# Excess Capacity and Pricing in Bertrand-Edgeworth Markets:

# Experimental Evidence[*]

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**Abstract**

We conduct experiments testing the relationship between excess capacity and pricing in re-peated Bertrand-Edgeworth duopolies and triopolies. We systematically vary the experimental markets between small amount of excess capacity (suggesting monopoly) and no capacity con-straints (suggesting perfect competition). Controlling for the number of firms, higher production capacity leads to lower prices. However, the decline in prices as industry capacity rises is less pronounced than predicted by Nash equilibrium, and a model of myopic price adjustments has greater predictive power. With higher capacities, Edgeworth-cycle behavior becomes less pro-nounced, causing lower prices. Evidence for collusion is limited and restricted to low-capacity duopolies.

*JEL – classification numbers:* C72, C90, D43

*Keywords:* Tacit collusion, excess capacity, Edgeworth cycles.

# 1    Introduction

The Bertrand-Edgeworth model of price-setting firms which operate under capacity constraints (Edgeworth, 1925) is one of the core oligopoly theories. By varying firms' capacities, it addresses the intermediate range between uncontested monopoly and perfect competition which is crucial for research in theoretical industrial organization. If capacities are sufficiently small, competition is ineffective and firms charge the monopoly price; whereas, if capacities are not binding, perfect competition emerges. In this way, the model generates market outcomes between monopoly and marginal-cost pricing thought to be intuitive for oligopoly. This is Edgeworth's (1925) main competitive advantage to Bertrand's (1883) approach which is often dismissed as a paradox.

A central feature of Bertrand-Edgeworth oligopoly is that there is often no static Nash equilibrium in pure strategies. Instead, there is typically a mixed-strategy equilibrium which predicts that firms charge prices above marginal cost but below the monopoly level, and averages prices are predicted to decline with capacity. (See, for example, the early references by Beckmann, 1965, and Levitan and Shubik, 1972). At its boundaries, the model exhibits discontinuities in that the nature of equilibrium changes. Once capacities are not binding any more, the Nash equilibrium is in pure strategies and prices are equal to marginal cost. Similarly, if there is no excess capacity at all, pure-strategy pricing at the monopoly level is the equilibrium.

In this paper, we provide a comparative-statics analysis of excess capacity in experimental Bertrand-Edgeworth markets. We run experiments with several levels of capacities, addressing the whole range of capacities between monopoly and perfect competition. Our experiments are thus suitable to shed light on the discontinuities just mentioned. We run two series of treatments as we consider both duopoly and triopoly markets.

The seminal reference analyzing experimental Bertrand-Edgeworth markets is Brown-Kruse

et al. (1994).[1] They analyze four-firm markets and vary both the information available to the participants and the level of industry capacity. Out setup differs from the one in Brown-Kruse et al. (1994) in several dimensions. They analyze three levels of industry capacity, but even for the largest level of capacity, marginal cost pricing is not a Nash equilibrium in their experiments. We run many capacity levels and we also include treatments where the (pure strategy) Bertrand outcome is the Nash equilibrium. Capacity levels in Brown-Kruse et al. (1994) are relatively high, and monopoly pricing is presumably difficult to achieve for participants: there are four sellers, but tacit collusion is known to occur in experiments usually only with two or three firms (Isaac and Reynolds, 2002; Huck et al., 2004). Only 9 to 13 percent of industry capacity are utilized at the monopoly price, and a relatively high discount factors of 0.78 would be required to sustain collusion in the infinitely repeated game. We consider fewer firms, the monopoly price is presumably more focal, and we also employ treatments where excess capacity is relatively small (86 percent of capacity is used at the monopoly price, the minimum discount factor is one half or less). While differences in the demand schedule prevent a direct comparison of our results to those of Brown-Kruse et al. (1994), our analysis should complement theirs in that we consider a richer set of capacities and vary the number of firms.[2]

Brown-Kruse et al. (1994) test the predictive power of various theories of price competition:

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[1]Following Dufwenberg and Gneezy's (2001) introduction of a simplified Bertrand-Edgeworth setting (which boils down to a Bertrand-Edgeworth setting with inelastic demand and one buyer), there has been a growing number of Bertrand-Edgeworth experiments. See, for example, Dufwenberg et al. (2007); Abbink and Brandts (2009); Apesteguia et al. (2007); Brandts and Guillén (2004) and Hinloopen and Soetevent (2008) study homogenous goods markets in which firms specify capacity and then select a price.

[2]Related to Bertrand-Edgeworth oligopoly are posted-offer markets (see e.g., Plott and Smith, 1978, or Ketcham, Smith and Williams, 1984). Posted-offer markets differ to Bertrand-Edgeworth markets in that, first, information is incomplete (sellers know only their own cost schedule) and, second, sellers have to choose a maximum number of units they wish to sell.

Competitive pricing, mixed-strategy pricing, tacit collusion and Edgeworth cycle behavior. Their main finding is that all of these theories help to explain the data. However, if a single theory were to be chosen to rationalize the data, Edgeworth-cycle theory would perform best. Edgeworth (1925, p. 116) had already argued that firms will engage in cyclic behavior. Firms will undercut each other's prices but undercutting a rival's price is only worthwhile up to a certain price level. Once this level has been reached, firms prefer jumping back to the monopoly price. Eventually, firms will arrive at the price vector from which they started and have thus completed an (Edgeworth) cycle. Brown-Kruse et al. (1994) find evidence for such cyclical behavior, as do some posted-offer experiments (see, for example, Plott and Smith, 1978; Ketcham, Smith and Williams, 1984; Davis, Holt and Villamil, 2002).[3]

Our basic results confirm those in Brown-Kruse et al. (1994). We find that average prices decrease as excess capacity goes up. While this is consistent with the static Nash equilibrium, the data are better explained by Edgeworth-cycle behavior. Not only are weighted average prices closer to the predicted Edgeworth cycle prices, but we cannot reject the hypothesis that firms are engaging in some form of myopic price adjustment. There is little tacit collusion.

The additional insights from our study are that the significance and the strength of these results depend on the capacity levels. First, we find that the predictive power of the static Nash equilibrium varies with industry capacities. Specifically, the gap between Nash predictions and observed average prices significantly increases alongside the level of excess capacity. Second, also the explanatory power of the model of myopic price adjustments depends on the capacity level. The Edgeworth price adjustment process is *stronger* for treatments with *lower* production capacities. As capacities become bigger and eventually not binding, the intensity of Edgeworth-cycle behavior

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[3]See also the recent related studies on price dispersion by Morgan et al. (2006) and Orzen (2008) where the equilibrium is also in mixed strategies.

diminishes. Regarding monopoly pricing, we observe that it is significantly and negatively correlated with industry capacity. When capacities are "small" and approach the monopoly level, a share of prices is indeed at the monopoly level.

Our data are also suitable to illuminate the discontinuities of the Bertrand-Edgeworth model to perfect competition and monopoly. While the intensity of Edgeworth cycles decreases with capacity, even in the case were capacities are such that marginal cost pricing is the pure-strategy equilibrium, Edgeworth-cycle theory still describes pricing behavior rather accurately. That is, even though in theory the Nash equilibrium regime changes from mixed to pure-strategy, we find no corresponding discontinuity in behavior in the experiment. A similar point applies to monopoly pricing. Even for the lowest level of capacity we study, the share of monopoly prices does not exceed 31 percent in individual markets and, again, much of the data still exhibits cyclical patters.

Finally, our results add to the existing literature concerned with the effect of the number of competitors on market outcomes. Three findings merit note. Firstly and consistent with the existing literature, increasing the number of firms keeping production capacity constant leads to lower market prices. Secondly, the extent to which prices are autocorrelated diminishes with triopolies vis-à-vis duopolies. Furthermore, the degree to which firms engage in Edgeworth cycles is lower in markets with three firms than in markets with two firms. Finally, we observe a drop in the frequency of monopoly pricing when we move from duopolies to triopolies. While there is some attempts at collusive behavior in two-firm markets, we find no such evidence in markets with three competitors.

