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SOCIAL LEARNING IN MARKET GAMES

3/2005

WORKING PAPER

Abstract - The aim of our experiments is to test the effect of different information settings on firms' behaviour in duopoly price and quantity games. We find that, when players have full information on their rivals' choices, the *imitation* rule prevails and such learning behaviour induces more competitive outcomes in the Cournot market designs. By the same token, when information on the average industrial profit is provided, there is evidence of an increase in cooperation, and the majority of players experiment with new strategies when their payoff falls below the average profit (F. Palomino and F. Vega-Redondo, 1999; H. Dixon, 2000)

Keywords: Learning, Cournot and Bertrand experiments.

J.E.L. Classification: D83, C91.

FORTHCOMING: Journal of Economic Behaviour & Organization, 2005

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1. Introduction

The effect of different information settings on firms' behaviour is a long debated issue, and there is little theoretical agreement on their predicted impact on competition[1]. The Nash prediction on oligopoly dynamic models, with fixed endpoints, suggests that the disclosure of individual firm's decisions or the publication of aggregate statistics on the market performance are irrelevant to the degree of market competition, since individual behaviour should be unaffected in both cases.

An alternative prediction has been put forward in most of the traditional Industrial Organization models on oligopoly (Stigler, 1964) and has inspired many regulatory and antitrust policies[2]. According to this point of view, whilst the publication of general statistics on industrial profitability has no impact on competition, since behaviour should be unaffected, the full disclosure of individual data is detrimental to competitive practices. In fact, when information is complete, cartels can be enforced, since any defection is immediately detected and punished and therefore collusion is encouraged.

Evolutionary models on learning and bounded rationality take a completely different perspective, and consider *all types of information* as relevant to individual behaviour, but the predicted effect on competition is different in the two cases we consider (full disclosure of individual data, publication of general statistics on the industrial profitability). Knowing, in fact, other people's actions *may* induce imitation of the more successful strategies. Such behavioural rules will increase the level of competition in the industry (F. Vega-Redondo 1997, K. R. Schenk-Hoppé, 2000).

On the other hand, information on the industry's average profitability might induce more collusive outcomes, if such markets signals are perceived by players as *aspiration levels* and they therefore try new strategies anytime their profits fall below such a threshold (F. Palomino and F. Vega-Redondo, 1999; H. Dixon, 2000; J. Oechssler, 2002).

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[1] S. Huck, H.-T. Normann, J. Oechssler, 2000.

[2] See S. Huck, H.-T. Normann, J. Oechssler, 2000, for a survey of European and American anti-trust policies on the publication of individual firms' data.

The aim of our work is to provide a test both of the *imitation rule* and the *aspiration rule* in duopoly markets. We report the results from a series of experiments on Cournot (homogeneous and differentiated products) and Bertrand (differentiated products) duopoly markets with no uncertainty and fixed endpoints. For each model, the experiments are designed with three alternative information settings. In the first treatment, participants are informed only on their own payoff for the period (Experimental Design 1; ED 1, hereafter); In the second treatment, participants are informed on their own performance, as well as on the average profit in all duopoly markets (Experimental Design 2; ED 2, hereafter). Finally, in the third design, players are informed on their own performance and their rivals' actions and profits (Experimental Design 3; ED 3, hereafter). In all experimental sessions, however, players were informed on the cost and demand functions and the number of periods the experiments lasted. We find that the *imitation* learning rule prevails when players have full information on their rivals' previous choices, and such learning behaviour induces more competitive outcomes in all three market models in our third treatment (ED 3). As for the *aspiration* learning rule, our evidence is in line with the predictions, in as much as we observe – in the two Cournot models - a greater proportion of players using cooperative strategies in the second treatment (ED 2) compared to our benchmark setting (ED 1) and to our "imitation" setting. Furthermore, we analyse the dynamics of the individual choices in the ED 2 and in the ED 3 treatments, in order to test whether aspiration and imitation rules were successful codes of behaviour. We find that, in the majority of the cases, players do experiment with new strategies when their payoff falls below the average (or the opponent's) profit, as predicted by the learning hypotheses.

The *imitation rule* has recently received quite a lot of attention (S. Huck, H. T. Normann, J. Oechssler, 2000; T. Offerman, J. Potters, J. Sonnemans, 2002, A. Bosch-Domenech, N. J. Vriend, 2003). The results of these studies generally confirm the existence of such behaviour in markets In two cases (S. Huck, *et al.*, 2000, T. Offerman, J. Potters, J. Sonnemans, 2002[3]) the imitation hypothesis is confirmed. In the third paper (A. Bosch-Domenech, N. J. Vriend. 2003) the hypothesis is rejected; however, the

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[3] In T. Offerman, J. Potters, J. Sonnemans, 2002, subjects played Cournot games in markets with three sellers. When information on individual quantities and profits was provided (as well as the information on the aggregate output level), the frequency distribution was actually bi-modal, with a peak at the collusive equilibrium and another peak at the Walrasian equilibrium.

authors find significant differences in behaviour in their experimental treatments, and, in the case of the "hardest" design (little information on the market structure and little time to make decisions) and markets with three sellers, their findings are in line with the other studies. The evidence on the *aspiration rule* is scanter, though this type of learning behaviour has a long historical tradition (H. Simon, 1955, 1956). To date, the only experimental study which tests the rule in an oligopoly game shows that cooperative outcomes[4] are more likely to occur when players are informed on the average profitability of the industry (H. D. Dixon, P. Sbriglia, E. Somma, 1998), as predicted in the evolutionary models. In contrast, here, we follow the F. Palomino and F. Vega Redondo dynamic learning model and analyse different models of market competition.

Though the study of both the imitation and the aspiration rules have so far been considered as relevant areas for the understanding of "social learning", there is no research work which provides a direct comparison between the two main aspects of the problem ("*imitate the average*", *"imitate the best"* (J. Oechssler, 2002), as we try to do here.

2. Theoretical Background and Experimental Predictions

The experimental designs are based on three types of duopoly market models. In the first case, firms choose the quantity to produce in each period and goods are homogeneous. The inverse demand function and the corresponding profit function for firm *i* are, respectively:

$$p = a - b(q_1 + q_2)$$

$$\pi_i = (p - c)q_i$$

By the same token, in the second case of quantity competition (differentiated goods), market demand and individual profits are represented by the functions:

$$p_i = a - b(q_i + \theta q_j)$$

$$\pi_i = (p_i - c)q_i$$

Finally, we consider a model of price competition, where the direct demand function is:

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[4] The experiments were based on H.D.Dixon *et al.* 1994 and H.D.Dixon *et al* 2002 models of market competition. The paper considered an oligopoly model where firms knew their own and the average pay-off in the industry. Firms chose decision rules for trading, and were matched according to a "playing the field" rule. The results showed that in most cases there was clear evidence of convergence to an equilibrium, and whilst both Cournot and Collusive outcomes were selected, the Collusive equilibrium was more common.

$$q_i = \alpha - \beta(p_i - \theta p_j)$$

Here, again, profits are:

$$\pi_i = (p_i - c)q_i$$

Table 1 reports the value of the demand coefficients in the three market models:

Table 1: Values of the Demand coefficients

	a	b	θ	α	β	θ
COURNOT H.P.	24	$\frac{1}{2}$				
COURNOT D.P.	24	$\frac{2}{3}$	$\frac{1}{2}$			
BERTRAND D.P.				24	2	$\frac{1}{2}$

Notice that:

$$\alpha = \frac{a}{b(1+\theta)} \text{ and } \beta = \frac{b}{b^2(1-\theta^2)};$$

In all three models, the cost function is given by:

$$C = cq_i;$$

where the marginal cost, *c*, is equal to zero.

Concentrating on the symmetric solutions in the market games, **(1)** – **(3)** report the values of the Nash, Collusive and Walrasian equilibria in the three models, respectively[5]. Table 2 reports the corresponding values of the equilibrium prices (quantities) and profits.

$$q_i^C = \frac{a-c}{3b} = 16 \; ; \quad q_i^{cc} = \frac{a-c}{b(2+\theta)} = 14.4 \; ; \quad p_i^b = \frac{\alpha - c}{\beta(2-\theta)} = 8 \qquad \textbf{(1)}$$

$$q_i^c = \frac{a-c}{4b} = 12; \; q_i^{cc} = \frac{a-c}{b(2+2\theta)} = 12; \; p^{cc} = \frac{a-c}{2} = 12;$$ [6] **(2)**

$$q_i^c = \frac{a-c}{2b} = 24; \quad q_i^{cc} = \frac{(a-c)}{2b} = 18; \quad p^b = 6:$$ [7] **(3)**

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[5] The superscripts stand respectively for the Cournot models (homogeneous, *c,* and differentiated products, *cc*,) and the Bertrand model of competition, (*b*).

