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An experimental study of mixed strategy equilibria in simultaneous price-quantity games

by Daniel Cracau* and Benjamin Franz†

Abstract

We study oligopoly games with firms competing in prices and quantities at the same time. We systematically compare our experimental results to the theoretical predictions using the mixed strategy equilibria for linear demand functions. For the duopoly game, we observe that the mixed strategy equilibrium predicts average outcomes better than Cournot and Bertrand do. Subjects' price choices are mainly between marginal cost and monopoly level but do not follow the equilibrium distribution. Although average prices and profits are above theoretical values, we do not observe a high level of collusion as expected in the literature. By comparing simulations based on the mixed strategy equilibrium to our experimental outcomes, we conclude that in this game price setting can be explained by strategic reaction to preceding round results. In contrast to the equilibrium prediction, we observe a decrease in prices and negative average profits for the triopoly game.

Keywords: Price-Quantity Competition; Mixed Strategy Equilibria; Experimental Economics; Learning Direction Theory
JEL: D43; L11

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1 Introduction

The first systematic analysis of economic games that include both, prices and quantities as strategic market interaction variables was conducted by Shubik (1955). The study of this types of game was the logical enhancement of the intensive research on pure quantity competition (Cournot, 1838) and pure price competition (Bertrand, 1883) in the systematic investigation of oligopolistic competitions.

When considering games that include price and quantity in an oligopolistic setting, one often distinguishes between three groups of games. The first class includes games that incorporate a price competition under a certain kind of capacity limitation. In all of these models, the production rate of a player is directly determined by their price choice, i.e. quantities are not included as decision variables. Starting with Edgeworth (1897), several models were developed to analyse the effect of a capacity binding on the outcome in markets with pure price competition. Levitan and Shubik (1972) showed that the characteristic properties of the equilibrium depend on the degree of capacity limitation. They derive the pure strategy equilibria for highly limited and excessive capacities. For intermediate capacity constraints, a mixed strategy equilibrium emerges. These results were generalised for arbitrary demand functions by Osborne and Pitchik (1986) and arbitrary cost functions by Maskin (1986).

The main characteristic of the second class of games is a sequential choice of both, prices and quantities by the players. Often, the models include a simultaneous decision on production capacities before a simultaneous price competition. In Kreps and Scheinkman (1983) it was proved that (under mild assumptions about demand) the unique equilibrium outcome in this game is identical to the Cournot outcome. More generally, Friedman (1988) shows that each pure strategy equilibrium in this setting is equivalent to the pure strategy equilibrium in the same game without price setting. Additionally, he proves that the equilibria in the game with simultaneous price setting before simultaneous quantity setting and in the pure price competition are identical.

In the third class — so called price-quantity (PQ) games — firms endogenously have to decide on their prices and their quantities at the same time. The main difference between the second class and the third class of games therefore is the sequence of actions. The PQ games are also known as price competitions with perishable goods and production in advance and are characterised by the absence of any pure strategy equilibria.[1] The first mixed strategy equilibrium was presented in Levitan and Shubik (1978), where a model with linear demand as well as positive inventory carrying cost is analysed. Moreover, Gertner (1986) establishes the mixed strategy equilibrium for more general settings and also provides equilibrium properties for increasing production cost. In this article we use an experimental setting to further investigate the game described in Gertner (1986).

The experimental literature on games of all previously described classes is continuously growing, see Engel (2007) for a comprehensive overview. Models with real simultaneous quantity and price choices, however, have scarcely been analysed in the laboratory. One example of an experimental PQ game is given in Brandts and Guillen (2007), where collusion in repeated duopoly and triopoly games with fixed groups is studied. Market demand in their setting is inelastic and subjects decide on prices and costly production simultaneously. They observe that markets tend to monopolistic prices as a consequence of either bankruptcy or collusion.

In this article, we experimentally investigate repeated duopoly and triopoly PQ games with a linear demand and without exogenous capacity constraints. In contrast to Brandts and Guillen (2007), we are interested in the validity of the mixed strategy equilibrium for these games derived in Gertner (1986), and thereby hope to contribute to the body of literature on classical oligopolistic competition. We provide the first systematic comparison between experimental data and the mixed strategy equilibrium of the PQ game. In Cracau and Franz (2011) we have already shown that an experimental analysis is appropriate for this investigation, as the mixed strategy equilibrium of the discrete (experimental) game converges towards the equilibrium of the continuous game, if the discretisation parameter is sufficiently low. In this pre-study, we focused on the numerical aspects of the discretised game. A careful analysis of the experimental data, particularly with respect to the complete equilibrium prediction and previous experimental literature, is therefore the main goal of this article.