The following section describes the model under scrutiny. Section 3 describes the experimental design and methodology; section 4 analyzes the results and section 5 concludes the paper.

# 2 The Model

We consider a symmetric Bertrand-Edgeworth oligopoly with $n$ firms. Denote by $k$ a firm's capacity such that $nk$ is industry capacity and $(n-1)k$ is the capacity of a firm's competitors. Firms' production costs up to capacity are assumed to be zero for simplicity.

There are $m$ buyers, each of whom buys one unit of the good as long as the price does not exceed $\bar{p}$. Buyers buy from the firm with the lowest price first. If this firm's capacity is exhausted, they move on to the second lowest price and so on. If two or more firms charge the same price and if their joint capacity exceeds the (remaining) number of customers, demand is split equally among firms.

We assume

$$nk > m > (n-1)k. \tag{1}$$

These assumptions imply that there is competition, but it is not perfect and static Nash equilibrium profits will be positive. If $m > nk$, all firms would charge the maximum price of $\bar{p}$ and there would no competition at all. If $(n-1)k > m$, any subset of $n-1$ firms can serve the entire market so there would be perfect Bertrand competition where price equals marginal cost in equilibrium. Since $m > (n-1)k$, equation (1) ensures the static Nash equilibrium is in mixed strategies. Due to the assumption, only two relevant contingencies exist for each firm. If a firm does not charge the highest price, it sells $k$ units. If a does firm charge the highest price, it sells $m - (n-1)k$ units.

## 2.1 Equilibrium Analysis

In this section, we derive the static Nash equilibrium, the minimum discount factor required for collusion in the repeated game and a prediction for markets characterized by myopic Edgeworth-cycle behavior. The proofs of the following three propositions can be found in the appendix.

**Proposition 1.** *The unique static Nash equilibrium is in mixed strategies with support $[\underline{p},\, \overline{p}]$ where*

$$\underline{p} = \overline{p}(m - (n-1)k)/k. \tag{2}$$

*In equilibrium, the probability that a firm charges a price of no more than $p$ is*

$$F(p) = \left(\frac{\overline{p}\,(m - (n-1)k) - pk}{p(m - nk)}\right)^{1/(n-1)} \tag{3}$$

*Equilibrium profits are $\pi^N = \underline{p}k$ and the expected weighted Nash equilibrium price is $p^N = \underline{p}kn/m$.*

This is the standard result for Bertrand-Edgeworth oligopolies with inelastic demand. Firms randomize in equilibrium and choose prices between the reservation price and some lower bound that depends on the excess capacity. Nash equilibrium profits and average prices vary between the monopoly level (for $nk = m$) and the perfectly competitive level (for $k = m$). Note that $F(\underline{p}) = 0$ and $F(\overline{p}) = 1$.

We now turn to the infinitely repeated game. Time is indexed from $t = 0, ..., \infty$ and firms discount future profits with a factor $\delta$, where $0 \leq \delta < 1$. We will look for subgame perfect collusive equilibria with profits higher than those of the static Nash equilibrium. When analyzing the repeated game, denote by $\pi_i^c$ the profit firm $i$ earns when all firms adhere to collusion. Let $\pi_i^d$ denote the profit when a firm defects, and $\pi_i^p$ is the profit per period when a punishment path is triggered. We assume that firms revert to the static Nash equilibrium after a defection, thus we have $\pi_i^P = \pi_i^N$.[4]

**Proposition 2.** *The minimum discount factor required for collusion in the infinitely repeated game is $\underline{\delta} = 1/n$.*

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[4]Note that the static Nash equilibrium payoff is equal to the minimax payoff here. Thus, harsher punishments do not exist.

The proposition shows that the minimum discount factor depends only on the number of firms but not on $k$. This is due to the symmetry of the model. Indeed, it is our aim to control for $\underline{\delta}$ given industry capacity, $kn$, because otherwise, we would change both capacities and $\underline{\delta}$ in the experiments.

The proof of the proposition shows that colluding at the reservation price $\bar{p}$ requires the lowest discount factor. Thus, while the folk theorem says that infinitely many outcomes can be a subgame perfect equilibrium of this game, both payoff dominance and minimizing the minimum discount factor suggest that players may coordinate on $\bar{p}$.

Finally, we consider Edgeworth-cycle behavior. The idea is that, in multi-period Bertrand-Edgeworth markets, firms may dynamically adjust their prices by best responding, assuming that the other firms keep their prices constant. Firms keep undercutting their rivals' prices until they reach a price level (which coincides with the lower bound of the support of the mixed-strategy equilibrium, $\underline{p}$) where they are better off charging the reservation price even if they do not sell their capacity at that price. In other words, in an Edgeworth cycle firms play the myopic best reply, holding naïve price expectations.

As all firms that do not charge the highest price in the market sell $k$, the myopic best reply is to undercut by the smallest amount (here equal to one for illustration) the rival firm that charged the highest price in the previous period. Formally

$$
p_i^{t+1} = \begin{cases} \max\{p_{j\neq i}^t\} - 1, & \text{if } \max\{p_{j\neq i}^t\} - 1 \geq \underline{p} \\ \bar{p} & \text{else} \end{cases} . \tag{4}
$$

These kind of myopic price choices suggest the following proposition.

**Proposition 3.** *Edgeworth-cycle pricing behavior implies an average price of* $(\bar{p} + \underline{p})/2$.

Proposition 3 is intuitive. If firms play a complete Edgeworth cycle, they charge each of the

prices in $[\bar{p} - \underline{p}]$ exactly once. Thus the average price is the mean of $\bar{p}$ and $\underline{p}$ where $\underline{p}$ is an in Proposition 1.

Neither Proposition 1 nor Proposition 3 do apply when $m < (n-1)k$ (see (1)). In that case, capacity constraints are not binding any more and the pure strategy Nash equilibrium is where price equals marginal cost. However, since firms make zero profits when price equals marginal cost, starting a new cycle by charging $\bar{p}$ does not reduce profits. In other words, the cost of deviating from equilibrium is zero.[5] For that reason (and this is supported by the data), we will apply the prediction in Proposition 3 also in the treatments where $m < (n-1)k$.

# 3    Experimental Design and Procedures

We ran a series of experimental Bertrand-Edgeworth markets. In all treatments, there were $m = 300$ computer-simulated consumers, who demanded one unit of a good at the lowest price, as long as that price did not exceed $\bar{p} = 100$. The main treatment variable is industry production capacity, which was always symmetrically distributed, and the number of firms in the market (two or three). The choice of capacity distributions was made such that we had treatments in which the static prediction was perfect competition, all the way to a distribution close to the point where firms had monopoly power. Table 1 summarizes the treatments. We also ran as an extra treatment a variant of treatment 250-250 (labeled 250-250FC), where firms had a fixed production cost. We elaborate more on this treatment in the analysis section.

We implemented the treatments with a fixed-matching scheme, and generated six markets (or groups) for each treatment. Subjects were told they were representing a firm in a market where they would meet with one (or two) other firms. Subjects participated in one treatment only and

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[5]On this issue in the context of Bertrand oligopolies with random (one shot) interaction, see Dufwenberg et al., 2007.

| $n = 2$ | treatment | 175-175 | 201-201 | 225-225 | 250-250 | 300-300 |
|---------|-----------|---------|---------|---------|---------|---------|
|         | $n \cdot k$ | 350 | 402 | 450 | 500 | 600 |
| $n = 3$ | treatment | 116-116-116 | 134-134-134 | 150-150-150 | | |
|         | $n \cdot k$ | 348 | 402 | 450 | | |

Table 1: Treatments

the capacity distribution was held fixed in each market, meaning that each subject dealt with one capacity only. Subjects were informed about all features of the market in the trading rules (instructions are reproduced in the Appendix).