[6] The equilibrium values of output and prices are the same in the Bertrand and the Cournot settings (S. Martin, 2002).

Table 2: Equilibrium values

	BERTRAND			COURNOT (H.P.)			COURNOT (D.P.)		
	p	q	π	p	q	π	p	q	π
WALRAS	6	18	108	0	24	0	6	18	108
NASH	8	16	128	8	16	128	9.6	14.4	138.2
JPM	12	12	144	12	12	144	12	12	144

The symmetric equilibrium values reported in **(1)-(3)** are the predicted outcomes of dynamic competition in three learning models we consider.

The Nash-Cournot and the Nash-Bertrand solutions reported in **(1)** are a natural benchmark for our tests, and there is wide experimental evidence that such solutions are enforced in the laboratory, under a large number of designs and models' variations[8]. Although we regard ED 1 as the baseline design, the Nash equilibrium can be implemented in all experimental settings we consider (ED 1, ED 2 and ED 3). The basic requirements for its implementation regard in fact the (finite) number of periods the game lasted and the absence of structural uncertainty (costs, demand and payoffs) and both requirements were met in all treatments.

A number of recent papers on this specific issue[9] have found that the emergence of a Nash equilibrium in market games is compatible with several learning rules (best reply, fictitious play, and, in some cases, qualitative response learning). Here, however, we do not attempt to analyse individual choices, assuming that the convergence to the Nash equilibrium is determined by some sort of adaptive learning process, without ruling out sophisticated behaviours.

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[7] For the equilibrium values in the differentiated products models we follow S. Huck, *et al.,* 2000. The values are calculated maximising the profit differential between firm i choosing strategy q_i and firm j choosing strategy $q_j^{'}$, that is:

$$\Delta(q_i, q_j^{'}) = \pi(q_i, q_j^{'}) - \pi(q_j^{'}, q_i).$$

[8] C. Holt, 1995.

[9] S. Rassenti, S. S. Reynolds, V. L. Smith. and F. Szidarovszky, 2000; R. Nagel and N. Vriend, 1999; S. Huck, H. Normann and J. Oechssler, 1999, P. Lupi, P. Sbriglia, 2003.

Claim I: if players follow adaptive learning rules, output and prices converge to the values reported in **(1)**, and the Nash equilibrium solutions represent the correct prediction for the three market games.

However, when subjects receive feedback information on the average industry-wide profit – as in ED 2 – we may observe a different pattern of behaviour, since *aspiration* rules are possible.

There is extensive research on *aspiration* rules and the implication of such learning behaviour has been studied in a number of repeated games (R. Karandikar, D. Mokerjee, D. Ray, 1998; F. Vega-Redondo, 1996; F. Palomino and F. Vega-Redondo, 1999; H. Dixon, 2000, J. Oechssler, 2002). The general result is that aspiration rules lead to cooperation in bilateral games "where the maximum joint payoff is attained by a symmetric strategy profile" (F. Palomino and F. Vega Redondo, 1999, p. 486). There are, however, differences in the predicted degree of cooperation, depending on the way aspiration learning is modelled. Such differences may be summed up comparing the two works of F. Palomino and F. Vega-Redondo, 1999 and H. Dixon, 2000.

In F. Palomino and F. Vega-Redondo, 1999, a population of agents is randomly paired to play the Prisoner's Dilemma game. At each point in time, they can observe the population mean payoff, which is taken to be the individual aspiration level[10]. Players use a simple decision rule: if they are earning below average they switch[11], with a positive probability, to a different strategy. It can be proved that, under fairly general conditions, the dynamics of the system converges to a state in which there is a positive fraction of co-operators, the amount of cooperation being dependent on the value of the coefficients in the PD game.

A stronger result is reached by H. Dixon in duopoly Cournot games, where firms adopt a similar rule of behaviour, considering the (overall) average profit as the individual aspiration level.

H. D. Dixon, 2000, considers an "economy" composed by several duopoly markets, where firms are matched to play a Cournot game. Firms observe their own payoff, but also the average profit in whole economy (the aspiration level).

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[10] Aspiration might however be linked to alternative statistics of the payoff distribution, such as the mode or the median; the authors prove that , also in these alternative settings, the model converges to a similar long run equilibrium.

[11] The "switching rate" is positively related to the magnitude of the profit differential.

At each point in time firms adopt a pure strategy. If their payoff is below average, then they are likely to experiment something new. If firms follow *aspiration* rules, then collusion becomes "the global attractor of the economic system" (H. Dixon, p. 223)[12].

The main difference between the two papers lies in the way strategic interaction is modelled. In F. Palomino and F. Vega-Redondo, 1999, a large population of agents is re-matched in each period to play the PD game; in H. D. Dixon a continuum of agents is arranged in pairs to play the Cournot game and their interactions last throughout the game. The fixed-matching rule ensures that there will be "feedback effects" inducing full cooperation as a stable long run equilibrium. In fact, whenever one player defects from the cooperative outcome, thus increasing his payoff, his action will leave his opponent dissatisfied with the current level of profits, thus inducing him also to defect. This behaviour will lower both players' profits and increase both players degree of dissatisfaction. In such contexts, the feedback effects will ensure that both players will go on experimenting new strategies until the former cooperative equilibrium is restored.

When matching is random, feedback effects are less effective even in a small population of agents (as in the experimental settings) and only partial cooperation can be observed in the long run. Figures 1 and 2 present the simulation of the homogeneous Cournot game in our experiments played by a finite population of agents (20) and over a number of periods (1000)[13].

INSERT FIGURE 1 AND 2

The players are, respectively, randomly matched in each period - F. Palomino and F. Vega-Redondo, PVR model - (Figure 1), or play with the same partner throughout the game - H. D. Dixon, HDD model - (Figure 2). The simulations were carried out modelling the "switching behaviour" in alternative ways, represented by each dotted line. In the case of the dotted lines *a* (Figure 1) and *e* (Figure 2) we assume that a player whose payoff is below average always switches to a new strategy, randomly chosen

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[12] Full convergence to the cooperative equilibrium in coordination and market games is proved also in R. Karandikar *et al.* 1998, and J. Oechssler, 2002.

[13] The specific number of agents (20) was chosen in order to draw comparisons with the experimental evidence. On the horizontal axis of Figure 1 and 2, it is reported the number of the available choices (0-48), on the vertical axis, the proportion of the total population of players.

from the available set. Dotted lines *d* (Figure 1) and *f* (Figure 2) follow F. Palomino and F. Vega-Redondo's model in assuming that the switching function[14] has the form:

$$f(\chi)=\frac{\chi^q}{v+\chi^q}$$

Finally, dotted lines *b*, *c* (Figure 1) and *g*, *h* (Figure 2) report the cases of "noisy experimentation" (H. D. Dixon, 2000, J. Oechssler, 2002), that is, we assume that there is a probability 1-β that the player will experiment with new strategies when the current payoff is below average, and a probability 1-γ that the player will stick to the same strategy when above average[15].

Figures 1 and 2 present a clear picture of the main difference between the random-matching and the fixed-matching settings. Whilst in both cases the proportion of the population playing strategies in the interval 10-13 (12 is the collusive outcome) is greater than the proportion playing strategies in the interval 14-17 (16 is the Nash outcome), there is a relevant difference in magnitude. In the fixed-matching setting, 60% of the population converges towards the 10-13 interval, and only 11% of the subjects are still playing strategies within the 14-17 interval, after 1000 iterations. In the random matching case, 15% of players are using strategies in the 10-13 interval, as opposed to 13% of players who are still using strategies within the 14-17 interval, after 1000 iterations[16].

As explained before, our experimental treatment ED 2 mimics F. Palomino and F. Vega Redondo model and players were randomly re-matched in each period. Our predicted experimental results will therefore be that in ED 2 we may observe an increasing proportion of firms switching to cooperative strategies, as stated in claim II.

Claim II: In ED 2, where information on the average profit in all markets for the previous period was provided, if firms follow aspiration rules, the predicted outcome are

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[14] See F. Palomino and F. Vega Redondo, 1999, p. 478. In Figure 1 and 2, the values of q and v are, respectively: $q = 2$ and $v = 0.2$. We run several simulations (using MonteCarlo techniques) with different values of both parameters. As before, these specific values of q and v were chosen in order to draw a comparison with the experimental evidence (see Section 4).