Our experimental results indicate that benchmarks from the Cournot, the Bertrand and the mixed strategy equilibrium do not predict subjects' price choices satisfactory. Although subjects chose prices seemingly at ran-

[1] Games with each firm deciding simultaneously on their price and quantity but in an exogenous sequence, however, are known to have pure strategy equilibria, e.g. Gelman and Salop (1983).

dom from a range between the monopoly price and marginal cost, the price distribution significantly differs from the mixed strategy equilibrium predicted in Gertner (1986). We additionally observe a difference between the price choices of preceding round winners and loser, with the latter tending to decrease their prices. A similar effect emerges in the mixed strategy equilibrium. Using simulations, however, we are able to show that the effect in the experiment is much more profound than in the mixed strategy equilibrium. We thus conclude that price setting underlies a strategic behaviour rather than a focal point or a random distribution.

The article is organised as follows: Section 2 introduces the basic model of the PQ game. The experimental procedure is presented in Section 3 and the experimental outcome follows in Section 4. In Section 5 we discuss these outcomes in comparison to the related literature and finally Section 6 briefly concludes and explores ideas for future investigations.

2 The model

In this section we present the general model used for the experiments along with theoretical results from the literature. We start by explaining the duopoly game, before stating some results for a general game with n (> 2) firms. Let us therefore initially consider a game of two firms ($i = 1, 2$) that decide simultaneously on their price p_i and their production level q_i. Products are assumed to be homogeneous between the firms and the market demand is a given function $D(p)$. The game follows the winner-takes-all-rule, i.e. the firm i with the lower price sells its full output q_i up to the market demand $D(p_i)$. The firm j ($j \neq i$) that decided on the higher price can now satisfy the residual demand, which is given through the efficient rationing rule

$$D(p_j|p_i) = D(p_j) - s_i \, ,$$

where s_i is the amount sold by the lower-price competitor i.[2] For the case of equal prices ($p_1 = p_2$), the market demand is shared equally between the firms, as far as the production levels q_i allow. These rules can be summed

[2]Davidson and Deneckere (1986) discuss different rationing rules. In general, the choice of the rationing rule can have a major impact on the equilibrium of an oligopoly game. For the model presented here, however, Gertner (1986) shows that the results are not affected by choosing efficient rationing instead of proportional rationing.

up by the following equation for the sales s_i of firm i (Gertner, 1986),

$$s_i(p_1, q_1, p_2, q_2) = \begin{cases} \min[q_i, D(p_i)] & , \text{ if } p_i < p_j \, , \\ \min\left[q_i, D(p_i) - s_j\right] & , \text{ if } p_i > p_j \, , \\ \min\left[q_i, D(p_i) - \min\left\{q_j, \frac{D(p_j)}{2}\right\}\right] & , \text{ if } p_i = p_j \, . \end{cases} \tag{1}$$

To find an expression for the payoff π_i of firm i we introduce the production cost $C(q)$, which is assumed to be equal for both firms. Using s_i as given in (1), the payoff π_i is given by

$$\pi_i = p_i s_i - C(q_i) \, .$$

Gertner (1986) explains that a pure strategy equilibrium does not exist in this game. Hence, we focus on a mixed strategy equilibrium, i.e. each of the firms' strategies can be described by the probability density function $f_i(p_i, q_i)$ that formally states the probability of firm i to play the strategy (p_i, q_i). According to Shubik (1959), the probability density function $f_1(p_1, q_1)$ and $f_2(p_2, q_2)$ form a mixed strategy equilibrium, if the integrals

$$\bar{V}_i = \int_0^\infty \int_0^\infty \pi_i(p_1, q_1, p_2, q_2) df_j(p_j, q_j) \, ,$$