Sessions lasted for at least 30 periods. From the $31^{st}$ period on, a random stopping rule was imposed with a continuation probability of 5/6. Subjects were fully informed about the minimum number of periods and the details of the termination rule. In each period, subjects were asked to enter their price in a computer terminal. Once all subjects had made their decisions, the round ended and a screen displayed the prices chosen by all firms in the market, as well as the profit of each individual firm. Finally subjects were told their accumulated profit up to that point.

Payments consisted of a show-up fee of £5 plus the sum of the profits over the course of the experiment. For payments, we used an "Experimental Currency Unit (ECU)". In all treatments, 25,000 ECU were worth £1.

The sessions were run in the F.E.E.L.E. lab at the University of Exeter during the Spring of 2008. The experiment was programmed in z-Tree (Fischbacher, 2007). Sessions lasted for about 60 minutes and average payment was £17 (roughly $31). We conducted two experimental sessions with nine participants for each of the three-firm markets and one session with twelve participants for each of the duopoly markets. The data for treatments 201-201 and 134-134-134 are taken from Fonseca and Normann (2008). These sessions were run by the same experimenter and using the same protocol at the Economics Experiments Laboratory of Royal Holloway College (University of London) during the Fall of 2004 and 2005. We have a total of 96 subjects participating in the

| Treatment | $K$ | Prediction $p^{EC}$ | $p^N$ | Data $p$ |
|-----------|-----|---------------------|-------|----------|
| 175-175 | 350 | 85.71 | 83.33 | 84.96 |
|  |  |  |  | (9.70) |
| 201-201 | 402 | 75.63 | 66.00 | 78.44 |
|  |  |  |  | (11.93) |
| 225-225 | 450 | 66.67 | 50.00 | 60.50 |
|  |  |  |  | (19.57) |
| 250-250 | 500 | 60.00 | 33.00 | 54.04 |
|  |  |  |  | (23.62) |
| 250-250-FC | 500 | 60.00 | 33.00 | 47.62 |
|  |  |  |  | (21.79) |
| 300-300 | 600 | 50.00 | 0.00 | 40.48 |
|  |  |  |  | (22.20) |
| 116-116-116 | 348 | 79.63 | 68.00 | 73.51 |
|  |  |  |  | (9.46) |
| 134-134-134 | 402 | 61.94 | 32.00 | 64.69 |
|  |  |  |  | (20.19) |
| 150-150-150 | 450 | 50.00 | 0.00 | 41.73 |
|  |  |  |  | (18.10) |

Table 2: Predicted and observed average weighted prices.

Exeter sessions plus 30 subjects who participated in the 201-201 and 134-134-134 treatments at Royal Holloway College.

# 4 The Results

## 4.1 Overview

Throughout, we consider data from period 11 onwards to allow for learning effects. Using the full data set would not alter the results qualitatively. Table 2 displays average weighted price for each treatment. The average prices of the treatments clearly differ. Counting each group average as one observation, a non-parametric Kruskal-Wallis test on the duopoly data (excluding the 250-250-FC data) is highly significant ($\chi^2 = 20.97$, $d.f. = 5$, $p = 0.0008$), as is the same test on the three-firm markets ($\chi^2 = 8.84$, $d.f. = 2$, $p = 0.0120$).

Table 2 suggests that industry capacity and prices are negatively correlated. The Spearman

correlation coefficient is quantitatively substantial and significant for both the duopolies ($\rho = -0.75$, $p < 0.0001$) and the three-firm markets ($\rho = -0.71$, $p = 0.0010$). If we compare treatments pairwise, we find that a rise in capacity almost always results in significantly lower prices (two-tailed Mann-Whitney U test, all tests $p < 0.05$), the exceptions being the comparisons between treatments 175-175 and 201-201, as well as between 116-116-116 and 134-134-134.

## 4.2 Analysis of the Nash equilibrium prediction

The negative correlation of average prices is predicted by the static Nash equilibrium. So, qualitatively, the Nash prediction is consistent with this trend. It is however clear that the Nash equilibrium does not do well in terms of the quantitative prediction. The rate of decrease in prices is less pronounced compared to what the mixed-strategy equilibrium predicts. It seems that, as excess capacity increases, the difference between predicted Nash prices and average weighted prices also goes up. Figure 1 shows the average market price for each capacity, as well as the predicted Nash price and Edgeworth cycle price. Indeed, a Jonckheere-Terpstra test using the difference between the average price for each market and the Nash prediction confirms that this gap significantly increases with industry capacity for both duopolies (J-T statistic 4.017, $p < 0.001$) and three-firm markets (J-T statistic 3.719, $p < 0.001$).[6]

Since the static Nash equilibrium of this game is in mixed strategies, it is desirable to look at the distribution of posted prices in each treatment and compare it to the predicted mixed strategy distribution. Figures 2 and 3 display the predicted and observed price distributions for the duopoly and triopoly markets, respectively.

As is readily observable from the figures, all the observed data distributions significantly

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[6]The Jonckheere-Terpstra test is a non-parametric test for more than two independent samples, like the Kruskal-Wallis test. Unlike Kruskal-Wallis, Jonckheere-Terpstra tests for ordered differences between treatments and thus requires an ordinal ranking of the test variable. See, e.g., Hollander and Wolfe (1999).
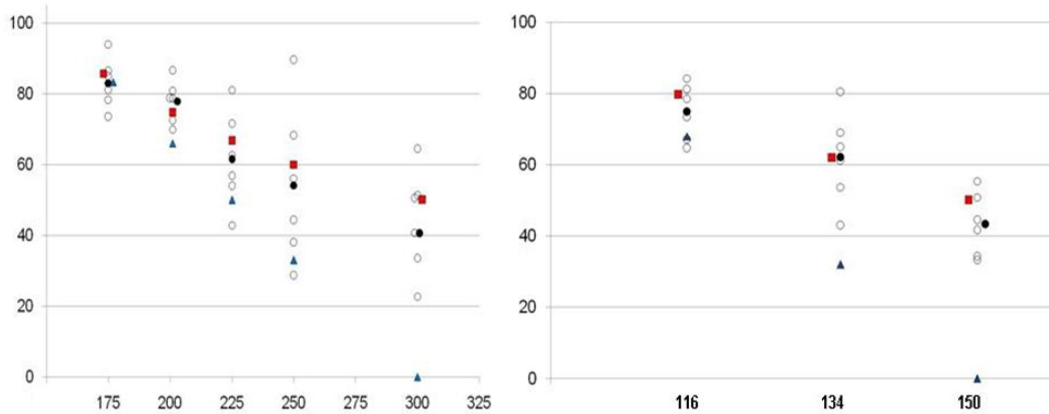
Figure 1: Group average prices for the duopolies (left) and triopolies (right). The squares are the Edgeworth-cycle prediction, the triangles are the Nash equilibrium prediction and the solid dots are the treatment average.

differ from their theoretical counterparts using Kolmogorov-Smirnov tests (all $p < 0.01$). This is consistent with evidence from Brown-Kruse et al. (1994), who reported significant differences between predicted mixed strategy distributions and observed price distributions.

An alternative interpretation of Nash behavior in this context is that subjects make in every period an independent draw with replacement from the mixed strategy equilibrium distribution of prices, $F(p)$. As such, one would expect there to be no correlation between current and previous prices. To test this hypothesis, we regressed the difference between the price posted by firm $i$ at time $t$ and the price posted by the same firm at time $t - 1$ on its lag plus a variable equal to the inverse of the period (*Perinv*) number to allow for time trends.

