. In this sense, an imitation process may generate many different imitation paths.

Let s^* be a candidate for an imitation equilibrium. In the definition of an imitation equilibrium only deviations by success leaders are considered.[3] Let i be a success leader. A deviation of i leads to a new state which we call a *deviation start*. A *deviation path* is an imitation path beginning with a deviation start.

Two kinds of deviation paths have to be distinguished. In a path with *deviator involvement*, the deviator i himself/herself has an imitation opportunity at some point. In an imitation path *without deviator involvement* this does not happen, and the deviator stays at his/her deviation strategy.

Suppose that a destination is reached by a deviation path without deviator involvement, and assume that at this destination the deviator's payoff is lower than at s^*. In this case the deviator will return to strategy s_i^* in s^*. This leads to a strategy combination which we call the *return start*. An imitation path beginning at a return start is called a *return path*.

An imitation equilibrium is defined as a destination satisfying the following four stability requirements (see Fig. 2):

(1) *Finiteness requirement*: No deviation path is infinite.
(2) *Involvement requirement*: The destination reached by a deviation path with deviator involvement must be the imitation equilibrium.

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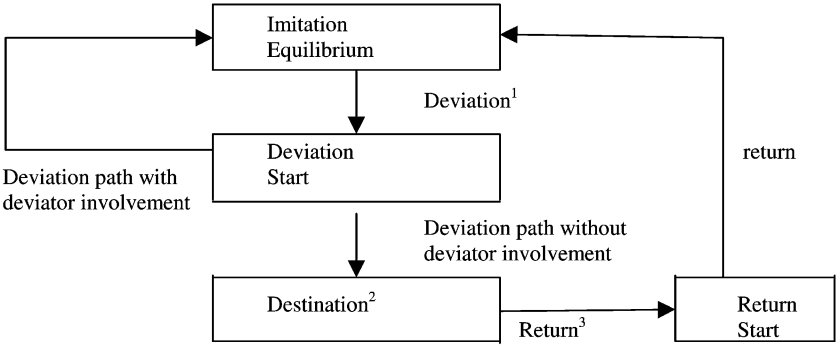
[2] This is known in the literature on evolutionary imitation rules as the "imitate the best max" rule. Of course a natural alternative is "imitate the best average" rule (see, e.g., Schlag, 1999). Using a stochastic stability approach Apesteguia et al. (2004) show that the predictions of both rules do not coincide in general. It remains a task for future research to connect the static concept of imitation equilibrium with the evolutionary imitation models.

[3] Note however that since for the price competition on the circle model we focus on symmetric imitation equilibria, this requirement does not play any role.



[1] Only success leaders engage in exploratory deviations.
[2] The deviator's payoff must be lower than at the equilibrium.
[3] The deviator returns to its old strategy in the equilibrium.

Fig. 2. Stability in imitation equilibrium.

(3) *Payoff requirement*: At every destination reached by a deviation path without deviator involvement the deviator's payoff is lower than at the imitation equilibrium.
(4) *Return requirement*: Every return path is finite and reaches the imitation equilibrium as its destination.

The interpretation of the finiteness requirement is straightforward. In the case of a destination reached by a deviation path with deviator involvement, the deviator has abolished experimentation in favor of imitation, and therefore cannot be expected to return. At a destination reached by a deviation path without deviator involvement, the deviator has no incentive to return, unless his/her payoff is lower at the imitation equilibrium. This leads to the payoff requirement. The return requirement is again straightforward.

Once we have introduced the notion of imitation equilibrium, we can present its predictions for the price competition on the circle model. *Interestingly enough, imitation equilibrium theory permits a less intense competition for the* 4- *and* 5-*player cases than for the* 3-*player case*. The symmetric imitation equilibria for the price competition on the circle model, where the reference group of i is i's left and right neighbors, are

$$p^I = \begin{cases} (2t/3 + c, 2t/3 + c, 2t/3 + c) & \text{for } n = 3, \\ \left(p^o, \ldots, p^o\right) \quad \text{with } t + c \geqslant p^o \geqslant 2t/3 + c & \text{for } n = 4, 5, \ldots. \end{cases}$$

For the intuition on the difference in these theoretical predictions consider the following stability analysis at $p = (p^o, \ldots, p^o)$, with $p^o = t + c$. This is the upper limit in the range of symmetric imitation equilibria with more than 3 firms. $p^o = t + c$ is also the Cournot equilibrium for any possible number of firms higher than 2. Assume that there are four firms and, for example, firm 2 deviates from (p^o, p^o, p^o, p^o) by a price cut of $\varepsilon > 0$. Then, it can be checked that

$$H_2\left(p^o, p^o - \varepsilon, p^o, p^o\right) > H_1\left(p^o, p^o - \varepsilon, p^o, p^o\right),$$

but since

$$H_4\left(p^o, p^o - \varepsilon, p^o, p^o\right) > H_2\left(p^o, p^o - \varepsilon, p^o, p^o\right),$$