[15] In other words, β and γ are the probabilities that the agent "makes mistakes" in his decision process. In Figure 1 and 2, *b* and *g* report the cases in which β=γ=0.01 (low noise); *c* and *h* report the cases: β=γ=0.1 (high noise).

[16] Dotted lines *a* and *e* in Figure 1 and 2. The results vary according to the specific "switching rule" adopted. The proportion of population playing collusive strategies increases, in the random case, with different parameters of *f(χ)*, (but it is never greater than 20%). On the contrary, in the fixed-matching model., high levels of noise significantly reduce the proportion of the population playing cooperative strategies (less than 20% in the interval 10-13).

not the Nash- Cournot and the Nash-Bertrand equilibrium values as in **(1)** and output and prices may converge to the values reported in **(2)** in the three market games.

In the third experimental design (ED 3) subjects could view the strategy chosen and the payoff received by their opponent, as well as their own profit in each period. Providing information on each individual firm in the same market allows players to imitate their opponent's choice, when that choice proves to be more profitable than their own.

Here again, the impact of imitative behaviour on the equilibrium selection in games has been analysed in a number of papers (F. Vega-Redondo 1996 and 1997, K. H. Schlag, 1998, P. Rhode and M. Stagerman, 2001, K. R. Schenk-Hoppé, 2000, C. Alós-Ferrer, 2004). According to the specific line of research we follow in our ED 3 experiments (F. Vega Redondo, 1996 and 1997), imitation positively influence the degree of competition even in industries with few sellers. Intuitively, imitating the best strategies, a firm will increase (decrease) its output every time the market price exceeds (is lower than) the marginal cost, and this process leads to competitive outcomes. Imitation seems to be a reasonable code of behaviour in complex environments, as market games, since it does not require sophisticated reasoning.

Claim III: if players imitate successful rivals, output and prices converge to the values reported in **(3)**, and the Walrasian equilibrium solutions represent the correct prediction for the three market games.

3. Experimental Designs and Financial Incentives

The experiments were conducted in Siena (June 2002, March 2004) and the subjects were recruited among undergraduate and graduate students of Law, Business and Economics. Participants received a fee for showing up (3 Euro) and they were paid according to their cumulative performance during the experiment (observed profits varied between 8 and 12 Euro per subject). Each market game lasted 20 rounds of one to three minutes each (minimum to maximum time allowed) and time was given for questions or observations, so to minimise any misunderstanding on the working of the computer program. On average, each experiment lasted between 30 and 40 minutes. Our first aim in designing the experiments was to give the market information signals their “best chance” to affect behaviour. Therefore, on one side we tried to provide clear and detailed information on the market structures and the basic rules of the games; on the other side, we tried to minimise the probability that specific behavioural outcomes (such as tacit collusion) would emerge as an effect of repeated interaction rather than as a reaction to market information. For this reason, we selected inexperienced players (students who had no previous experience in market experiments), the sessions lasted only 20 periods, and the single stage game lasted a relatively short time (1-3 minutes). Most importantly, we chose to match the students randomly in each period – whenever such procedure was in line with the theoretical predictions. A random matching design was therefore adopted in the ED 1 and ED 2 treatments, where the Nash and the partial cooperative solutions are compatible with such protocol, whereas in the ED 3 treatment, players faced the same opponent throughout the entire game. It must be mentioned that students were always informed on the way they would be matched during the experiments.

The natural question is then: what part of our results is due to the effects of the different informational signals and what part is due to the effect of the matching procedure?[17] In principle, having three information settings and two matching protocols may generate confusion on the correct interpretation of the evidence, since the way people are matched when playing market experiments is not a neutral factor. We can provide a partial answer to the question, examining each treatment in turn. Overall, we believe that: i) the short duration of the sessions, ii) the fact that the subjects chose quantities from a finite grid (rather than form a quantity/profit table[18]), and, iii) the random matching procedure, were aspects that limited the amount of cooperation we generally observe in all our data sets. For ED 1, comparing the data sets of both Cournot models with a pilot study, which had the same matching but more periods (40), we notice that, in our pilot, output converged to values closer to the Nash equilibrium, though the difference was small. In the ED 3 treatment, we can compare our present experiments with a random matching version for the same models[19], and this comparison show that, in the random matching environment, the output dynamics

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[17] We thank an anonymous referee for this suggestion.

[18] See K. Ostmann, R. Selten, 2001 on this specific issue.

[19] See: C. Altavilla *et al.,* 2003 and L. Luini and P. Sbriglia, 2004

converged to values closer to the Walrasian equilibrium than in the fixed environment[20]. As for the ED 2 treatment, we cannot compare our evidence with a corresponding fixed-matching version, since the only existing paper (H. D. Dixon, *et al.*, 1998) was based on a completely different oligopoly model (it was, in fact, an experimental test of H. D. Dixon *et al.*, 2002) and subjects selected reaction functions ("production plans"), rather than output levels, as in our paper. In that context, however, the JPM strategy and the Copy Cat strategy (which in some cases is close to the JPM outcome) were the most played in all the experiments (in fact, 8 experiments out of 10 converged to a cooperative mixed equilibrium, with varying proportions of JPM and CC strategies; one experiment converged to the Cournot equilibrium and the last one converged to values of the output between the Cournot and the Stackelberg equilibria). One of the reasons for which we selected the PVR version of the aspiration learning rule was that it allows a clear experimental framework in which the effect of the informational signal can be isolated. We are nevertheless aware that the degree of cooperation may suffer from the chosen matching procedure, but we are mainly interested in the differences in the output dynamics between ED 2 and ED 3 (as well as to provide an answer to Claims 1-3), rather than assessing the correct amount of cooperation triggered by the aspiration rule, which, however, is an interesting question and should be dealt in further research.

The number of participants varied between 16 and 20 (8 to 10 active markets in each period), and the experiments consisted of nine sessions (three for each information design and each market model). In the instructions (see appendix 2), participants were informed on the value of the demand parameters and costs. Specifically, in each stage, they could choose a level of output (price) in the interval 0-48 (0-24) (only integer values) and, the maximum value of the aggregate output at which individual profits would be zero was clearly indicated on the computer screen. In the second and third treatment (ED2, ED3), subjects received information about the average profitability and the rivals' actions and profits. Table 3 reports a summary of the main statistics for the three treatments.

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[20] See L. Luini and P. Sbriglia, 2004, for a comparative analysis.

Table 3: Experimental Designs

	H. COURNOT			D. COURNOT			BERTRAND		
	markets	periods	Inform.	markets	periods	Inform.	markets	periods	Inform.
ED 1	18	20	π_i	18	20	π_i	18	20	π_i
ED 2	18	20	π_i $\overline{\pi}$	16	20	π_i $\overline{\pi}$	16	20	π_i $\overline{\pi}$
ED 3	20	20	π_i , π_j q_j	20	20	π_i , π_j q_j	20	20	π_i , π_j p_j

4. Results

We now report the results from the market experiments, answering the claims that were enunciated in section 2. We will focus on each experimental design, i.e. ED 1, ED 2 and ED 3. Comparing the data across the three designs for each market model, we will then try to assess whether information did matter and whether it affected the process of equilibrium selection.

In particular, if the three experiments trigger different dynamics, as suggested in the previous sections, then we would expect that firms produce most in ED 3, as it approaches the Walrasian equilibrium, and least in ED 2 with its collusive benchmark. Indeed, the empirical results are largely in line with the predictions.

- **Experimental Design 1: *Adaptive learning rules***

Figure 1 reports the trend of average quantities in the three experimental setting, for each market model, throughout the 20 periods. In particular, the first line refers to the ED 1. Observing the time series, it is possible to gain an initial insight on the process of equilibrium convergence in the three models. In all three cases, in fact, the average individual choice converged to values close to the Nash-Cournot equilibrium, but with substantial differences in the Bertrand and Cournot model with differentiated products.

In these two experiments, considering the last three periods of play, one can observe a significant divergence from the equilibrium values of quantity and price, respectively. Average output choices varied in fact between 16.6 and 16.4, exceeding the equilibrium value of 14.4, whilst, in the Bertrand setting, average prices settled around the equilibrium value of 8 in the periods 13-17, and then increased in the final stages, reaching the value of 10 in periods 19-20.