are constant for all strategies (p_i, q_i) played with positive probability according to $f_i(p_i, q_i)$. Shubik (1959) refers to $\bar{V}_i$ as the value of the game for firm i, i.e. the maximum guaranteed profit it can achieve if the strategy of the opposition player is known. Note that in the case of the symmetric game considered here, the mixed strategy equilibrium is also symmetric, which means $f_1 \equiv f_2$. For our experiments we make the following simplifying assumptions of linear demand and cost curves:

$$D(p_i) = a - bp_i \, , \qquad C(q_i) = cq_i \, ,$$

where a, b and c are non-negative constants. We are therefore considering a game with constant marginal cost, for which Gertner (1986) proved that all Nash equilibria satisfy $\bar{V}_i = 0$. The mixed strategy equilibrium derived in Gertner (1986) has the property that all strategies with positive probabilities are situated on the line $p = D(q)$, i.e. each firm always produces exactly the market demand $D(p_i)$ corresponding to the chosen price p_i. The probability distribution for the prices is given through the distribution function

$$F(p) = \begin{cases} 0\,, & \text{for } p < c\,, \\ 1 - c/p\,, & \text{for } c \leq p < a\,, \\ 1\,, & \text{for } p \geq a\,. \end{cases} \tag{2}$$

In particular, this implies that each firm has two options: (i) it can leave the market by choosing $p_i = a$ with a (non-zero) probability of c/a or (ii) it can stay in the market and choose a price from the interval $[c, a)$ using the distribution function $F(p)$ as given in (2). Looking at the probability density function corresponding to $F(p)$, we see that firms are more likely to play lower prices than higher prices. The lower price firm earns a positive profit, while the other firm faces losses equal to its production costs $C(q)$, but expected profits are equal to zero.

One can easily generalise the rules of the game for an arbitrary number ($n \geq 2$) of firms. The existence of a mixed strategy equilibrium can be generalised from the duopoly to the oligopoly game (Gertner, 1986). The distribution function related to the mixed strategy equilibrium in the oligopoly settings takes the form

$$F_n(p) = \begin{cases} 0\,, & \text{for } p < c\,, \\ 1 - (c/p)^{\frac{1}{n-1}}\,, & \text{for } c \leq p < a\,, \\ 1\,, & \text{for } p \geq a\,. \end{cases} \tag{3}$$

In particular, this implies that with increasing n the probability of market entry decreases, but the average price played in case of market entry increases. Similarly to the duopoly game, the expected profit for each of the firms is zero.

3 Experimental Procedure

Our experiment was designed to fit the simplest form of a PQ game. We label our duopoly treatment as *PQ2* and our triopoly treatment as *PQ3*. Each treatment consists of a two-stage game with fixed groups of randomly assigned subjects. Each subject in a group controlled one of the symmetric firms A or B (or C in the *PQ3* treatment). In the five rounds of the first stage, we let each firm act in a monopolistic market to allow the participants

time to get used to the game. Afterwards, in the 20 rounds of the second stage, firms competed in a common (duopoly or triopoly) market.
We used the simplified linear demand function $D(p) = 100 - p$ ($a = 100, b = 1$) and let subjects choose prices in the range $[0, 100]$. Additionally, subjects had to choose production levels in the range $[0, 100]$.[3] For both, price and quantity choices we allowed for 0.001 increments. This small increment was chosen, because we have shown that the mixed strategy equilibrium in our discrete PQ game converges to the one in the continuous game if the increment is sufficiently small (Cracau and Franz, 2011). We fixed the constant marginal production cost at $c = 10$. After the subjects' simultaneous decisions, profits were calculated as presented in the model in Section 2. Then, all players were shown a summary with prices, production levels and profits. At the end of the experiment, subjects' total payoff consists of the sum of the payoff of all 25 rounds. Bankruptcy during the course of the game was not considered.[4] In the *PQ3* treatment, we added a fixed payment of 3 Euro at the end of the experiment.
We collected ten independent observations in the *PQ2* and nine independent observations in the *PQ3* treatment during three sessions in June 2011 and July 2012 at the MaXLab experimental laboratory at the University of Magdeburg. The experimental software was programmed using z-Tree (Fischbacher, 2007). Participants were mainly students from economic fields, recruited via ORSEE (Greiner, 2004). On average, the participants in the *PQ2* treatment earned 10.69 Euro and the participants in the *PQ3* treatment earned 9.18 Euro in a 45-minute session.