Table 2
Theoretical predictions

Prediction	Prices	Individual profits per period
Symmetric imitation equilibrium for $n = 3$	187	80
Symmetric imitation equilibrium for $n > 3$	[187, 227]	[80, 120]
Cournot equilibrium	227	120
Joint-profit maximization	340	233

firm 2 is not a success example for firm 1. Furthermore, since

$$H_2\left(p^o, p^o - \varepsilon, p^o, p^o\right) < H_2\left(p^o, p^o, p^o, p^o\right),$$

firm 2 returns to the original strategy which shows that (p^o, p^o, p^o, p^o) is stable against this deviation. In the case of 3 firms, the stabilizing role of firm 4 in the above process is not present, and hence when firm 2 deviates by a price cut of ε, firms 1 and 3 imitate firm 2. Then $(p^o - \varepsilon, p^o - \varepsilon, p^o - \varepsilon)$ is a destination, and since

$$H_2\left(p^o, p^o, p^o\right) > H_2\left(p^o - \varepsilon, p^o - \varepsilon, p^o - \varepsilon\right),$$

firm 2 returns to the original strategy. However, since now

$$H_2\left(p^o - \varepsilon, p^o, p^o - \varepsilon\right) < H_2\left(p^o - \varepsilon, p^o - \varepsilon, p^o - \varepsilon\right),$$

firm 2 has an imitation opportunity and moves to $p^o - \varepsilon$. Therefore, the return path does not lead to (p^o, p^o, p^o), which shows that this is not an imitation equilibrium.

3.3. *Joint-profit maximization outcome*

The unique symmetric joint-profit maximization outcome is $p^J = (\bar{p} - 1/2t, \ldots, \bar{p} - 1/2t)$, for any $n = 2, 3, \ldots$. The price $\bar{p} - 1/2t$ is the highest one at which all customers are served. It can be seen easily that a higher price taken by all would decrease joint profits.

Table 2 summarizes the theoretical benchmark, using the parameters presented in Table 1.

4. Experimental procedure

We conducted 12 plays with 3 players, 6 plays with 4, and 6 plays with 5 players. The information on the market and the round-by-round information were the same in the three treatments. Namely, players knew that the experiment lasted 200 periods, that in each period each of them had to choose a price from 0 to 500 and that they could use up to 6 decimals, that the profit function was deterministic and dependent only on current prices, and that the exchange rate from Taler (the experimental currency) to Euro was 0.0005 Euro/Taler. Furthermore, participants also knew that it was possible to get negative profits, and that for this reason everybody was endowed with an initial capital of 1500 Talers. They were told that if a participant reaches a cumulated capital of zero or lower, this participant would have to leave the experiment. They knew that such a participant would get 4 Euro for participating. After each round players got information on their own prices, profits, cumulated profits, and also on the prices and profits of the two immediate neighbors. Players, however, were not given information on the precise profit function, nor on the number of firms, nor on the consumers' maximum willingness to pay.

The experiments were run in the *Laboratory for Experimental Economics* at the University of Bonn. A total of 90 students were recruited through posters on campus. The computerized program was developed using *RatImage* (Abbink and Sadrieh, 1995). Instructions were handed out to subjects and read aloud. An English translation of the instructions is shown in Appendix A. After instructions had been read and questions answered, subjects were randomly assigned to independent and visually isolated cubicles equipped with computer terminals. No communication between subjects was allowed. No time restrictions were imposed. On average, a session, including the instructions phase, lasted less than two hours. Players, right after the completion of the 200 periods and before being privately paid in cash, were asked to fill a short questionnaire. In this questionnaire participants were asked to describe reasons for their decisions. We report the questionnaire in Appendix B. Average earnings were around 16.15 Euro, with a minimum of 4 and a maximum of 22 Euro.

Only one of the subjects got bankrupt. This happened in a play of the 5-person case. Since a bankruptcy changes the theoretical values of the game we exclude this play from the evaluation.

5. A first look at the results

Figures 3, 4, and 5 show the distributions of individual prices, grouped by intervals of 5, for the 12 plays with 3 players (Fig. 3), the six plays with 4 players (Fig. 4), and the five plays with 5 players (Fig. 5). The intervals are of the form

$$\{5k, 5k+1, 5k+2, 5k+3, 5k+4\} \quad \text{with } k = 0, 1, 2, \ldots.$$

The predictions of imitation, Cournot, and joint-profit maximization are marked in the figures. It can be seen immediately that in the 3-player plays, prices tend to be lower than in the 4- and 5-player cases. This is in agreement with the theory of imitation equilibrium. In the 3-player case there is only one symmetric imitation equilibrium at the price of 187. In the case of 4- or 5-players the symmetric imitation equilibria fill the whole range of prices from 187 to the Cournot equilibrium price at 227.

In Fig. 3 the three highest frequencies of intervals are in the range from 185 to 199. In Fig. 4, however, the three highest frequencies are in the rage from 220 to 234.

In Fig. 5 the distribution is less smooth. The four highest frequencies are in the intervals from 195 to 199, from 220 to 224, from 245 to 249, and from 295 to 299. One cannot expect that the overall distribution of prices closely reflects any theoretical value which has to be approached by a learning process. However, it is important that behavior in 3-person plays tends to be more competitive than in 4- and 5-person plays as predicted by imitation equilibrium theory, contrary to the economic intuition that more competitors entail lower prices.