We find that the coefficient on the lag of the regressor is significant in all duopoly and triopoly treatments. However, the coefficient on the lag of the regressor gets smaller as total capacity increases. Running the autocorrelation regressions separately for each session (and counting each of the coefficients obtained as one observation), we find that this effect is significant for the duopolies (J-T statistic $= 3.505$, $p < 0.001$) but not significant for triopolies (J-T statistic $= 0.970$, $p = 0.166$. This indicates that the degree to which prices are autocorrelated diminishes with excess capacity
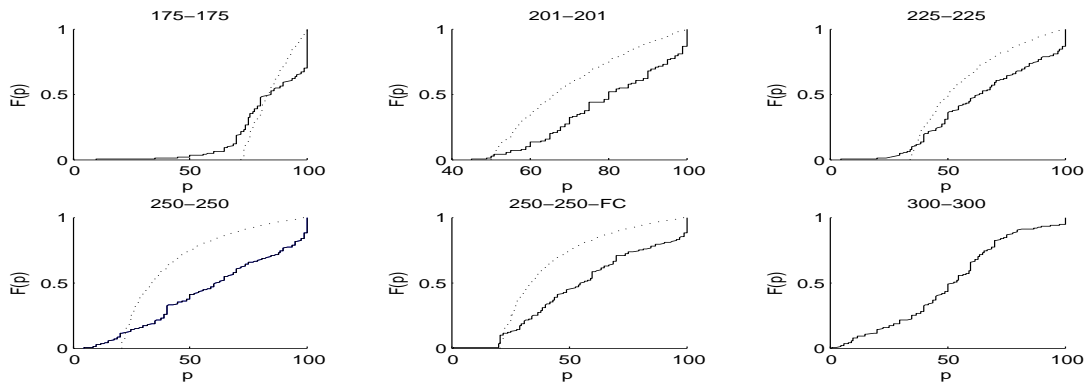
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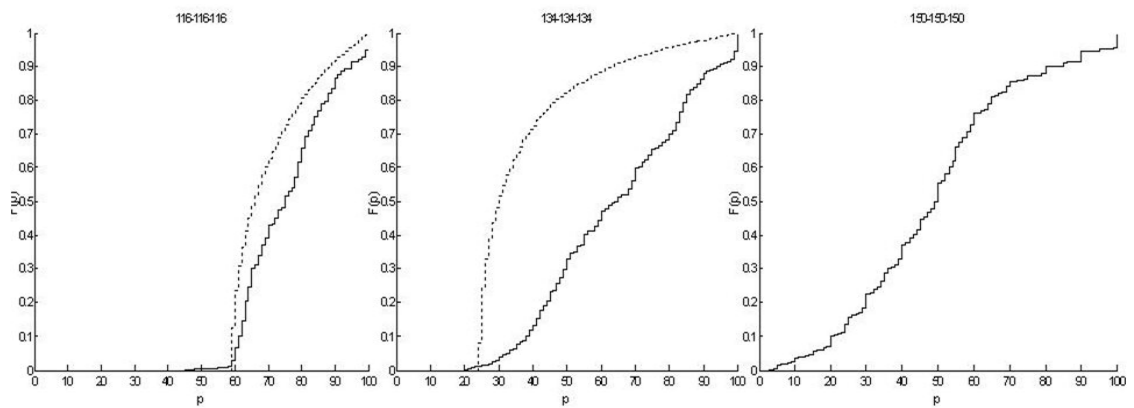Figure 2: *Predicted (dotted line) and observed cumulative price distributions, duopoly treatments*



Figure 3: *Predicted (dotted line) and observed cumulative price distributions, triopoly treatments*

| $(P_t - P_{t-1})$ | (175-175) | (201-201) | (225-225) | (250-250) | (300-300) | All |
|---|---|---|---|---|---|---|
| $(P_{t-1} - P_{t-2})$ | -0.571** | -0.560** | -0.431** | -0.384** | -0.289** | -0.418** |
| | (0.039) | (0.073) | (0.038) | (0.037) | (0.061) | (0.035) |
| Perinv | -5.416 | 35.535 | -10.575 | 6.059 | -95.486 | -13.697 |
| | (28.311) | (14.642) | (28.130) | (50.526) | (41.069) | (16.444) |
| Const | 0.747 | -1.929* | 0.400 | 0.122 | 4.293 | 0.693 |
| | (1.420) | (0.508) | (0.951) | (2.012) | (1.905) | (0.716) |
| N | 240 | 396 | 384 | 348 | 312 | 1584 |
| R-squared | 0.33 | 0.31 | 0.18 | 0.14 | 0.09 | 0.17 |

Table 3: Autocorrelation of prices: duopolies

| $(P_t - P_{t-1})$ | (116-116-116) | (134-134-134) | (150-150-150) | All |
|---|---|---|---|---|
| $(P_{t-1} - P_{t-2})$ | -0.348** | -0.213** | -0.223** | -0.237** |
| | (0.063) | (0.065) | (0.038) | (0.031) |
| Perinv | -7.614 | 51.805 | -30.729 | -3.329 |
| | (28.669) | (43.757) | (44.318) | (22.809) |
| Const | 0.254 | -2.554 | 1.860 | -0.057 |
| | (1.538) | (2.259) | (2.536) | (1.233) |
| N | 414 | 360 | 396 | 1170 |
| R-squared | 0.12 | 0.05 | 0.05 | 0.06 |

Table 4: Autocorrelation of prices: triopolies

and with the number of firms.

To conclude, the static mixed-strategy equilibrium captures the negative correlation between average prices and industry capacity well. On the other hand, it is obvious that subjects do not randomize in the way the theory stipulates. Central for our research question is the finding that, with higher capacities, the gap between the Nash prediction and average prices gets bigger.

## 4.3   Tacit Collusion

We now address the issue of collusion. One can see in Figures 2 and 3 that there is some mass on the reservation price in all treatments. As discussed in the theory section, while many possible prices may sustain collusion in equilibrium, the maximum price, $\overline{p}$ is the natural candidate, both because it is payoff dominant and also because it requires the smallest discount factor in the repeated game. When looking at the aggregate data across treatments we find some limited evidence of collusion.

13% of posted prices are equal to $\bar{p}$ in the duopoly treatments and 5% in the triopoly condition. When we look at the proportion of cases where all subjects posted $p = \bar{p}$ in a given period, the percentage drops to 3% in the duopoly conditions and 0% in the triopoly conditions.

However, these averages mask the variation that exists across different capacity configurations. We find that in the duopoly case, the share of $p = \bar{p}$ prices goes significantly up as total capacity goes down. Using each market as one independent observation, the Spearman correlation between share of $p = \bar{p}$ and capacity is high and significant ($\rho = -0.51$, $p = 0.004$); using a Jonckheere-Terpstra test we can reject the hypothesis that shares of $p = \bar{p}$ is constant across treatments in favor of the alternative that it rises as total capacity drops (J-T statistic = -2.85, $p = 0.004$).

When we turn to the triopoly data, we find very little evidence of collusion. The relative frequency of $p = \bar{p}$ is constant at 5% across all treatments, and the relative frequency of three firms simultaneously posting prices equal to 100 is zero. We can reject therefore any relationship between capacity and share of $p = 100$ prices using either Spearman's $\rho = 0.01$ ($p = 0.958$) or the Jonckheere-Terpstra test (J-T statistic = 0, $p = 0.999$). Previous studies of Bertrand markets (Dufwenberg and Gneezy, 2001) found that the degree of competition increased dramatically when the number of firms went from two to three (and four). In their paper, firms were not capacity constrained and thus able to serve the entire market. Our evidence suggests that even when capacities are binding, such that no firm is able to serve all consumers, cooperation is too difficult to sustain as one moves beyond a simple duopoly. Table 5 summarizes the results.

A possible explanation for the frequency of $p = \bar{p}$ observations is that subjects may have attempted to signal the intention to collude by repeatedly posting the maximum price over a number of periods, even when such actions are not reciprocated by the other subjects. We found that in about half of all $p = 100$ observations, one firm posted a price of 100 in two or more

| Treatment | $p = 100$ | all firms $p_t = 100$ |
|---|---|---|
| 175-175 | 0.31 | 0.16 |
| 201-201 | 0.10 | 0.01 |
| 225-225 | 0.13 | 0.02 |
| 250-250 | 0.12 | 0.02 |
| 300-300 | 0.04 | 0.01 |
| Total | 0.13 | 0.03 |
| 116-116-116 | 0.05 | 0.00 |
| 134-134-134 | 0.05 | 0.00 |
| 150-150-150 | 0.05 | 0.00 |
| Total | 0.05 | 0.00 |

Table 5: Relative frequency of collusion

consecutive periods without being matched by its counterpart(s). As such, we argue that these observations are consistent with (failed) attempts to signal collusion intentions.