4 Results

In the first (monopolistic) stage of the game, subjects earned on average 88% of the possible monopoly profits. As this is in line with the literature (Potters et al., 2004), we conclude that all participants understood the experimental procedure and produced reliable observations.

Tables 1 and 2 summarise the experimental results for both treatments. As firms could sell quantities at different prices subject to the rationing rule,

[3]For reasons of simplicity, production levels were limited to demand at the chosen price. Thus, choosing a price equal to 100 automatically corresponds to a market exit.

[4]For subjects with a negative total balance from the second stage, we set earnings equal to zero for this stage.

Table 1: *PQ2* — Summary of experimental results for all 20 rounds.

Obs.	AWP	Production	Profits	Collusion
1	31.50	106.80	850.95	no
2	17.88	103.20	192.52	no
3	52.51	58.90	1838.92	yes
4	23.44	134.26	309.70	no
5	15.34	153.42	-256.30	no
6	26.17	120.80	573.30	no
7	24.57	105.91	527.25	no
8	23.50	119.20	455.50	no
9	18.95	114.50	107.46	no
10	48.10	66.25	1757.50	yes
Av.	28.20	108.32	635.68	-

we follow Brandts and Guillen (2007) in presenting the average weighted market prices (AWP). Thereby, the prices at which units are sold are weighted by their respective market shares. Moreover, we present total market production and total profits.

To evaluate these outcomes, we calculate benchmarks corresponding to the Cournot and Bertrand equilibrium, the mixed strategy equilibrium and the cooperative solution of the game. The benchmarks are presented in Table 3.

We see that observation 3 and 10 in the *PQ2* treatment have lower production levels and higher average profits than the other observations. As these two observations are close to the cooperation benchmark, we identify them as collusive. Once both participants have agreed on a price at the or close to the monopoly level, the demand is shared equally between the parties. This yields high profits for both players. For the remaining eight observations, we do not observe cooperation, indicated by the low AWP and profits. In the *PQ3* treatment, we see no cooperation at all.

The average AWP for the competitive pairs in the *PQ2* treatment is 22.67 and thus between the Cournot and Bertrand prediction. Moreover, it seems to be close to the prediction of the mixed strategy equilibrium. However, Figure 1 illustrates that the distribution of prices differs visibly from the mixed strategy equilibrium prediction given in (2). We observe a greater fraction of prices in the range $[10, 55]$ than predicted. In total, we only observe 18 out of 320 ($\approx 5.6\%$) prices above the monopoly / cartel price

Table 2: *PQ3* — Summary of experimental results for all 20 rounds.

Obs.	AWP	Production	Profits	Collusion
1	11.66	200.73	-983.93	no
2	17.15	126.43	-200.94	no
3	17.67	108.95	114.07	no
4	12.53	219.40	-1159.28	no
5	13.31	147.04	-374.99	no
6	19.70	107.50	291.32	no
7	16.87	183.22	-511.58	no
8	12.63	132.58	-480.85	no
9	15.19	129.82	-126.77	no
Av.	15.19	150.63	-381.44	-

Table 3: Theoretical benchmarks.

Prediction	AWP	Production	Profits
Cournot (duopoly)	40	60	1800
Cournot (triopoly)	32.5	67.5	1518.75
Bertrand	10	90	0
mixed strategy (duopoly)	19	134.95	0
mixed strategy (triopoly)	23.68	140.26	0
cooperation	55	45	2025

$p = 55$, compared to the 18.2% predicted by the mixed strategy equilibrium. Market exit decisions were not observed frequently, prices equal to 100 were not observed at all. However, we observe 9 decisions with quantities equal to zero which we denote as a market exit.[5] This is in contrast to the predicted 10% market exits in the mixed strategy equilibrium. Overall, we conclude that subjects may perceive prices above the monopoly price as implausible and therefore choose from a modified distribution with prices in the range $[10, 55]$, i.e. between marginal cost and the monopoly level.

In order to analyse various trends in the behaviour of the participants in the *PQ2* treatment, we now look at the time development of the market description values presented in Table 1. First, the evolution of the AWP over time is presented in Figure 2. We see no significant trend, except for a drop in prices during the first 3 rounds. This initial drop occurs, because the

[5] To unify the distribution function, we set prices equal to 100 for all market exits.