In Table 3 we see the average prices and median prices for 3-, 4-, and 5-player plays. The phenomenon of lower prices in the three-person case is also visible there. There is almost

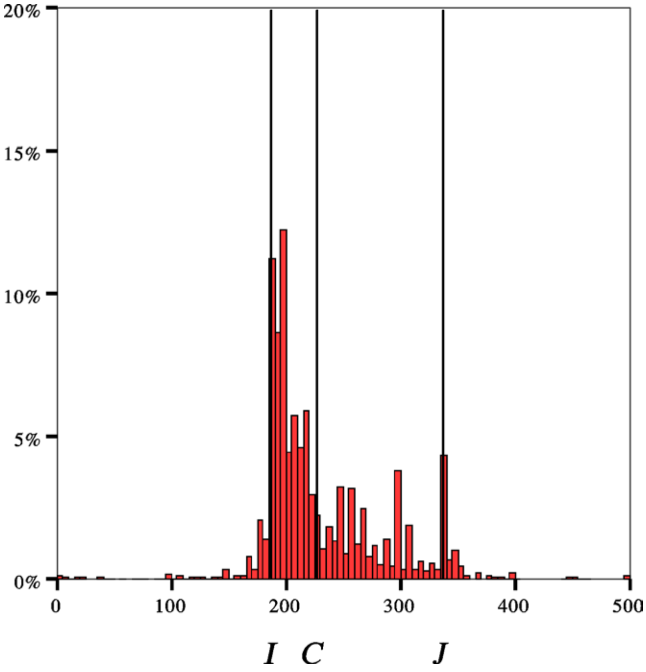


Fig. 3. Distribution of individual prices for the 12 plays with 3 players.

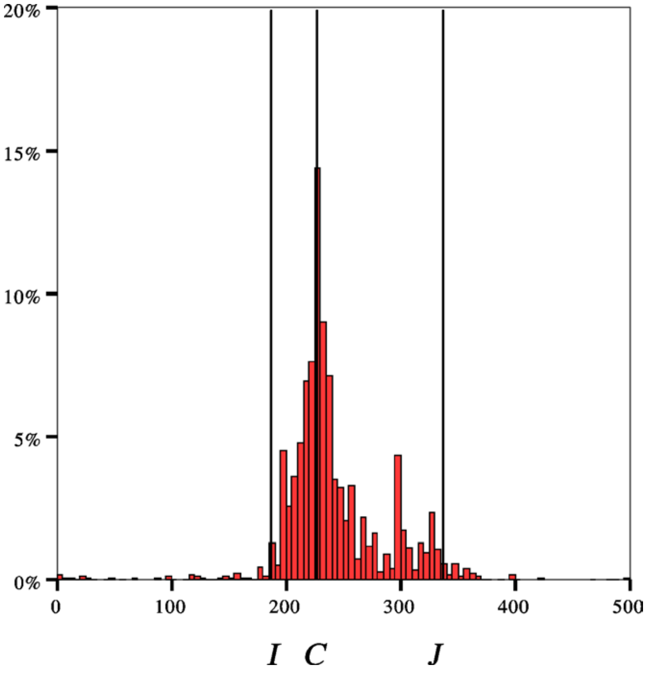


Fig. 4. Distribution of individual prices for the 6 plays with 4 players.

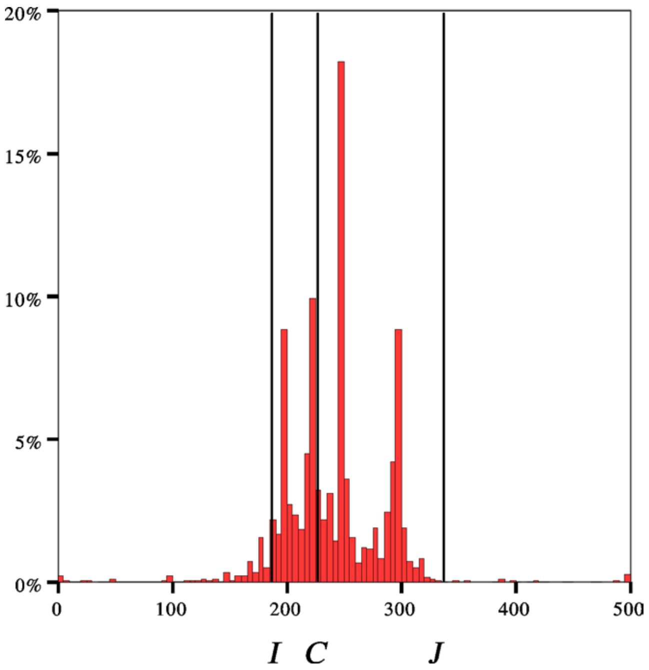


Fig. 5. Distribution of individual prices for the 5 plays with 5 players.

Table 3
Average and median prices by number of players

No. of players	Average price	Median price
$n = 3$	231	233
$n = 4$	242	244
$n = 5$	241	246

no difference between the 4- and 5-player cases. Admittedly, the average and median prices are above the range of imitation equilibrium prices in all three cases. Among the theories considered here, the Cournot equilibrium best explains the prices of Table 3. However this impression is treacherous. The averages hide what is really going on. In fact the individual plays are very different from each other.

The time series of all prices for play 1 of the 3-player case is shown by Fig. 6. This is a clear example of behavior converging to the joint-profit maximization price 340. It can also be said that for some time, some players tried to gain an advantage by undercutting and were punished by others. In the comments player 2 explicitly mentioned the “education” of neighbors if they choose prices other than the joint-profit maximizing price of 340. Player 3 remarks “one player alone can destroy the equilibrium if he tries to gain at the cost of others.”

Figure 7 shows the time series of all prices for play 8 of the 3-player case. This is an example of unstable cooperation. Cooperation is reached and breaks down after a while. The establishment of cooperation is repeated several times.