Finally, recall that the minimum discount factor in the infinitely repeated game is $\underline{\delta} = 1/n$ for our game, suggesting that triopolies find it easier to collude. From the average prices, this hypothesis is rejected. Given some level of industry capacity, the triopolies have lower prices. On the other hand, its is remarkable that the triopolies manage to sustain higher markups on top of the Nash equilibrium prediction than the duopolies. We will come back to this issue in the Discussion below.

## 4.4 Analysis of the EC prediction

Brown-Kruse et al. (1994) suggest that subjects' behavior may be consistent with Edgeworth cycles. Table 2 confirms this. Figure 1 suggests that, at least at the aggregate level, Edgeworth cycles are a much better predictor of behavior than the Nash equilibrium in both the duopoly and triopoly conditions.

In order to construct a formal test of Edgeworth cycle pricing, we follow Brown-Kruse et al. (1994) in running OLS estimations of individual price adjustments across periods in all treatments. We estimated the following equation: $P_{i,t} - P_{i,t-1} = \beta_0 + \beta_1(P_{i,t}^E - P_{i,t-1}) + \beta_2(P_{i,t-1}^E - P_{i,t-2}) + \epsilon_{i,t}$.

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The dependent variable is the change in prices from period $t$ to $t-1$; the independent variables are the predicted Edgeworth adjustment and its lag. Based on this estimation, we are able to formulate a number of hypotheses. The first hypothesis is that there is no price adjustment process; that is, $\beta_1 = \beta_2 = 0$. The second hypothesis is that firms make an immediate and perfect Edgeworth adjustment, which implies $\beta_0 = 0$, $\beta_1 = 1$ and $\beta_2 = 0$. The third hypothesis, $\beta_1 = 0$ is that any adjustment is not immediate; finally, the fourth test is that there is no lag in the adjustment process, $\beta_2 = 0$.

Tables 6 and 7 show the results from estimating the equation treatment by treatment in both the duopoly and triopoly conditions. Table 6 quantifies the extent to which duopolists make myopic adjustments to their rival's actions in the previous period. The coefficient of $\beta_1$ is positive and significant in all treatments, as it is if we pool all treatments. The coefficient of $\beta_2$ only significantly different from zero in treatments 175-175 and 225-225, as well as for the pooled data. The findings are similar for the triopoly conditions. This indicates that firms, on average, are making immediate, if only partial, adjustments to rivals' previous period prices.[7]

Estimating the Edgeworth price adjustment equation at the subject level and performing the aforementioned tests broadly lead us to reject the hypothesis that the observed price adjustments are either immediate or perfect. It confirms the picture that the Edgeworth adjustment process is only partial. This is consistent across duopolies and triopolies and it is qualitatively similar to the evidence presented by Brown-Kruse et al. (1994). The noticeable discrepancy is that we

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[7]Feedback from post-experimental questionnaires reinforces this belief. We transcribe a representative description by a subject of her behavior in the experiment: "Initially, I tried to set a price that would undercut the price set by company A by a small amount so as to maximise profit. However, when the price set by company A got around 30, I predicted that the next round it would be lower, something like 20-25 and so I set my price at 100. By forgetting about setting the lowest price and selling 75 units at 100 I was guaranteed a profit of 7500. If instead I had tried to undercut company A by setting my price at, say 20, I would only have made 5550 profit and this was less than 7500."

|  | (175-175) | (201-201) | (225-225) | (250-250) | (300-300) | All |
|---|---|---|---|---|---|---|
| $\beta_1$ | 0.521** | 0.499** | 0.485** | 0.454** | 0.465** | 0.465** |
|  | (0.088) | (0.046) | (0.052) | (0.034) | (0.024) | (0.020) |
| $\beta_2$ | -0.248* | -0.043 | -0.0892 | -0.105* | 0.041 | -0.079 |
|  | (0.090) | (0.069) | (0.053) | (0.040) | (0.042) | (0.029) |
| $\beta_0$ | -0.829 | 0.074 | -1.422 | -1.908 | 0.154 | -0.994 |
|  | (0.558) | (0.124) | (1.068) | (1.851) | (0.246) | (0.503) |
| Obs. | 240 | 300 | 384 | 348 | 312 | 1584 |
| R-squared | 0.29 | 0.23 | 0.22 | 0.25 | 0.29 | 0.24 |

Table 6: Edgeworth-cycle estimates at treatment level: duopolies

|  | (116-116-116) | (134-134-134) | (150-150-150) | All |
|---|---|---|---|---|
| $\beta_1$ | 0.467** | 0.412** | 0.388** | 0.398** |
|  | (0.024) | (0.076) | (0.095) | (0.064) |
| $\beta_2$ | 0.014 | -0.046 | -0.131** | -0.093* |
|  | (0.052) | (0.035) | (0.031) | (0.033) |
| $\beta_0$ | -1.342* | -1.241 | -1.481 | -1.224** |
|  | (0.417) | (0.559) | (0.775) | (0.393) |
| Obs. | 414 | 360 | 396 | 1170 |
| R-squared | 0.31 | 0.17 | 0.24 | 0.22 |

Table 7: Edgeworth-cycle estimates at treatment level: triopolies

report a higher rejection rate for the third hypothesis, which may indicate a worse performance of Edgeworth cycle behavior in our data set. This evidence is summarized in Table 8.

A closer look at the price distributions in Figure 2 also suggests discrepancies with Edgeworth cycle theory. First, we see in a number of treatments that there is mass at $p = 100$ (this is clearest in the case of 175-175), which may be indicative of collusion. Second, in almost all treatments, we also see that the lower bound of the pricing distribution is below the theoretical lower bound (which is the same value in the Edgeworth cycle).

We now turn our attention at how treatments impact Edgeworth cycles (noting aside that Brown-Kruse et al. (1994) only consider the pooled data set containing all their treatments for the previous analysis). Going back to Table 8, we can also see the frequency with which our null hypotheses are rejected treatment by treatment. The first thing to notice is that the percentage of rejections of hypothesis (1) (no Edgeworth adjustment) is quite high across all treatments.

| Treatment | (1) $\beta_1 = 0, \beta_2 = 0$ | (2) $\beta_0 = 0, \beta_1 = 1, \beta_2 = 0$ | (3) $\beta_1 = 0$ | (4) $\beta_2 = 0$ |
|---|---|---|---|---|
| 175-175 | 0.58 | 0.42 | 0.58 | 0.00 |
| 201-201 | 0.75 | 0.75 | 0.75 | 0.17 |
| 225-225 | 0.67 | 0.67 | 0.83 | 0.08 |
| 250-250 | 0.67 | 0.92 | 0.75 | 0.17 |
| 300-300 | 0.67 | 0.92 | 0.83 | 0.08 |
| Duopolies | 0.83 | 0.82 | 0.88 | 0.08 |
| 116-116-116 | 0.61 | 0.94 | 0.78 | 0.11 |
| 134-134-134 | 0.67 | 0.61 | 0.67 | 0.06 |
| 150-150-150 | 0.72 | 0.72 | 0.72 | 0.17 |
| Triopolies | 0.78 | 0.80 | 0.80 | 0.09 |

Table 8: Fraction of rejection of null hypotheses at the 5% level by treatment

Furthermore, the fraction of rejections of hypothesis (4) is quite low across all treatments. This suggests that while there is in fact some type of Edgeworth price adjustment ongoing, it is imperfect.