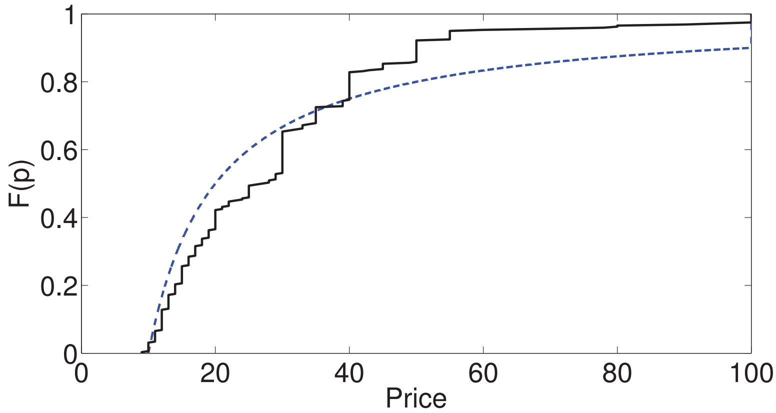


Figure 1: *PQ2* — Probability distribution function. Observations (solid line), prediction (dashed line).

players were biased towards the monopoly price $p = 55$ from the first stage of the game. This bias, however, disappears quickly as the participants get used to the new situation and the AWP stays on the lower level.

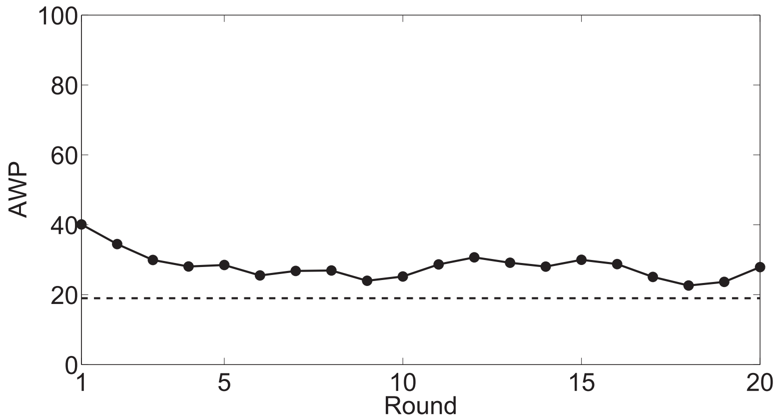


Figure 2: *PQ2* — Average weighted price. Observations (solid line), prediction (dashed line).

The development of profits over time in the *PQ2* treatment can be found in Figure 3. We, again, see no significant trend. We observe that the total payoff for participants in the non-collusive pairs is positive in 14 out of 16 cases. We calculate the average profit over all rounds of the competitive pairs to be 172.52. This result contrasts the predictions made by the mixed strategy equilibrium, where the expected profit of both players is 0. Using a one-sided Wilcoxon Signed-Rank test, this difference proves to be significant ($p = 0.0197$).

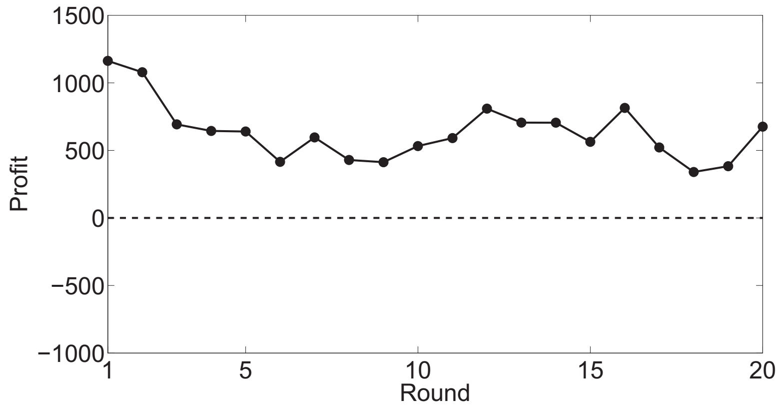


Figure 3: *PQ2* — Average profits. Observations (solid line), prediction (dashed line).