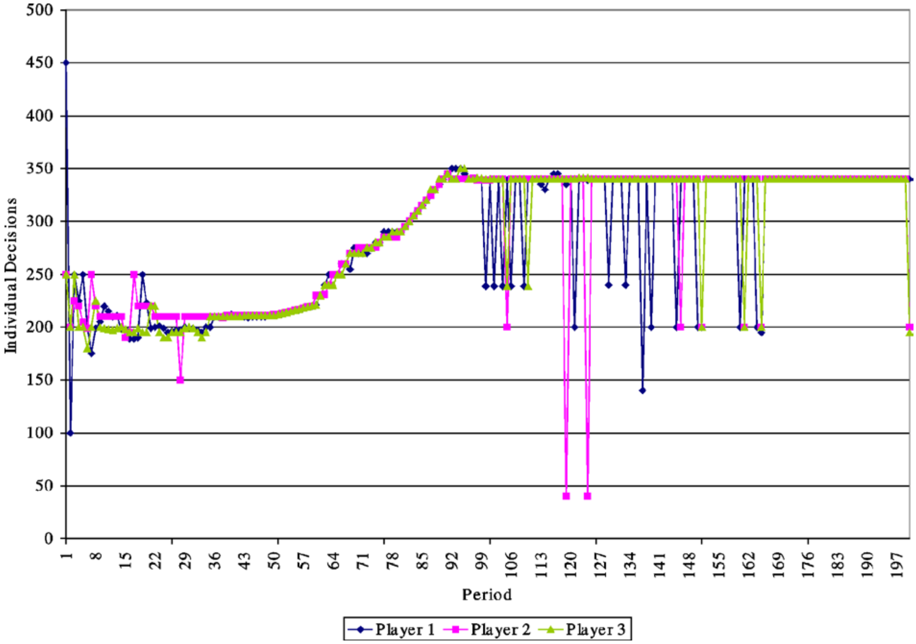


Fig. 6. Time series of all prices for play 1 of the 3-player case.

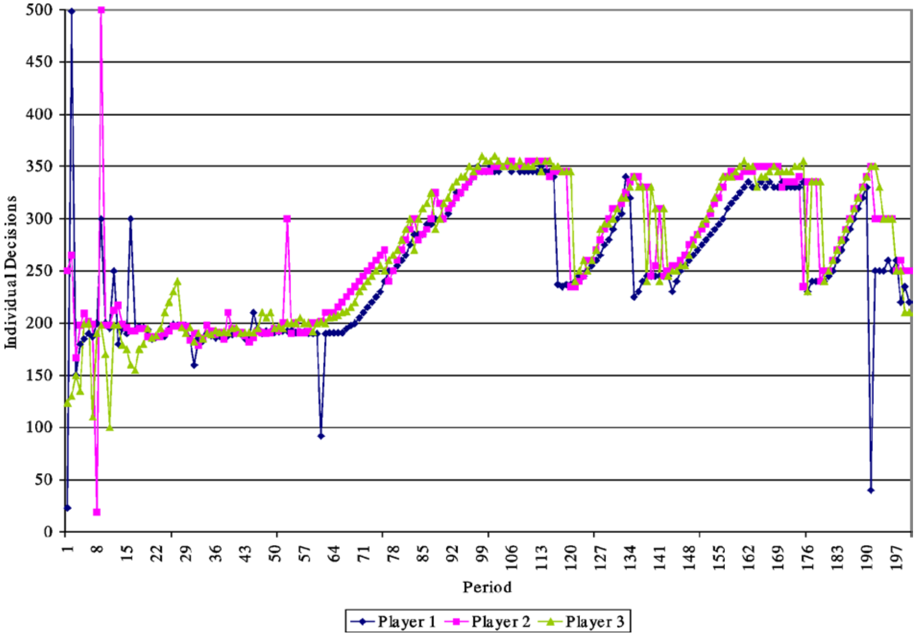


Fig. 7. Time series of all prices for play 8 of the 3-player case.

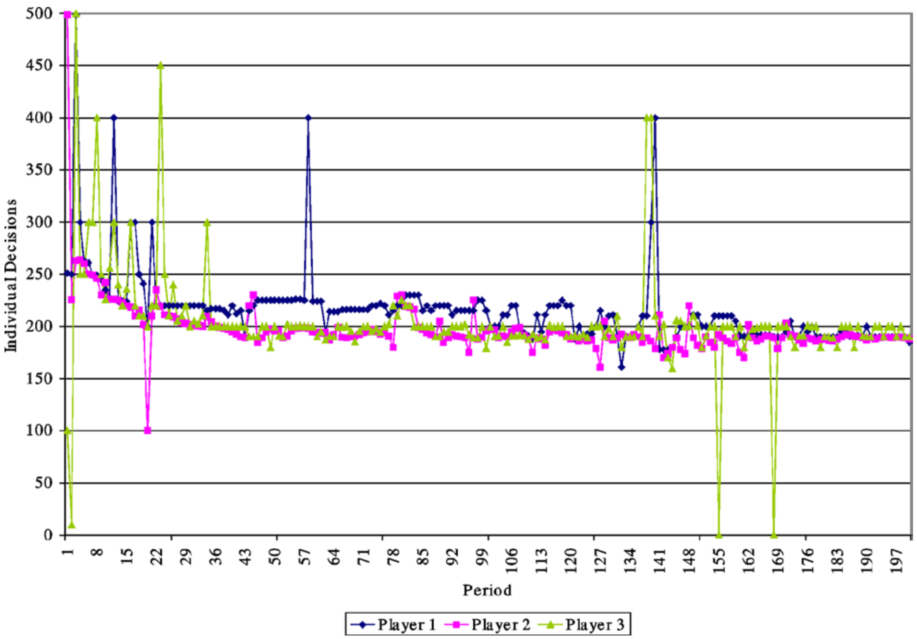


Fig. 8. Time series of all prices for play 9 of the 3-player case.