Focusing our attention to hypothesis (2), we see a significantly rise in the rejection frequency as the industry production capacity goes up – it would be perfectly monotonic if not for treatment 201-201 (J-T statistic 3.013, $p < 0.01$). This indicates that the higher total capacity is, the less likely it is that firms are making perfect Edgeworth adjustments. The rejection rates of treatments 250-250 and 300-300 are already close to 100%, meaning that almost no subject in that treatment is doing perfect Edgeworth price adjustments. This is consistent with the evidence presented in Table 2. The difference between the average expected Edgeworth cycle prices and the observed prices increases as we move from the low excess capacity treatment (175-175) to the the high excess capacity treatment (300-300). The same pattern is not apparent from the triopoly data (J-T statistic -1.659, $p = 0.95$.) This may be because subjects have difficulty in tracking pricing behavior of more than one competitor.

The results also suggest some level of heterogeneity in behavior across markets within the same treatment. Figure 4 displays price histograms for treatment 175-175, which was the treatment in which Edgeworth price adjustments were most salient. We see a high level of heterogeneity across
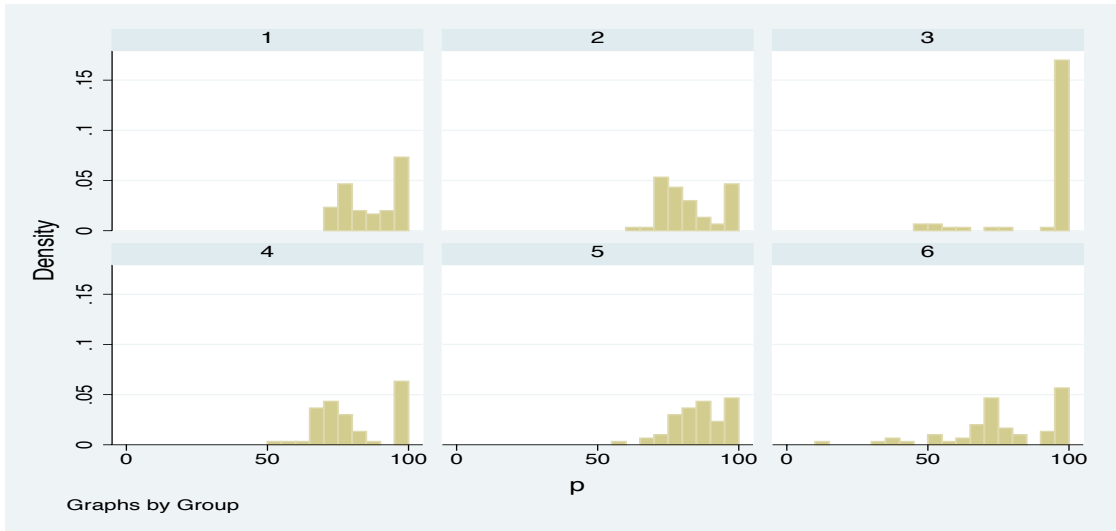
Figure 4: *Histogram of pricing decisions by group, treatment 175-175*

different groups; group 3 appears to be quite collusive, with a very high frequency of observations close to or including $p = 100$, while group 6 has a distribution of prices which includes price levels significantly below the lowest predicted price (75). A similar conclusion can be drawn from the other treatments. The complete set of histograms for all treatments is available upon request. In short, Edgeworth cycles predict of aggregate (treatment-)level behavior well, but its fits less well with individual behavior.

## 4.5 Aspiration Levels

Could loss aversion be a cause for the higher prices (compared to Nash) observed in the experiment? As noted above, as excess capacity increases, the difference between predicted Nash prices and average weighted prices also goes up. It seems plausible that, for high levels of excess capacity, subjects' earnings might fall below some (unobserved) aspiration level and thus causes subjects to charge higher prices. Such an effect has been found in price-setting oligopoly experiments where subjects incurred fixed cost for participating in the market (Offerman and Potters, 2006), and in experimental Cournot oligopolies where a merger caused one firm to fall behind its pre-merger

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profit level (Huck et al., 2007).

In order to test for aspiration levels, we ran a variant of the 250-250 treatment in which we introduced a fixed cost of 5000 ECU in every period. This is the maximum fixed cost that does not alter the mixed strategy equilibrium. As one can see from Table 2, there are no significant differences in weighted prices. If anything, price are even lower with the fixed cost, although not significantly so (Mann-Whitney U test, $p = 0.873$). We can reject the hypothesis that prices generated from the two treatments come from different distributions (Kolmogorov-Smirnov test $D = 0.1577$, $p \leq 0.001$). The main difference between the two distributions comes from the fact that there are no observations below $\underline{p}$ in the treatment with fixed costs, as opposed to the 205-250 treatment without fixed costs. It seems that the existence of such costs acts as a deterrent to excessive competition.

## 4.6 Discussion

Our main research question is how variations in industry capacity affect pricing behavior in Bertrand-Edgeworth oligopolies. Essentially, we found the following effects: firstly, the larger capacities, the bigger the gap between average static Nash equilibrium prices and observed prices. Secondly, with larger capacities the monopoly price is charged less frequently. Thirdly, the larger industry capacity, the less predictive power myopic Edgeworth cycles have.

The second and the third finding constitute a puzzle. The puzzle is that lower capacities are associated with both more pronounced Edgeworth-cycle behavior and more monopoly pricing. After all, Edgeworth-cycle behavior is based on playing a (myopic) best-reply which is non-cooperative behavior, whereas setting the monopoly price should be considered as tacit collusion.

Our explanation is as follows. Suppose there is no excess capacity at all. Then participants would surely charge the monopoly price almost all the time. All our predictions (static Nash, tacit

collusion and Edgeworth cycles) converge to the monopoly price as $nk \to m$. With a positive amount of capacity, subjects play Edgeworth cycles. As capacities get bigger, the high-price firm earns relatively less money. Thus, the larger industry capacity, the more "expensive" it becomes to be the high-price firm, and the more random subjects' price choices become as a result.

What this reasoning boils down to is that playing the Edgeworth cycle is an (imperfect) form of tacit collusion. Subjects do not always charge the monopoly price, nor do they take regular turns in being the high-price firm. However, subjects can afford to play relatively predictable pricing patters when excess capacity is low. Thus, with higher capacities Edgeworth cycles lose some of their predictive power. Subjects still do not play the static Nash equilibrium but they do fall further below the Edgeworth-cycle prediction with higher capacities. Their behavior becomes more, not less, competitive.

Accepting the notion of Edgeworth cycle as a form of tacit collusion, it seems less puzzling that monopoly pricing and the intensity of the Edgeworth cycles are both negatively correlated with industry capacity. Note also that, with smaller capacities, the monopoly price will be played more frequently because the numbers of periods required for a complete cycle is smaller. Finally, we saw the number of markets where all firms charge the monopoly price (and these few markets are not consistent with Edgeworth cycles) is rather small. Thus even if some industries charge the monopoly price most of the time, Edgeworth cycles still accurately describe the treatments with low capacities.

There is yet another puzzle in our data. There is *relatively* more collusion with higher capacities in the sense that prices are increasingly above the Nash level. While the absolute price level is decreasing with capacities, collusion defined relatively to Nash is increasing with capacities. The notion that subjects play more collusively when excess capacity is consistent with the prediction that tacit collusion should be easier with three firms, not in duopoly. (Recall the minimum discount

factor in the repeated game is $1/n$.) But, if there is more "collusion" with higher capacities, how does this fit with less monopoly pricing? The answer could lie in the fact that even imperfect Edgeworth cycle behavior will lead to a price distribution that puts more weight to the top part of the support than the mixed strategy Nash equilibrium price distribution. As such the average price will not decline with capacity as quickly as the predicted Nash price.