INSERT FIGURE 3

The same conclusion may be reached looking at the relative frequencies of play of the individual strategies (averaged over the last three periods) in each model. These frequencies are reported in Table 4 and Figure 4. Figure 4 depicts for each level of the aggregate quantity (on the horizontal axis), the percentage of outcomes (on the vertical axis) that fall in the interval {3,…,25}.

INSERT FIGURE 4

The lines in the graphs represent the trend measures of the outcomes[21].

In the first model (Cournot HP), the relative frequencies are distributed in the interval 11-26, with a peak around the Nash value. In the second model (Cournot DP), the peak is around the values of 17-18, which is considerably higher than the Nash equilibrium, and little cooperation is observed in the final stages. As far as the Bertrand experiment is concerned, there is an opposite situation, with a peak around the Nash value of 8, and a peak around the values 9-12, closer to the cooperative equilibrium. What we have examined so far allows us to provide an answer to Claim 1:

Result 1: in ED 1, the Nash prediction results to be a robust prediction of the individuals' behaviour in two cases out of three. In the Bertrand market, play converges to the Nash value during the experiment and then diverges in the final stages.

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[21] The trends are calculated with the polynomial smoothing technique. The order of the polynomial was fixed to 6.

Table 4 – Frequency of the Strategies

Frequency - ED 1

Strategies	Bertrand	Cournot H.P.	Cournot D.P.
1	-	1	-
2	-	-	-
3	-	-	-
4	1	-	-
5	2	-	-
6	3	1	-
7	2	1	-
8	**9**	-	-
9	**9**	1	-
10	**8**	1	-
11	**12**	-	-
12	4	2	2
13	1	1	3
14	1	3	7
15	-	5	**5**
16	-	**4**	**9**
17	1	**6**	**9**
18	1	**7**	**11**
19	-	**2**	4
20	-	4	3
21	-	4	-
22	-	3	-
23	-	3	1
24	-	2	-
25	-	1	-
26	-	-	-
27	-	-	-
28	-	-	-
29	-	-	-
30	-	-	-
31	-	2	-

Frequency - ED 2

Strategies	Bertrand	Cournot H.P.	Cournot D.P.
1	-	1	-
2	-	-	-
3	-	1	-
4	-	2	-
5	-	1	-
6	1	3	-
7	1	1	-
8	**5**	**6**	2
9	**11**	**3**	2
10	**5**	**7**	**5**
11	**4**	**7**	**5**
12	**10**	**3**	**4**
13	**1**	**2**	**6**
14	2	1	0
15	3	2	1
16	1	-	6
17	-	3	5
18	1	4	5
19	3	1	3
20	-	3	1
21	-	2	-
22	-	1	-
23	-	-	-
24	-	-	2
25	-	-	-
26	-	-	-
27	-	-	-
28	-	-	-
29	-	-	-
30	-	-	-
31	-	-	-

Frequency - ED 3

Strategies	Bertrand	Cournot H.P.	Cournot D.P.
1	-	-	-
2	-	-	-
3	1	-	-
4	2	-	-
5	**4**	-	-
6	**13**	-	1
7	**10**	1	1
8	**12**	-	-
9	**6**	4	-
10	**5**	2	2
11	3	1	-
12	4	1	3
13	-	-	1
14	-	2	-
15	-	3	1
16	-	3	**6**
17	-	3	**16**
18	-	6	**19**
19	-	1	**4**
20	-	**1**	3
21	-	**3**	2
22	-	**8**	0
23	-	**7**	1
24	-	**4**	-
25	-	-	-
26	-	1	-
27	-	3	-
28	-	2	-
29	-	1	-
30	-	1	-
31	-	-	-

- **Experimental Design 2:** ***Aspiration learning***

As before, in Figure 3, Table 4 and Figure 4 we report, respectively, the output (price) trends, and the relative frequencies of play, averaged over the last three periods in each session of the ED 2 treatment.

Two things can immediately be noticed from the second line of Figure 3. First, there is no indication that choices were converging towards the collusive equilibrium (in two cases, Cournot D.P. and Bertrand D.P. there was on the contrary a closer convergence to Nash – i.e., a decrease (increase) in competitiveness in the Cournot (Bertrand) model in the final stages of the games). Second, the time series show a higher speed of convergence if compared to the first experimental design (ED 1). In the market model Cournot H.P. the average quantity (in the last three periods) was around the value of 18, and it was not significantly different from the value of the average output in the same model in ED 1; in the second market model (Cournot D.P.), however, the average quantity was significantly lower than in the alternative information setting (ranging in ED 2 around the values of 14-15). By the same token, in the Bertrand model, prices approached the Nash value of 8 (the average price varied around 7.6 and 8.3), while in ED 1 they ranged around the average value of 10.

If we look at the relative frequencies of strategies, averaged over the last three periods (Table 4 and Figure 4), a slightly different picture is observed. In fact, in two cases out of three (both in the Cournot models), we can actually see a significant increase – compared to the same models in the ED 1 design - in the proportion of subjects who were playing strategies 11-12 (close to the Collusion value). In the Cournot model with homogeneous products, the cumulative frequency of participants playing strategies 11-12 increased from 1.8 per cent (ED 1) to almost 11 per cent (ED 2). In the second Cournot model, there was an increase in cooperation from 1.38 p.c. to about 16.7 p.c..

Comparison between the frequencies of Nash equilibrium and Collusive equilibrium strategies confirms what we have so far stressed, that is, information on average industrial profitability does have an effect on cooperation, but there is no evidence of convergence to the JPM outcome. This can be stated as follows:

Result 2: In ED 2, the Nash prediction of individuals' behaviour in all three market models is confirmed. However, in both the Cournot markets, there was a significant increase in the proportion of subjects playing strategies close to the JPM outcome.

Finally, we analyse the correspondence between the simulated distributions of the PVR model (Figure 1, Section 2) and the experimental evidence in the Cournot model with homogeneous products. Figure 5 reports the simulations of the PVR learning model, for the Cournot HP setting, considering 18 players and 20 iterations, as in the experiments. As before, the dotted lines mimics different "switching behaviours", where *b* represents PVR "switching" function (see Section 2). Comparing the theoretical (dotted line *b*) distribution and the experimental evidence, there is an interesting aspect that can be noticed. The two distributions – theoretical and observed (at period 20) - have the same median, and though there are too few observations to carry out statistical tests, the observed distribution (at period 20) has a peak in the "cooperative" interval, with about the 20% of the population playing strategies within the interval 10-13.

INSERT FIGURE 5

- **Experimental Design 3:** ***Imitation learning***

Finally we explore the effects of imitation or spite in market models, by looking at the evidence in the third experimental design (ED 3).

In Figure 3 (third line) and Table 4, we report the average quantities (prices) and relative frequencies of play. The difference of results between this experimental design and the other two is immediately evident. In both the Cournot models, the average quantities ranged between 20 and 24, e.g., closer to the Walrasian theoretical benchmark. In the Bertrand setting the average prices were between 5 and 7.

Table 4 clarifies some aspects of the experiments. In the first Cournot model, average quantities were around 20-22, close to the Walrasian equilibrium output, and the relative frequencies show that, in the last three periods, the Walrasian choice (23-24) was the most used strategy among players. In the two remaining cases, there was a slower convergence to the Walrasian values, but the average quantity (20-21) and price (6-7) were significantly higher (lower) than the quantity and price achieved in the alternative information contexts. Notice also that players chose actions closer to the Walrasian levels than to the Nash equilibrium.

Examining the tables and the values of the frequencies of the strategies, we can conclude that in the two Cournot settings the imitation hypothesis work and both markets are more competitive than in the previous experimental design. As for the Bertrand model, we do not find a significant difference in final equilibrium values in ED 2 and ED 3, if not that in the third setting, prices tend to be lower than in both the alternative contexts.

We are able now to state our third result and therefore to provide an answer to Claim 3:

Result 3: In ED 3, the Walrasian equilibrium values are a robust prediction of the individuals' behaviour both in the Cournot and Bertrand markets, which are significantly more competitive than in the alternative designs.

There is a final aspect of our investigation that we wish to emphasise, related to the general impact of information on behaviour. Does information matter? How did information affect the behaviour of the experimental subjects? We can answer to both questions by looking at the time series presented in this section. Information does affect individual behaviour: we performed a χ^2 test to compare the ED 2 and ED 1, and ED 3 and ED1, respectively, and we rejected the null hypothesis that there was no difference among the series (5% significance level). The question on *how* information affects behaviour is an interesting one and has two answers. First in Ed 2 and ED 3, there was a faster process of convergence to market equilibrium. Second, information lowered the *variance* of the individuals' choices. This implies that subjects used *all* types of information we provided to build up their decisional routines. We feel that this provides strong support to evolutionary models.