Play 9 of the 3-player case is shown by Fig. 8. This figure suggests convergence to the imitation equilibrium. Player 1 tried to establish cooperation but did not succeed. He writes in the description of the reasons for his decisions: "I have tried to increase prices even if this could imply losses in the short run." He answers the question about changes of his decision behavior in the course of the experiment as follows: "Unfortunately my neighbors did not follow, therefore I chose lower prices." The other players said in the questionnaires that they wanted to maximize their payoffs. Figure 8 suggests that they tried to do this relying on imitation.

Figure 9 shows play 2 of the 5-player case. This example shows that cooperation can happen even with 5 competitors.

The fact that in the 3-player case prices tend to be somewhat lower than in the 4- and 5-player cases suggests that imitation plays an important role in our data. However, cooperation is clearly very much present in the behavior of our subjects. Cooperative intentions are very often expressed in the questionnaires. We have to try to disentangle the effects of imitation and cooperation.

6. Cooperation

In this section we shall introduce some operational definitions connected to cooperation. An average price is counted as *cooperative* if it is nearer to the joint-profit maximization price than to the Cournot equilibrium price.

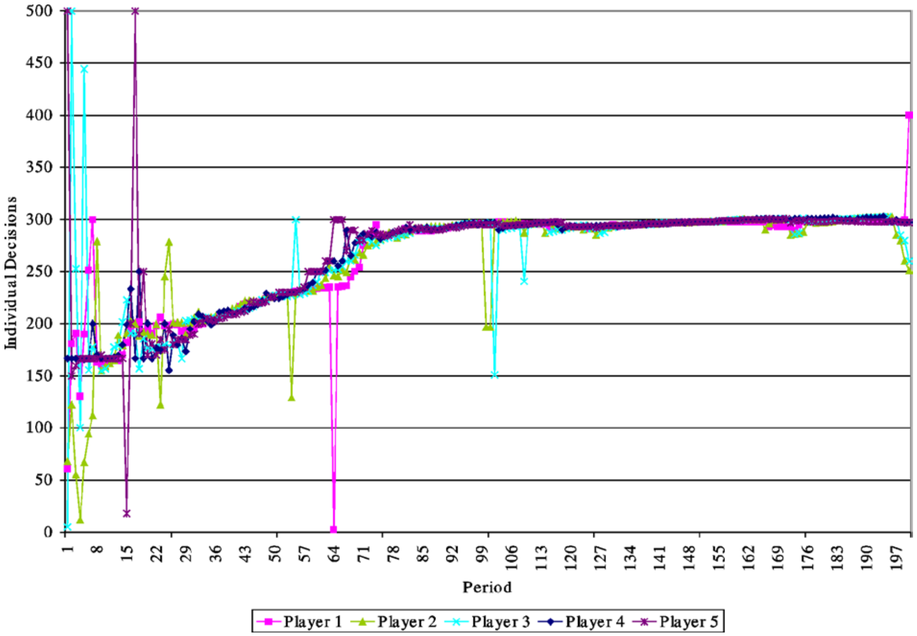


Fig. 9. Time series of all prices for play 2 of the 5-player case.

Cooperation is often interrupted by deviation and punishment. These interruptions may be of short duration like in Fig. 6, or they may last for a longer time like in Fig. 7. In order to remove occasional interruptions of cooperation we computed average prices for groups of 10 consecutive prices from 1 to 10, 11 to 20, and so on, until 191 to 200.

In this way we receive a time series of 20 values for every play. We call this the *block average time series*. A play is classified as *cooperative* if the block average time series reaches at least once a value closer to the joint-profit maximization price than to the Cournot equilibrium price. A cooperative play is called a play with *stable cooperation* if the block average price remains cooperative until the end of the experiment, after it has become cooperative. Other cooperative plays are plays with *unstable cooperation*.

For every cooperative play we define the *number of periods before cooperation* as the number of periods until a cooperative average price is reached for the first time in the play. In noncooperative plays this number is defined as to 200, in spite of the fact that occasionally a cooperative average price may also be reached in such plays. This happens mostly at the beginning of plays, when the subjects sometimes explore very high prices. Our definition of cooperation avoids classifying plays with only isolated cooperative average prices as cooperative.

Table 4 provides an overview concerning the incidence of cooperation. Cooperative plays are more frequent for plays with 3-players than for plays with 4- and 5-players. However, the difference is not statistically significant. Similarly, cooperation seems to be reached a little earlier in plays with 3-competitors than in those with 4- or 5-competitors. However, these differences are also not significant.

Table 4
Cooperation

No. of players	Cooperative plays	Stable cooperative plays	Plays without cooperation	Average No. of periods before cooperation[a]
$n = 3$	7	4	5	146
$n = 4$	2	1	4	168
$n = 5$	2	2	4	155

[a] The average is taken over all plays, including those without cooperation.

Typically, cooperation is reached by small steps. Some players increase their prices by small amounts and others follow. This creeping ascent to cooperation stops as soon as the joint-profit maximization price is reached, but sometimes also earlier. In this way the players who initiate cooperation do not loose too much. It is interesting that cooperation is possible without any knowledge of the exact relation between prices and profits. Cooperation can be achieved by a collective process of trial and error. Remarkably, in connection with this observation, Huck et al. (2004a) show theoretically, in the context of a Cournot oligopoly, that if all firms increase, respectively decrease, their output as long as this leads to higher profits, then this process converges to the joint-profit maximization outcome.