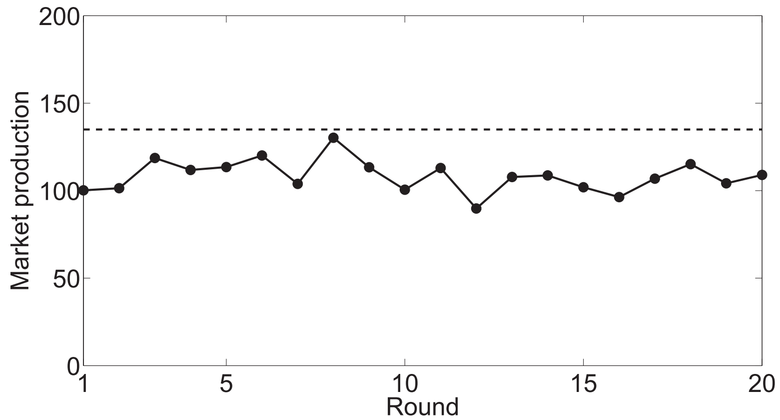


Figure 4: *PQ2* — Average market production. Observations (solid line), prediction (dashed line).

Figure 4 shows the evolution of the market production in the *PQ2* treatment, where we see no trend in time. The average market production for the competitive pairs is 119.76. This is below the expected value of the mixed strategy equilibrium but still above the Cournot and Bertrand predictions and even above total market size. We observe overproduction because firms had to decide on their production level before knowing their actual demand. The mixed strategy equilibrium predicts the production to be equal to the demand at the price in the same decision ($q = D(p)$). We find no evidence for this characteristic in the experimental outcome, as only 56% of the production decisions satisfied $q = D(p)$ (see Figure 5). We find no significant difference in profits between players who chose to produce the full market demand and players who did not. We therefore conclude that subjects had no disadvantage from deviating from the equilibrium condition $q = D(p)$.

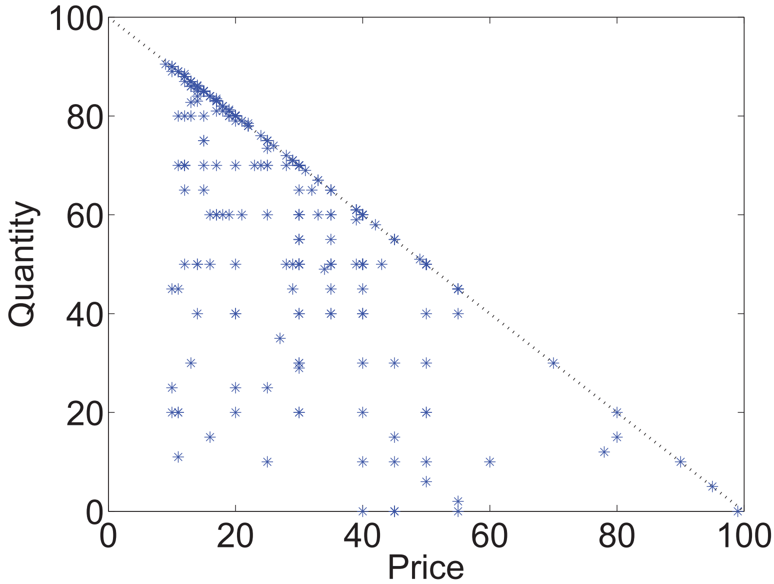


Figure 5: *PQ2* — PQ pairs. Observations (blue stars), prediction (dashed line).

Result 1. *In the duopoly treatment, the observed behaviour differs markedly from the equilibrium predictions, as can be seen in the different price distribution, the lower than expected production levels and the positive average profits.*

For the *PQ3* treatment, Figure 6 illustrates that the distribution of prices does not fit the mixed strategy equilibrium prediction given in (3) ($n = 3$).

In contrast to the predicted 31.62% market exits, we only observe market exit decisions in 13 out of 540 choices in this treatment. As in our duopoly treatment, we observe the vast majority of prices in the range $[10, 55]$. In total, we only observe 35 out of the 580 ($\approx 6\%$) prices above the monopoly price $p = 55$.