5. Changing regimes: the study of aspiration and imitation learning

In this section we study the stochastic behaviour of the agents in two experimental designs: ED2 and ED3. The aim is to evaluate whether the quantity that a player chooses in each period is influenced by the information that he has concerning the average market profit (ED2) or the profit of his opponent (ED3).

Moreover, the results of the previous section indicate that aspiration rules fail the convergence test, e.g., we do not observe convergence to the Collusive equilibrium outcome in the three duopoly markets under investigation. This result raises the question as to whether aspiration rules are plausible codes of behaviour in complex environments, as market games, and how common they became among the subjects engaged in the ED2 experiments.

We addressed the above mentioned issues by estimating a *Markov-switching autoregressive models (*henceforth *MS-AR)* on the individual data set of the 50 subjects participating in the in ED2 and the 60 subjects who participated in the ED3. We recall here that the rationale underlying aspiration rules is that the probability that individuals change their choice increases with the profit differential between their payoff and the observed previous period average payoff. On the other hand, the rationale underlying imitation rules is that the players' choices are affected by the profit differential between their own and their opponent's profit. In this case, a negative profit differential would provide an incentive to change the strategy the player chose in the previous period and to imitate the opponent. In the following, we assume that discrete shifts follows a two state Markov process with an *AR(1)* component for each player.

Formally, the decision rule may be expressed as a *MSM(2)-AR(1) model*[22] of the form:

$$y_t - \mu_{s(t)} = \alpha\left[y_t - \mu_{s(t-1)}\right] + \varepsilon_t \quad , \quad \varepsilon_t \approx N(0,\sigma^2)$$

where y_t represents the difference between the individual profit and the average market profit for ED2 and the difference between the individual profit and the opponent profit for ED3; and the unobserved random variable $s(t)$, is a generic ergodic Markov chain defined by the transition probabilities:

$$p_{ij} = P(s(t) = j | s(t-1) = i) \text{ and } \sum p_{ij} = 1 \text{ ; } \forall i, j \in (1,2)$$

Specifically, $s(t)$ takes the values of 1 if a player is in a low profit state (which means the subject tries new strategies- experimentation state) and 2 if a player is in a high profit regime (the subjects does not try new strategies- no experimentation state); the conditional mean, $\mu_{s(t)}$, switches between the two states:

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[22] These models, studied by Hamilton J. (1990), have been extensively used for their ability in replicating business cycle features. In particular, as in MS-AR models the regime shift governing process generates dynamic factor structures, they synthesize both non-linear and dynamic factors modelling for evaluating the macroeconomic fluctuations. The non-linearity of the MSM arises because the process is subject to discrete shift in the mean, between the two states.

$$\mu_{s(t)} = \begin{cases} \mu_{s(t)} < 0 & \text{if } \mathrm{s}_{\mathrm{t}} = 1 \ (\text{no experimentation}) \\ \mu_{s(t)} > 0 & \text{if } \mathrm{s}_{\mathrm{t}} = 2 \ (\text{experimentation}) \end{cases}$$

The transition probabilities provide the probability of moving from one state to another. Our hypothesis is that the above process follows a 2-state Markov chain. It is then possible to collect the transition probabilities in a 2×2 transition matrix:

$$P = \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{bmatrix}$$

where p_{ij} represents the probability of moving from state *i* to state *j*. In other words, p_{12} is just the fraction of the times that the system is in state *1* and moves to state *2*.

The models' coefficients and the unobserved Markov chain are obtained by Maximum Likelihood Estimates (MLE) estimates, testing the existence of the two regimes in the individuals' decision process.

In Tables 5 and 6 the MLE estimates are reported for the two Cournot experiments and the Bertrand market, respectively. The signs of the estimated coefficients for the conditional mean in the first state are for each player negative, representing therefore the experimentation state.

Table 5: Maximum Likelihood Estimates of Parameters – ED2

	μ_1	μ_2	α_1	p_{12}	p_{21}	Test
			(Bertrand)			
Player 2	-5.84	29.30	-0.01	0.26	0.08	Yes
Player 4	-0.24	57.90	-0.26	0.16	0.15	Yes
Player 16	1.33	69.30	-0.66	0.17	0.26	Yes
			(Cournot DP)			
Player 5	-63.76	4.29	-0.84	0.32	0.17	Yes
Player 8	-15.46	20.66	-0.48	0.16	0.26	Yes
Player 13	-82.55	4.02	-0.01	0.22	0.62	Yes
			(Cournot HP)			
Player 4	-36.66	40.78	-0.51	0.16	0.31	Yes
Player 10	-20.20	16.45	-0.49	0.18	0.35	Yes
Player 18	-27.14	55.18	0.13	0.38	0.28	Yes

Table 6: Maximum Likelihood Estimates of Parameters – ED3

	μ_1	μ_2	α_1	p_{12}	p_{21}	Test
			(Bertrand)			
Player 1	-71.25	4.97	-0.30	0.01	0.15	Yes
Player 9	-19.11	9.14	-0.13	0.15	0.09	Yes
Player 12	-21.83	10.30	0.15	0.13	0.18	Yes
			(Cournot DP)			
Player 1	-18.69	11.01	-0.25	0.17	0.31	Yes
Player 4	-5.68	24.78	-0.24	0.19	0.11	Yes
Player 15	-7.36	3.05	-0.15	0.13	0.13	Yes
			(Cournot HP)			
Player 8	-21.63	21.83	-0.16	0.15	0.18	Yes
Player 15	-17.81	38.26	-0.21	0.24	0.25	Yes
Player 20	-7.14	25.18	0.26	0.14	0.28	Yes

The tables present the MLE coefficients for some selected players[23]. These players share some common features. First of all, at least for one period the quantity (price in Bertrand) chosen by the player was exactly the same as his opponent. Second, the profit differential of the player has been volatile over the sample period. This means that all players that had a constantly positive (or negative) profit differential, i.e. the difference between its own profit and the profit of its opponent (average market profit in ED2) was positive (or negative) in each period, are not considered. Finally, for these players the Wald test support the existence of two states operating during the experiments.

The estimated transition probabilities in column 4 and column 5 of Tables 5 and, representing the probability of moving from one state to another are, for almost all players, not very low. This means that the two regimes are estimated not to be very persistent.

Figures 6 and 7 complete our investigation reporting the individual smoothing probability of regime 1 together with the observed values of y_t.

The Figures report the estimated probabilities for some selected player in different contexts.

Consistent over the three models (Cournot DP, Cournot HP and Bertrand) and over the two experiments, the results suggest that when a player experienced a loss in terms

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[23] We do not report the whole estimates for saving of space. However, all results are available upon request.

of profit differential, the probability of changing his quantity choice, and then the probability of adapting his choice to the choice of his opponent, increases. On the contrary, when the difference between his profit and the profit of his opponent is positive, the players usually do not change the quantity (price in Bertrand) they have chosen in the previous period.

The overall picture which can be gained by our hypothesis testing is that the *aspiration rule* is adopted in the large majority of the cases. From the Figures is possible to observe that the probability of being in the experimentation state is relatively high each time the difference between the individual profit and the average market profit is lower than zero.

The significance of the parameters estimated by maximum likelihood is tested by applying standard Wald test.

In particular, a further step of the analysis consists of testing whether there have been two regimes operating over the sample period. Implementing the following Wald test can assess this hypothesis:

$$H_0 = p_{11} = 1 - p_{22}$$

$$\frac{[p_{21} - (1 - p_{12})]^2}{\mathrm{var}(p_{21}) + \mathrm{var}(p_{21}) + 2\,\mathrm{cov}(p_{21} p_{21})}$$

where the above statistic is distributed as a $\chi^2(1)$.

The results of Wald tests are reported in the last column of Tables 5, 6 and 7. In particular, for each player the table report whether the test cannot reject the existence of the two states (YES in Tables) at 5% significance level or, on the contrary, the test reject the null hypothesis (NO in Tables).

As we can see from Tables 5 and 6, the Wald tests clearly reject the hypothesis of having only one state operating during the sample period for all selected players. Looking at the all markets in the two experiments the test rejects the presence of two regimes in less than 20% of the cases. The highest numbers of rejections are found in the Bertrand markets. These results corroborate the evidence coming from the previous section: players operating in the Cournot models are more competitive compared to players in the Bertrand model.