7. Stronger competition before cooperation among three than among four and five

For every play we have computed the *average price before cooperation*. This is the average of all prices of a play before cooperation is reached for the first time. We also computed the averages of average prices before cooperation for all plays with 3-, 4-, and 5-players. Table 5 shows the overall average prices, together with these averages for prices before cooperation.

We can see that the average price before cooperation tends to be lower for $n = 3$ than for $n = 4, 5$. A permutation test on the basis of the average price before cooperation for the individual plays shows that this result is significant at the 0.01 level (two-sided).

The result is a qualitative confirmation of imitation equilibrium theory. However, even for $n = 3$ the average prices before cooperation is considerable higher than the theoretical value of 187. This is partially due to our definition of a cooperative average price. We count only prices above 283.5 as cooperative. Therefore, in the process of reaching cooperation many relatively high prices have to be attained before this limit is reached. Unfortunately, it is not easy to find a non-arbitrary definition of cooperation which includes the earlier part of the creeping ascent to the joint maximum.

The result is remarkable since stronger competition for fewer players is not predicted by any other oligopoly theory. Imitation equilibrium predicts a lower price for 3-players than for 4- or 5-players, and this phenomenon is actually observed. In the last section of this paper we will discuss the connection of this finding with the experimental literature on the relation between market size and competitiveness.

Table 5
Average price before cooperation

No. of players	Overall average prices	Averages for prices before cooperation
$n = 3$	231	211
$n = 4$	242	228
$n = 5$	241	223

8. Direct evidence for imitation

In the last section we have seen that the theory of imitation equilibrium is to some degree confirmed by the comparison of average prices before cooperation for $n = 3$ on the one hand, and $n = 4, 5$ on the other hand. In the following we want to explore the question whether there is also direct evidence for imitation on the level of individual behavior.

Given how large the size of the action space is (any price between 0 and 500 with up to 6 decimals), we cannot expect that subjects will copy the strategy of someone else. Instead, here we study whether subjects respond to the direction suggested by imitation. Consider the situation of a player at the beginning of a period which is not the first one. Suppose that the player has an imitation opportunity. The last period's price of the player to be imitated may be higher than the player's own price. In this case we speak of an *upward* imitation opportunity. Analogously, the player has a *downward* imitation opportunity if the price to be imitated is lower than his/her own price. In principle, a player could have an upward and a downward imitation opportunity at the same time, because both of his/her neighbors may have equal profits higher than his/her own profits, and one of the neighbors may have a higher price and the other a lower one. However, there was no such case in our data. Thus, a player has either an upward or a downward imitation opportunity, or none at all.

A player may move his/her price up or down or not at all. Table 6 shows the relative frequencies of all combinations of imitation opportunity and price movement. The entries in this table on the diagonal are greater than those which would be obtained if the imitation opportunity and the movement would be independently distributed with the respective marginal distributions. This is how it should be in the presence of imitation, since an upward imitation opportunity should predominantly lead to an upward movement, a downward imitation opportunity to a downward movement, and no imitation opportunity to no movement at all. The *diagonal surplus* is the sum of the entries in the diagonal minus the sum of the values these entries would have under the counterfactual independence assumption described above. In the case of Table 6 the diagonal surplus is 0.11.

A table like Table 6 can be constructed for each play separately. For 22 out of the 23 plays, the diagonal surplus is positive. A binomial test shows that this is significant on the 0.001 level (one-sided). Consequently, we can say that imitation is clearly present in the behavior of the subjects.

9. Cooperation and imitation

In this section we analyze the connection between cooperation and imitation. *We will show that cooperative attempts can be explained as deviations from imitative behavior.*

Table 6
Imitation opportunity and movement

Imitation opportunity	Movement Up	Down	None
Upward	**0.09**	0.03	0.03
Downward	0.11	**0.17**	0.13
None	0.19	0.08	**0.16**

Table 6 also shows the influence of attempts towards cooperation. Downward imitation opportunities are often not taken by players who try to achieve cooperation. Such players will also move upwards in situations where there is no imitation opportunity.

For each player let a_{21} be the number of upward movements and a_{22} the number of downward movements in cases of a downward imitation opportunity. The quotient $a = a_{21}/a_{22}$ measures the tendency of a player to move upwards rather than downward in spite of a downward imitation opportunity. We can look at the quotients $a = a_{21}/a_{22}$ as an indicator of the cooperativeness of a player. The more cooperative a player is, the more willing he/she may be to signal cooperativeness by an upward movement in face of a downward imitation opportunity. Therefore we call $a = a_{21}/a_{22}$ the *cooperativeness indicator* of a player.

The *maximal cooperativeness indicator* of a play is defined as the maximum of all the cooperativeness indicators of all players in this play. We computed a biserial correlation coefficient between the cooperativeness of a play in the sense of the definition given in Section 6, and the maximal cooperativeness indicator of a play. This biserial correlation extended over the 23 plays is equal to 0.472, which is significant at the 5% level, two-tailed.

A player is called a *cooperator* if his/her cooperativeness indicator is greater than one. This means that a cooperator is more willing to move upwards than downward in the face of a downward imitation opportunity. This definition of a cooperator is quite strong and does not exclude the possibility that somebody that is not classified as a cooperator also sometimes raises the price as a cooperative signal, even if most of the time he/she does not behave in this way in the face of downward imitation opportunities.