Finally, we discuss our findings regarding the discontinuities of the Bertrand-Edgeworth model when capacities become non-binding or when there is no excess capacity at all such that pure-strategy equilibria emerge. We found no comparable discontinuity in the data. Indeed, our treatments with "large" excess capacity suggesting perfect competition exhibited, to a large extent, cyclical behavior even though capacities were not binding at all. The perhaps provocative conclusion from this is that Bertrand experiments (or at least those Bertrand experiments with inelastic demand like Dufwenberg and Gneezy, 2000; Brandts and Guillén, (2004); Dufwenberg et al., 2007; Abbink and Brandts, 2009) may consider the Bertrand-Edgeworth outcome as a plausible prediction. At marginal cost pricing, profits are zero. As a result, players then choose to switch to the maximum price without losing profits (marginal cost pricing is not a strict Nash equilibrium). Doing so also gives them zero profit but it starts a new cycle. This is clearly boundedly rational behavior. Dufwenberg et al. (2007) indeed show that, in Bertrand-Edgeworth experiments, agents have little incentive to stick with the equilibrium. Specifically, they show that the introduction of a price floor actually leads to lower prices because the floor increases the cost of deviating from equilibrium. With "small" levels of excess capacity, we also found evidence for cyclical behavior. Here, however, behavior seems more in line with the theory. Average Nash equilibrium prices and the support of the mixed strategy converge to the monopoly price when excess capacities are small. This is what is occurring in the data.

# 5   Conclusion

This paper examines pricing behavior in Bertrand-Edgeworth markets. In particular, we are interested in studying the effect on prices of increasing total production capacity. The game-theoretical analysis of this class of games predicts that a Nash equilibrium in pure strategies does not exist if the total production capacity in the market is higher than demand, but any subset of firms cannot serve the market by themselves. The only Nash equilibrium is in mixed strategies, where firms randomly select from a unique distribution. Originally, Edgeworth (1925) had proposed an alternative approach. He claimed that firms would engage in successive price adjustments relative to their rivals' prices in the previous period. Firms would undercut each other up to the point where it would be more profitable to charge the monopoly price, thus creating a cycle.

When considering data at the aggregate level, our findings confirm the results of the seminal Bertrand-Edgeworth experiments by Brown-Kruse et al. (1994). In other words, Nash theory predicts the subjects' pricing behavior only partially and only qualitatively well. Observed weighted average prices move in the direction predicted by static Nash equilibrium: the higher the total production capacity is, the lower prices are. This is occurs in both duopoly and triopoly conditions. However, the rate of decrease in prices is much lower than predicted. When we focus our attention to pricing distributions, we find significant differences between predicted Nash price distributions and the observed price distributions. We also find some evidence of attempts at collusive behavior. The proportion of posted prices equal to the maximum price is negatively correlated with total capacity. However, with the exception of one group, those attempts are largely unsuccessful.

By contrast, a model of myopic price adjustments provides a better fit of the data. Not only are average weighted prices closer to the predicted Edgeworth cycle prices, but we cannot reject the hypothesis that firms are engaging in some form of myopic price adjustment. Crucially, (and perhaps counter-intuitively) the Edgeworth price adjustment process is stronger for treatments

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with lower production capacities. As we move closer to the perfectly competitive case, the intensity of Edgeworth cycle behavior diminishes. As a result, the difference between expected average Edgeworth-cycle prices and observed prices also increases.

In our data prices are significantly above predicted Nash prices—also in the case where Nash equilibrium prices are equal to marginal cost. It appears that capacity unconstrained duopolies are, at least to some extent, also driven by Edgeworth-cycle behavior. The tendency for Bertrand markets to deviate from equilibrium where price equals marginal cost is not new. Dufwenberg and Gneezy (2000) had found Bertrand duopolies consistently priced above marginal cost. We add the novel explanation[8] that, because cost from deviating from equilibrium are low, Edgeworth cycles explain rather well non capacity constraint Bertrand markets.

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[8]Made also by Dufwenberg et al. (2007), in a different context.

# Appendix A: Proofs

**Proof of Proposition 1.** If firm $i$ charges $p$, the probability that firm $i$ is the firm with the highest price is $(F(p))^{n-1}$, and $1 - (F(p))^{n-1}$ is the probability that firm $i$ does not charge the highest price. In equilibrium, the expected profit of all prices contained in the support must be the one given in the Proposition, $\bar{p}(m - (n-1)k)$, that is,

$$p\left[(F(p))^{n-1}(m - (n-1)k) + (1 - (F(p))^{n-1})k\right] = \bar{p}(m - (n-1)k). \tag{5}$$

Manipulating (5) yields

$$p\left[(F(p))^{n-1}(m - nk) + k\right] = \bar{p}(m - (n-1)k) \tag{6}$$

$$(F(p))^{n-1} = \frac{\bar{p}(m - (n-1)k) - pk}{p(m - nk)} \tag{7}$$

This verifies that a firm earns $\pi^N$ for any price is the support provided the other firms randomize according to $F(p)$.

The sales-weighted average Nash price is derived as follows. If $q_i$ denotes the number of units sold by firm $i$, the weighted average price is $\sum_{i=1}^{n} p_i q_i / \sum_{i=1}^{n} q_i$. From $\sum_{i=1}^{n} q_i = m$ and since $\sum_{i=1}^{n} p_i q_i = \sum_{i=1}^{n} \pi_i^N$ in Nash equilibrium, we obtain $p^N = \sum_{i=1}^{n} \pi_i^N / m = \underline{p} k n / m$ as claimed.

Finally, uniqueness of the equilibrium is simply implied by the observations that (i) there cannot be a pure-strategy equilibrium; (ii) there cannot be a mixed-strategy equilibrium which puts positive weights on prices outside the support since prices $p < \underline{p}$ are weakly dominated by $\bar{p}$; (iii) there cannot be a mixed-strategy equilibrium on $[\underline{p}, \bar{p}]$ with different randomization weights because, as can be seen from the derivation of the equilibrium $F(p)$ above, if firm $i$ chooses any price $p$ more frequently than $F(p)$, firm $j$ would best respond by charging the pure strategy $p - \epsilon$, which cannot be an equilibrium. $\square$

**Proof of Proposition 2.** Suppose first that firms successfully collude by tacitly agreeing to charge

a price of $p \leq \bar{p}$. Then collusive profits are $\pi_i^c = pmk/(nk) = pm/n$ (that is, each firm gets its symmetric share of industry profit). Defecting with a price marginally smaller than $p$, firm $i$ can get $\pi^d = pk > \pi_i^c$. Finally, $\pi_i^p = \bar{p}(m - (n-1)k)$. Collusion is a subgame perfect Nash equilibrium only if $\pi^c/(1-\delta) \geq \pi^d + \pi^p\delta/(1-\delta)$ or

$$\delta \geq \frac{\pi^d - \pi^c}{\pi^d - \pi^p} = \frac{p - pm/(nk)}{p - \bar{p}(m - (n-1)k)/k} \tag{8}$$

From $\partial\delta/\partial p < 0$, colluding with a price smaller than $\bar{p}$ not only decreases profits but also requires a higher discount factor. Therefore, we analyze perfect collusion where firms charge the reservation price $\bar{p}$ when colluding. With $p = \bar{p}$, (8) simplifies to $\delta \geq 1/n$. $\square$

**Proof of Proposition 3.** The best response characterized by (4) implies that prices are chosen from the interval $[\underline{p}, \bar{p}]$ (which coincides with the support of the mixed-strategy equilibrium). To prove the proposition, we need to show that prices are uniformly distributed over the interval. Let $\varepsilon$ denote the smallest money amount by which one firm can undercut another firm's price.