However, looking at the behaviour of the players in the two experiments, the estimated models suggest that the number of players who follows the decision rules outlined above in ED2 is slightly higher that the same number of players in ED3. This evidence can be partially explained by taking into account the different information that a player has in the two experiments. In ED2, each player knows the average behaviour of the market. This means that each choice is made by considering a larger number of subjects (all players) than when the same choice is made in ED3, where the players only know the profit of his opponent. Then, we can conclude that having a lower profit than the market average is perceived as a worst situation than just having a lower payoff than one person. So, in the former case, more players decided to change their choice.

From what we have said so far, the *aspiration rule as well as the imitation rule* can be seen as successful predictions for individuals' behaviour, although there is not sufficient evidence that *aspiration* leads to Pareto outcomes in oligopoly games.

6. Conclusion

In this paper we analysed the importance of information on learning behaviour in several experimental markets. We have considered three informational settings and we have studied the equilibrium convergence process in three market models, for each of the alternative scenarios. Our investigation has provided some significant insights. First, *information does matter:* the process of equilibrium convergence is, in fact, quite different in the alternative contexts. Second, *information strongly affects the selection of the final equilibrium.*. Third, *information affects the process of individual learning*, as it is proved by our analysis of the aspiration rule. These three conclusions are, in our opinion, a positive, though not conclusive, test of the recent evolutionary theory on individual learning and bounded rationality. Our work leaves, in fact, two unresolved puzzles. First, though pervasive, aspiration rules do not lead to collusion. Moreover, we do not attempt a comparison among the different rules, nor it is possible to test *which* information (e.g., individual firms' data or information on the average industrial profitability) would be more relevant for the individual choice process. We believe that both problems should attract attention in the future, in order to provide complete tests of the alternative rationality paradigms.

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Appendix 1: Translation of Instructions

Welcome to our experiment. Today your participating in a market experiment and you will play the role of a firm selling a certain product at a certain price. This instruction sheet will tell you the basic information you need to have in order to participate, but if there is any problem, please do not hesitate to ask the organizers. A copy of the instruction sheet is available on your computer. During the experiment you can view it by hitting the key…
PLEASE DO NOT TRY TO COMMUNICATE WITH OTHER STUDENTS IN THE ROOM.

The markets. You are a firm selling a certain product, whose production costs are zero. There will be only another firm in your market, selling the same type of good, which it produces at zero cost. You both will have to decide how much (at which price -Bertrand) to sell (of) your product, over a number of market "days".
At the beginning of each period, you anonymously make the decision on which quantity (price Bertrand setting) of your product you are going to offer for the day. The other firm will do as well.
Your aim is to make the highest profit from the sale of your product. When both decisions are recorded, the resulting market price and profits are calculated.
Please notice that the more you want to sell, the lower will be the price you will receive for it. When the total quantity (i.e, the quantity you both wish to sell for that day) exceeds a certain value units, shown on your screen, the price is zero and so will be your profits that day.
(For the Bertrand setting: the higher is your price that day, the less you are going to sell. When the market price exceed a certain value, shown on your screen, you are not able to sell anything and your profits are zero)
The experiment consists of twenty periods (days). In each period (day) you will interact with the same firm (*only for ED 3*) .

Profits. In each period, your profits will be calculated multiplying the quantity you sold by the market price. At the end of the experiment you will be paid the cumulated profit for all the market periods, at the exchange rate of 18 Euro cents for 100 experimental profit units gained.

Information (ED 3):

At the end of each day it will be shown on your screen how much you earned in that period and your cumulated profits (from the second period on). Furthermore, you can view the decisions taken by your opponent, that is, you will see his/her choice and his/her resulting payoff.

Information (ED 2):

At the end of each day it will be shown on your screen how much you earned in that period and your cumulated profits (from the second period on). Furthermore, you will be informed on the average profit throughout all markets in the experiment. (ED2).

Information (ED 1):

At the end of each day it will be shown on your screen how much you earned in that period and your cumulated profits (from the second period on). (ED1)

How long is the experiment going to last? The actual experiment will start after three trial runs, where you have the opportunity to get familiar with the computer design and rules. Please do not hesitate to ask if anything is unclear to you. After that, there will be 20 market days, which will last a minimum of three minutes each.

How are you going to be paid? Immediately after the experiments, you will be paid discretely by the organizers in the room, according to your cumulated profits.

Figura 1: Aspiration Learning with Random Matching - PVR model
1000 iterations

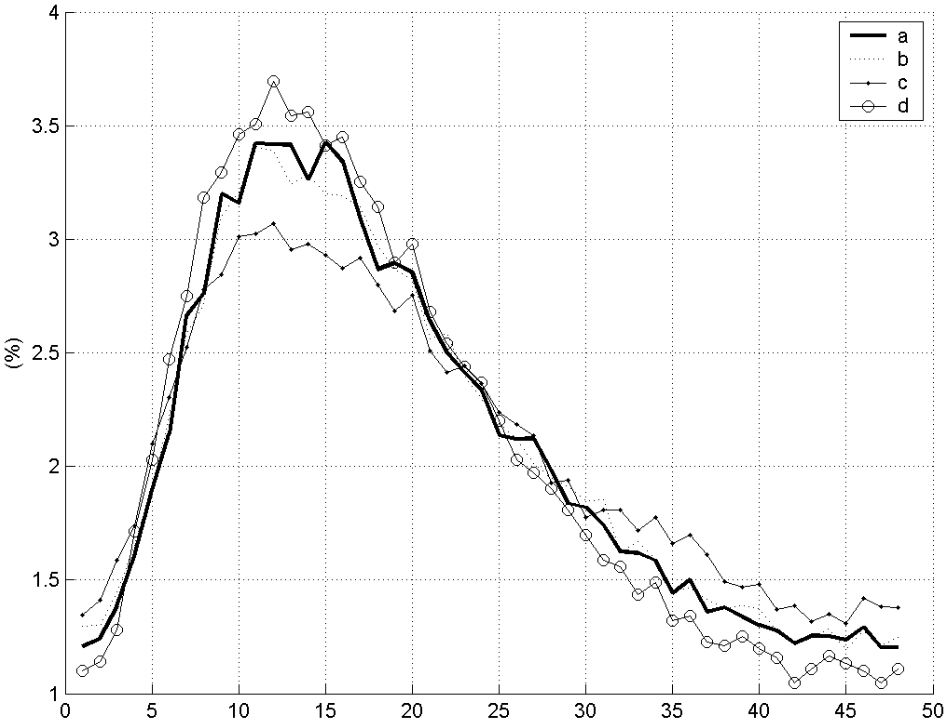


Figura 2: Aspiration Learning with Fixed Matching - HDD model
1000 iterations

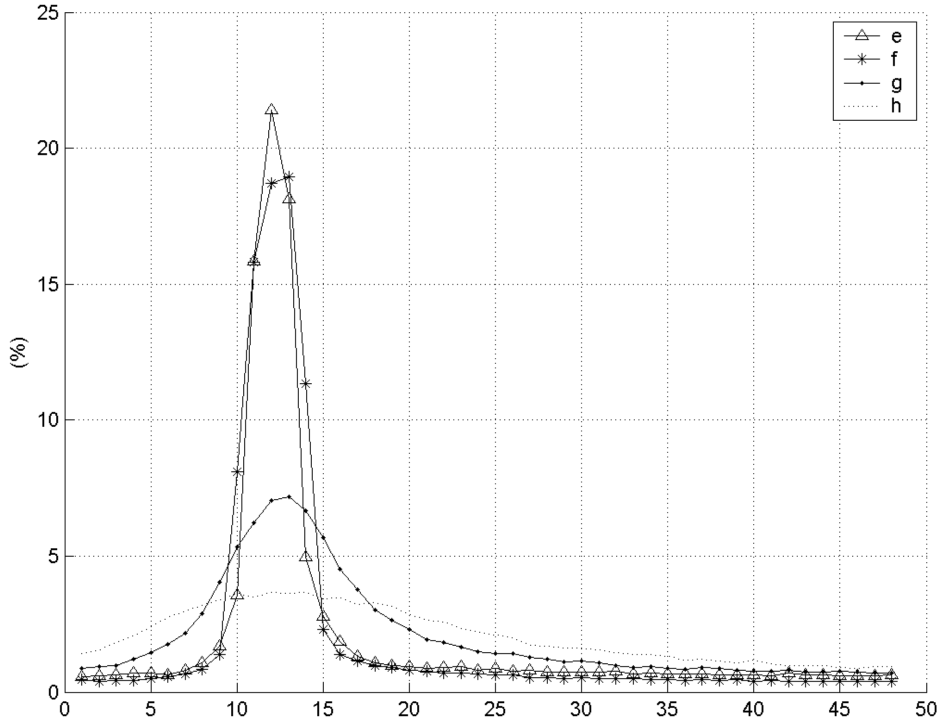
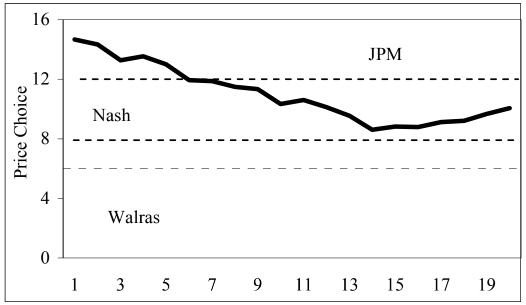
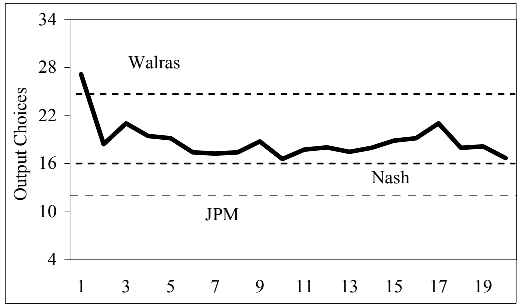