The presence of at least one cooperator in a play seems to facilitate the attainment of cooperation. This is shown in Table 7. Clearly, Table 7 has more entries on the main diagonal than outside the main diagonal. This is significant by Fisher's exact test on the 1% level of significance.

A cooperator more often than not chooses to increase his/her price in order to induce other players to follow him/her upward, even in the face of a downward imitation opportunity. Such players initiate a creeping ascent to a high price level, as shown by Figs. 6, 7, and 9, which then may be followed by other players.[4]

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[4] Note that a player by initiating such a process incurs losses, and hence his/her behavior is not well captured by the trial and error process of Huck et al. (2004a), mentioned in Section 6. A cooperator, in this sense, is willing to incur short-run losses in order to get long-run gains.

Table 7
Plays with cooperators

	Cooperative plays	Non-cooperative plays
At least one cooperator	7	1
No cooperator	4	11

The opposite behavioral effects of cooperation and imitation can also be seen in the fact that the diagonal surpluses tend to be lower in plays with cooperation than in plays without cooperation. A permutation test yields a significance on the 0.01 level (two-sided). There is also a positive Spearman rank-order correlation of $r_s = 0.556$ between the number of periods before cooperation and the diagonal surplus. This confirms the impression that a play shows the more presence of imitation the less cooperative it is.

The behavior of the subjects is partially influenced by imitative tendencies, and partially by attempts to cooperate. Both kinds of behavior have different consequences. One may say that cooperation crowds out imitation, when it happens. Nevertheless we do not want to exclude the possibility that some other influences not considered here enter the picture. Thus, probably also exploratory behavior has a role, as suggested by the theory of imitation equilibrium.

10. Discussion

Our results show that behavior in the price competition oligopoly on the circle can be explained by imitation and cooperation. Imitation has the tendency to move prices in the direction of imitation equilibrium, whereas cooperation has the tendency to move prices upwards in the direction of the joint-profit maximization price.

Imitation has also been observed in other oligopoly experiments (Offerman et al., 2002; Huck et al., 1999, 2000; Bosch-Domènech and Vriend, 2003; Apesteguia et al., 2004).

Offerman et al. (2002) report on 3-person Cournot oligopolies repeated over 100 periods. There were three treatments called Q, Qq, and $Qq\pi$. In the first treatment Q only feedback on aggregated quantities was given, in the second treatment Qq also feedback on individual quantities, and finally in the treatment $Qq\pi$, in addition to this, feedback on individual profits were given. Especially their treatment $Qq\pi$ shows strong tendencies towards imitation, but also towards collusive outcomes. This is in agreement with our findings. In the treatments Q and Qq there seems to be a greater role for Nash equilibrium. In all three treatments the subjects had complete information about the game, and receive enough feedback for the computation of best replies. Nevertheless, in treatment $Qq\pi$, with information on individual actions and profits, Nash equilibrium does not seem to attract behavior, while the imitation prediction is approached very often.

Two papers by Huck et al. (1999, 2000) report on various oligopoly experiments. In the first paper, Cournot oligopolies with four players are run over 40 periods. In each period a player could change his/her action with a probability of $2/3$. There are 5 treatments varying with respect to the information on game structure and feedback. In these games the imitation equilibrium is the Walrasian outcome with equal quantities for all players. The results show that information on the game structure decreases competitiveness, whereas more feedback on profits and actions of the others increases it. Imitation equilibrium is a theory for low market information and good feedback about actions and profits of other players. Under these conditions Huck et al. find evidence for imitation. However, cooperation seems to be less visible in their games. Maybe, in similar experiments run over a greater number of periods more cooperation could be observed.

In the Cournot oligopoly experiments by Huck et al., average quantities were often higher than Cournot quantities. This is somewhat surprising in view of the old experimental oligopoly literature. In the 1950s, Cournot theory was strongly rejected by theoreticians but actually, earlier experimental research supported it, in the sense that it seemed to yield a better explanation than other theories. Deviations, when they occurred, tended to be in the direction of lower outputs and of more cooperation (Sauermann and Selten, 1959; Hoggatt, 1959; Fouraker and Siegel, 1963; and Stern, 1967).

The second paper by Huck et al. (2000) reports on oligopoly experiments with differentiated products run with four players over 40 periods. There were treatments with quantity variation and price variation, and also with feedback on average actions of the others on the one hand, and in addition to this, feedback on individual actions and profits of the others, on the other hand. The subjects could make use of a profit calculator which permitted them to compute best-replies. In the high feedback cases imitation seems to be more important than in the low feedback cases under quantity and price competition.[5]

In the price variation experiments, under both feedback conditions, there is a substantial presence of prices higher than the Nash price, indicating some tendencies toward cooperation. Maybe also here, the picture could be different for a greater number of periods. Since subjects had access to a profit calculator in all games, regardless of the feedback conditions, it might be argued that the differences between low and high feedback must be due to social comparison effects rather than to cognitive factors. However, it is quite possible that many subjects who receive feedback on profits and actions of the others, readily rely on this kind of information and do not even try to use the profit calculator. The subjects may not be aware of the fact that hypothetical profit calculations are a better guide to behavior than imitation of successful others.