Suppose first that there are $n > 2$ firms and let $p_1 \geq p_2$ denote the two (weakly) highest prices charged in $t = 0$. If $p_1 > p_2$ strictly, the high-price firm will charge $p_2 - \varepsilon$ in $t = 1$ and all other firms will set $p_1 - \varepsilon$ in $t = 1$. Then $\max\{p_{j\neq 1}^{t=1}\} = p_1 - \varepsilon$ for all firms and thus *all* firms will charge $p_1 - 2\varepsilon$ in $t = 2$. But then all firms will charge $p_1 - 3\varepsilon$ in $t = 3$, $p_1 - 4\varepsilon$ in $t = 4$ and so on until the firms switch to $\bar{p}$ and eventually charge $p_1 - 2\varepsilon$ to begin a new Edgeworth cycle. Hence, all prices in $[\underline{p}, \bar{p}]$ are chosen exactly once by all firms in a cycle (except for the first two periods) and thus prices are uniformly distributed. The same holds if $p_1 = p_2 \geq p_3...$ in $t = 0$. All firms set the same price already from period $t = 1$ on and then play the Edgeworth cycle.

With $n = 2$ firms, the pattern is slightly different. As there is only one rival for each firm, $\max\{p_{j\neq i}^t\}$ is always the price of the other firm. This trivially leads to Edgeworth cycles where all prices are played and are thus uniformly distributed. To see this, suppose that in $t = 0$ firms choose

|  | $t = 0$ | $t = 1$ | $t = 2$ | $t = 3$ |  | $t = 6$ | $t = 7$ | $t = 8$ | $t = 9$ |
|---|---|---|---|---|---|---|---|---|---|
| firm 1 | $\widehat{p}$ | $\widetilde{p} - 1$ | $\widehat{p} - 2$ | $\widetilde{p} - 3$ | ... | $\widehat{p} - 6 = \underline{p}$ | $\widetilde{p} - 7$ | $\overline{p} - 1$ | $\widetilde{p} - 5$ |
| firm 2 | $\widetilde{p}$ | $\widehat{p} - 1$ | $\widetilde{p} - 2$ | $\widehat{p} - 3$ | ... | $\widetilde{p} - 6$ | $\overline{p}$ | $\widetilde{p} - 4$ | $\overline{p} - 2$ |

Table 9: An Edgeworth-cycle for duopoly

$p_1 = \widehat{p}$ and $p_2 = \widetilde{p}$. As long as prices are above the lower bound, firms will set $p_1 = \widetilde{p} - t \cdot \varepsilon$ and

$p_2 = \widehat{p} - t \cdot \varepsilon$ in odd numbered periods; whereas, in even numbered periods, firms will set $p_1 = \widehat{p} - t \cdot \varepsilon$

and $p_2 = \widetilde{p} - t \cdot \varepsilon$. Whenever $p_j = \underline{p}$ in period $t$, firm $i$ will switch to $\overline{p}$ in $t + 1$, resulting in the

same pattern of firms undercutting their rival's $t - 1$ price. As prices are played exactly once over

an Edgeworth cycle, they are thus uniformly distributed. The below Table illustrates this with an

example.□

# Appendix B: Sample Duopoly Instructions

Instructions

Hello and welcome to our experiment. Please read this instruction set very carefully, since through your decisions and the decisions of other participants, you may stand to gain a significant amount of money. We ask you to remain silent during the entire experiment; if at any point in time you require assistance, please raise your hand.

In this experiment you will be in the role of a firm, which is in a market with another firm. The firms produce some good and there are no costs of producing this good.

This market is made up of 300 identical consumers, each of whom wants to purchase one unit of the good at the lowest price. The consumers will pay as much as 100 Experimental Currency Units (ECU) for a unit of the good.

In each market there will be 2 firms, A and B. You can find your type written on the top right-hand corner of this instruction set. Each firm will be able to supply 300 consumers.

The market will operate as follows. In the beginning of each period, all firms will set their selling prices. Then the firm who set the lowest price will sell its capacity at the selected price. The firm who set the second lowest price will not have any customers left to supply.

If more than one firm set the same price and if the number of consumers firms can supply is higher than the number of consumers who haven't bought the good, then they will split the available consumers proportionally to their capacity. In order to fix ideas, let us go over a couple of illustrative examples:

Example A:

Suppose that the two firms choose the following prices: Firm A sets a price of 85 and firm B chooses a price of 75. Firm B set the lowest price and therefore sells its 300 units first at a price of 75, making a profit of 22,500 ECU. Firm A set the highest price and therefore will not supply any customers, therefore making 0 ECU.

Example B: Suppose that the two firms choose the following prices: Firm A and firm B both set a price of 70. Given that they set the same price and also given that their combined capacity (600 units) is larger than the number of customers, they will have to share the available customers. Since their capacities are equal, so will their share of the sales. Hence, both firms will sell 150 units at a price of 70 each unit, therefore making a profit of 10,500 ECU.

At the end of each period, all the firms are informed of the chosen prices by all firms and their own profits. There will be at least 30 periods in this experiment once the 30th period is over, the computer will throw a "virtual" dice that will determine whether the experiment continues. If a value of 6 is shown, the experiment is over. If any other value is shown, the experiment continues.

You will be matched with the same participants in every period.

At the end of the experiment, you will be told of the sum of profits made during the experiment, which will be your payment. You will receive £1 for every 25,000 ECU you earn during the experiment. Additionally you will receive £5 for participating.

# Appendix C: Sample Triopoly Instructions

Instructions

Hello and welcome to our experiment. Please read this instruction set very carefully, since through your decisions and the decisions of other participants, you may stand to gain a significant amount of money. We ask you to remain silent during the entire experiment; if at any point in time you require assistance, please raise your hand.

In this experiment you will be in the role of a firm, which is in a market with two other firms. The firms produce some good and there are no costs of producing this good.

This market is made up of 300 identical consumers, each of whom wants to purchase one unit of the good at the lowest price. The consumers will pay as much as 100 Experimental Currency Units (ECU) for a unit of the good.

In each market there will be 3 firms, A, B and C. You can find your type written on the top right-hand corner of this instruction set. Each firm will only be able to supply a fraction of the 300 consumers. Firms A, B and C will each be able to supply 116 consumers.

The market will operate as follows. In the beginning of each period, all firms will set their selling prices. Then the firm who set the lowest price will sell its capacity at the selected price. Then, the firm who set the second lowest price will supply either its capacity or whatever is left of the market at the chosen price and so on.

If more than one firm set the same price and if the number of consumers firms can supply is higher than the number of consumers who haven't bought the good, then they will split the available consumers proportionally to their capacity. In order to fix ideas, let us go over a couple of illustrative examples:

Example A:

Suppose that the three firms choose the following prices. Firm A sets a price of 85, firm B sets a price of 76 and firm C chooses a price of 63. Firm C sets the lowest price and sells 116 units first, making a profit of 63 x 116 = 7308 ECU. Firm B set the second lowest price and has a remaining 184 customers to sell to. Therefore it will sell 116 units at price of 76, thus generating profits of 116x76=8816. Firm A set the highest price. Because firms B and C have already sold their output, there are 68 customers left. Firm A will then sell 68 units at a price of 85, generating 5780 units of profit.

Example B:

Suppose that the three firms choose the following prices. Firm A sets a price of 50, firm B chooses a price of 45 and firm C chooses a price of 50. This means that firm B will sell all its output first to 116 customers and make 5220 ECU profit (116x45). This leaves 184 customers left to supply. Given that both firm A and C have set the same price and the fact that they can sell a combined total of 232 units, this means they will have to share whatever customers are left. Given that both firm A and C can sell 116 units each, this means they will share the 184 consumers equally. So firm A and C will sell 92 units at a price of 50, making 4150 ECU profit.

At the end of each period, all the firms are informed of the chosen prices by all firms and

their own profits. There will be at least 30 periods in this experiment; once the 30th period is over, the computer will throw a "virtual" dice that will determine whether the experiment continues. If a value of 6 is shown, the experiment is over. If any other value is shown, the experiment continues.

You will be matched with the same participants in every period.

At the end of the experiment, you will be told of the sum of profits made during the experiment, which will be your payment. You will receive £1 for every 15,000 ECU you earn during the experiment. Additionally you will receive £5 for participating.

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