Figure 3: Average Quantities

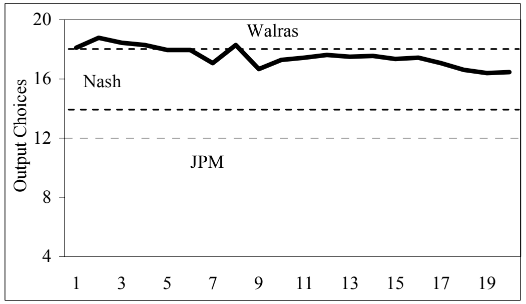
Bertrand Market (D.P.) - ED 1



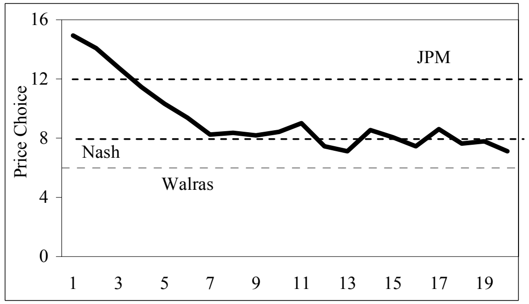
Cournot Market (H.P.) - ED 1



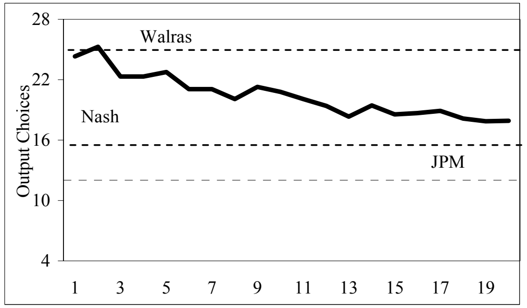
Cournot Market (D.P.) - ED 1



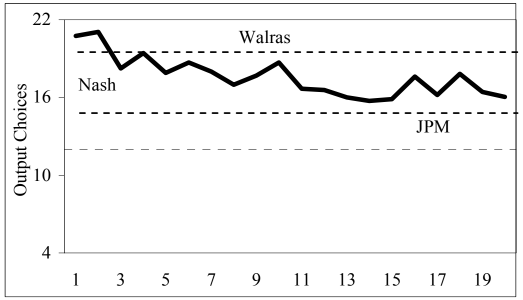
Bertrand Market (D.P.) - ED 2



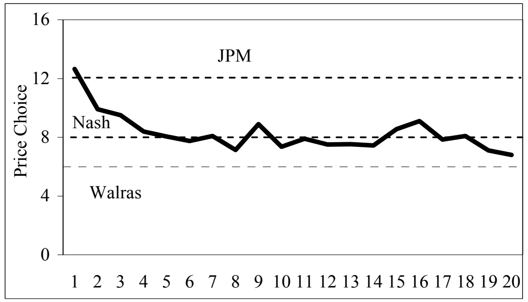
Cournot Market (H.P.) - ED 2



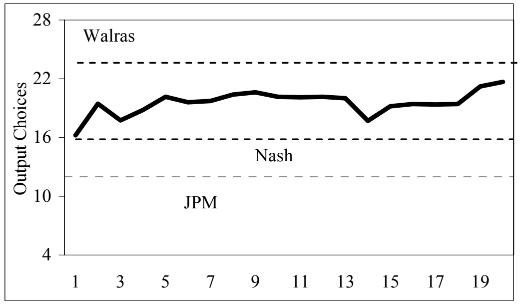
Cournot Market (D.P.) - ED 2



Bertrand Market (D.P.) - ED 3



Cournot Market (H.P.) - ED 3



Cournot Market (D.P.) - ED 3

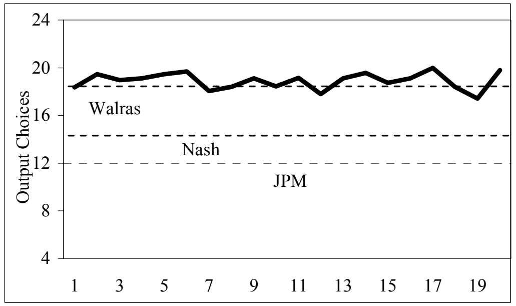
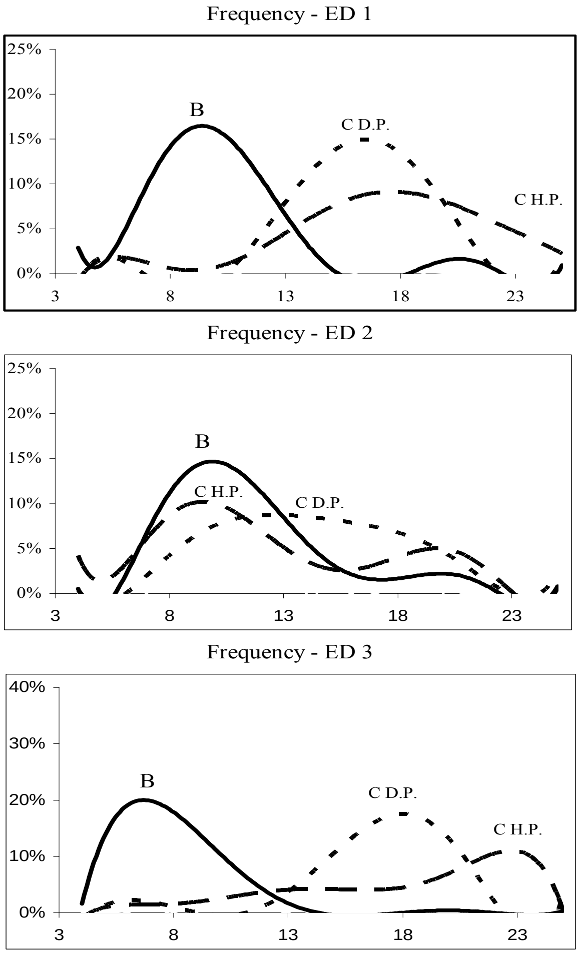