Bosch-Domènech and Vriend (2003) conducted Cournot oligopolies with two or three players, extended over 22 rounds. They had three treatments "easy," "hard" and "hardest," which differ with respect to the effort required for profit calculations. The hypothesis is that imitation will drive behavior in the last two treatments. In the "easy" duopoly case, results in the last 2 periods were concentrated on the joint-profit maximization and Cournot equilibrium. In the "easy" triopoly experiments, behavior is around Cournot equilibrium. Finally, in the "hard" and "hardest" conditions, in both the duopoly and triopoly experiments, behavior is dispersed over a wide range, including the imitation range. Bosch-Domènech and Vriend show that in no treatment there is a tendency towards the Walrasian

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[5] This, together with the experiment by Offerman et al. (2002), suggests that the information feedback is a relevant variable for the predictive success of imitation. There are other price competition experiments (sometimes framed in terms of first-price auctions) that look to the effect of information feedback. See, for example, Isaac and Walker (1985), Dufwenberg and Gneezy (2002), and Ockenfels and Selten (2003). However, since these experiments were not directed towards imitation, we do not review them here.

outcome. The authors conclude that imitation was not significantly present in their data. Interestingly, treatments "hard" and "hardest" are comparable to some of the treatments in Huck et al. (1999), where imitation seemed to be more prevalent. However, there are some differences in the designs of the two studies that may account for these different results, like for example the number of firms, and the number of periods. Bosch-Domènech and Vriend show, by means of a computational analysis, that in fact the number of firms may play a significant role explaining the differences. However, it remains an open question to elucidate the *behavioral* impact of such variables.

Apesteguia et al. (2004) study 3-player Cournot oligopolies randomly matched from populations of 9 subjects over 60 periods. The matching technology is as follows: each player is randomly allocated one of three *roles*, that is kept fixed for the entire experiment. At each period, subjects are randomly matched into three *groups*, such that always each group is formed by one subject from each role. Subjects do not have information on the payoff function. The treatments differ in the subjects' reference group. In one treatment subjects are informed of the actions and payoffs of subjects in the same role as him/herself, in another of the actions and payoffs of subjects in the same group as him/herself, and finally in a third treatment subjects get all the above information. The results provide support for a generalized evolutionary imitation model both on the aggregate and individual level. However, like in the previous cases, cooperation does not seem to play a role in their data. Once more, it seems that the time horizon of the experiment may play a fundamental role in this respect.

The relation between market size and degree of competitiveness has also been the focus of experimental research. In Cournot markets, Huck et al. (2004b) provide a recent review of a number of experiments (including those already cited in this section) with respect to the "number effects."[6] They conclude that "collusion sometimes occurs in duopolies and is very rare in markets with more than two firms." This contrasts with our results, where there was no significant difference between the number of collusive plays in the 3-firm case versus the 4- and 5-firm treatments. However, there is an important difference between our experiments and those reviewed in Huck et al. We study price competition, while they only look to quantity competition experiments.

Experimental studies addressing the issue of "number effects" in price competition include Fouraker and Siegel (1963), Dolbear et al. (1968), and Stoecker (1980). These studies conclude that there is a negative relation between prices and market size. More recent studies include Dufwenberg and Gneezy (2000), and Abbink and Brandts (2002a, 2002b). Dufwenberg and Gneezy (2000) analyzes the classical Bertrand price competition model, Abbink and Brandts (2002a) study a model of price competition under decreasing returns, and Abbink and Brandts (2002b) focus on price competition under cost uncertainty. Again, these papers conclude that more firms in the market place lead to a higher degree of competition.

Therefore, it emerges that there is a remarkable difference between our results, and those reported in the literature. There are many variables that differ between our study and those in the literature, but probably the most significant are the nature of interaction,

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[6] See also Holt (1995).

the degree of information on the relation between prices and profits, and the temporal horizon. Our design involves a spatial competition situation, in an environment with very little information, repeated over a large number of periods. The precise influence of these variables on the maintenance of collusion in relatively large market sizes, remains as an open question for future research. Importantly, our results make clear that statements on the influence of market size on competitiveness should be taken with care. Institutional and informational aspects may play a significant role.

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Appendix A. The written instructions

Rounds: The experiment is composed of 200 rounds.

Prices: In every round each participant has to choose a price between 0 and 500. You can use up to 6 decimals.

Profit: Profits depend on prices. Randomness does not play any role at all in this relation. The connection between prices and profit is the same in every round. This connection will not be announced to you though. Profit can also be negative.

Cumulated Profit: You begin with an initial capital of 1500 Taler. The cumulated profit of the next round is the sum of the current profit and the previous cumulated profit.

Feedback: After every round you get information on:

(1) Your own price, your profit, and your cumulated profit.
(2) The prices and profits of two other participants, with whom you interact and who are called your "left" and "right" neighbors. These neighbors stay the same in every round, but are kept anonymous during the whole experiment.

Besides your neighbors, other participants might interact with you.

Bankruptcy: If your cumulated profit becomes zero or negative, you have bankrupted and therefore must leave the experiment. In the case one of your neighbors bankrupts in the course of the experiment, you will be informed of this.

Payment: The final cumulated profit after the 200 rounds will be paid to you according to the following exchange rate: 1 € per 2000 Taler. Moreover you will receive a lump sum payment of 4 € irrespective of your performance in the experiment. In the case you bankrupt, you will receive a total of 4 €.

Appendix B. The questionnaire

(1) Describe briefly the reasons for your decisions:
(2) Did your strategy change during the course of the experiment? If so, how did it change?
(3) Would you follow a different strategy in retrospect? If so, which and why?
(4) Comments on the experiment.

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