Figure 4: Frequency of strategies



Frequency - ED 1

Frequency - ED 2

Frequency - ED 3

Figure 5: Aspiration learning with Random Matching – PVR model – 20 iterations

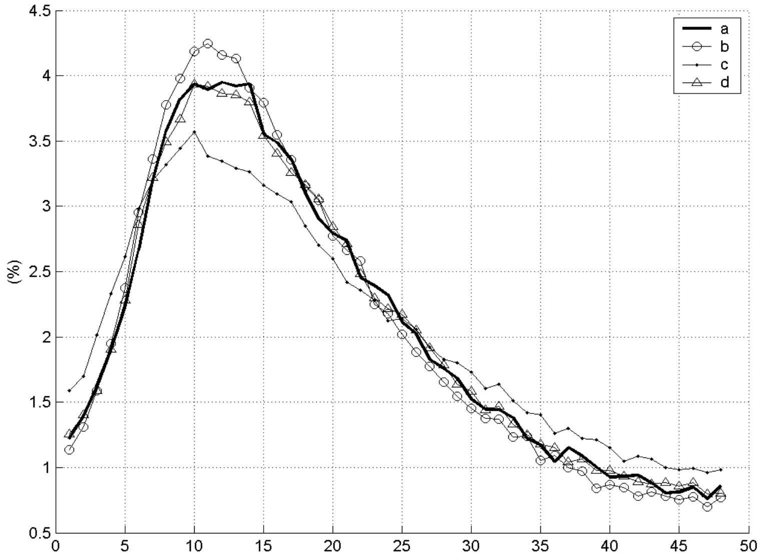
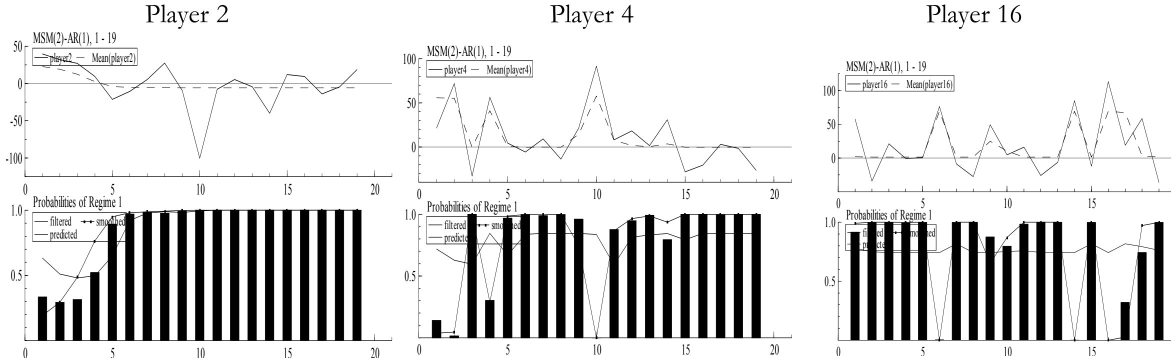


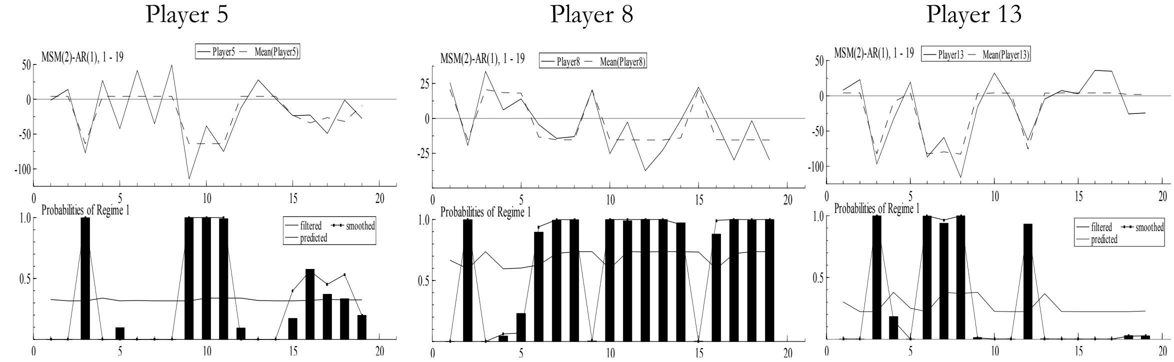
Figure 6: Smoothed Probabilities of Regime 1 – ED2

Bertrand



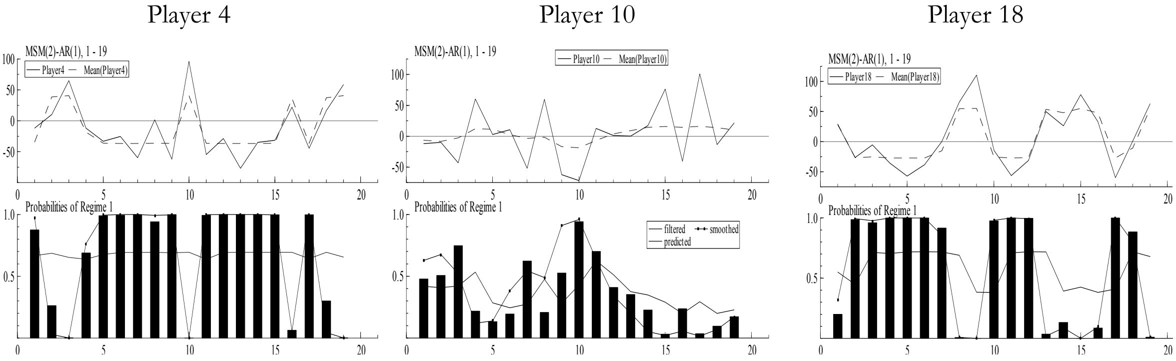
Player 2 Player 4 Player 16

Cournot DP



Player 5 Player 8 Player 13

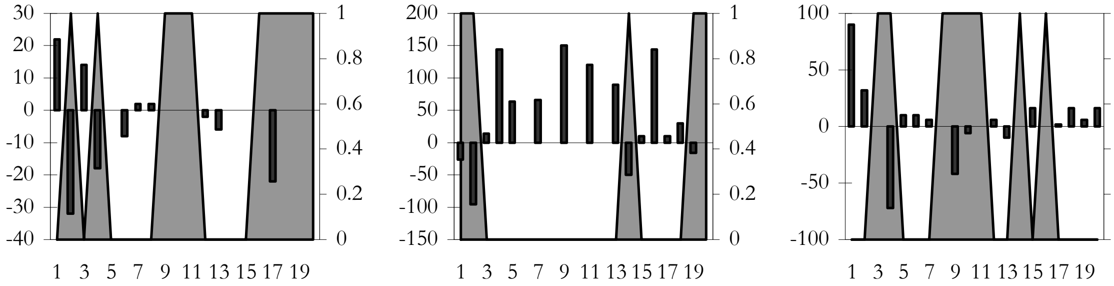
Cournot HP



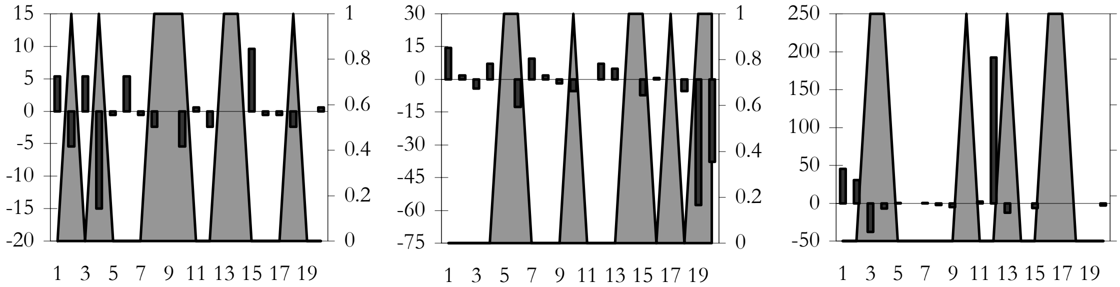
Player 4 Player 10 Player 18

Figure 7: Smoothed Probabilities of Regime 1 – ED3

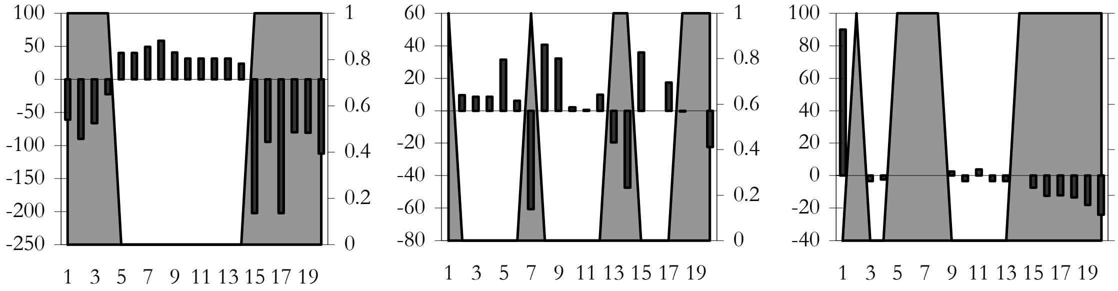
Bertrand


Player 1 Player 9 Player 12

Cournot DP


Player 1 Player 4 Player15

Cournot HP


Player 8 Player 15 Player 20