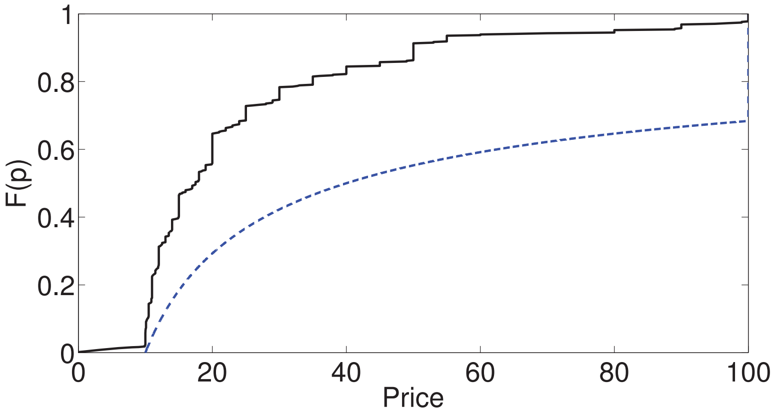


Figure 6: *PQ3* — Probability distribution function. Observations (solid line), prediction (dashed line).

The market dynamics in the *PQ3* treatment are comparable to those in the duopoly treatment. Figure 7 illustrates the development of the AWP over time. Similar to the *PQ2* treatment, we see a drop in prices during the first rounds but no further significant trend. Overall, the AWP stays on a lower level than in the duopoly treatment.[6]

Result 2. *In contrast to the equilibrium prediction, prices in the triopoly treatment were lower compared to the duopoly treatment.*

Figure 8 shows the profits over the 20 rounds in the *PQ3* treatment. Except for the first round, profits are negative. This difference to the equilibrium prediction of zero profits is significant (one-sided Wilcoxon Signed-Rank test $p = 0.0197$). We see a slight positive trend with profits seeming to converge to zero (rank order correlation $r = 0.7206$, $p = 0.000546$). Overall, we observe that the total payoff is negative for 20 out of 27 participants.

[6] We observe the same effect for individual price choices, with the average price in the *PQ2* treatment (28.74) being higher than in the *PQ3* treatment (22.92).

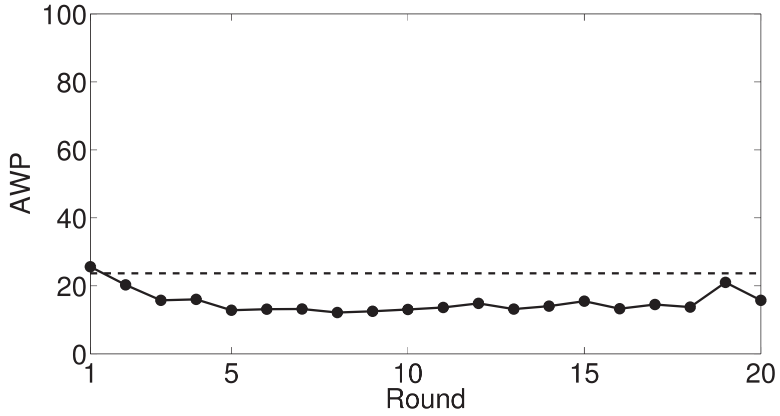


Figure 7: *PQ3* — Average weighted price. Observations (solid line), prediction (dashed line).

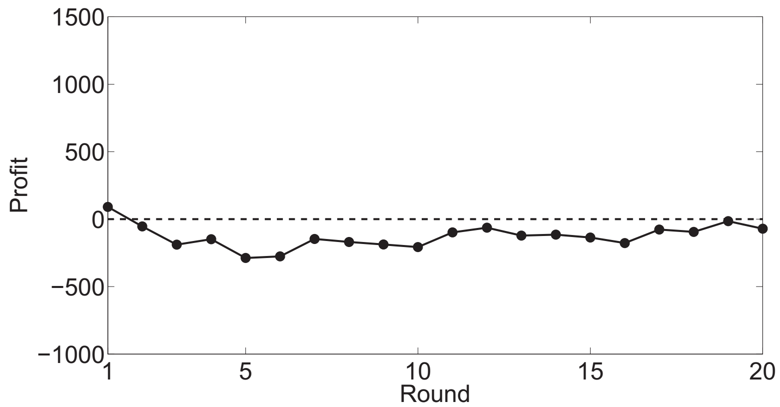


Figure 8: *PQ3* — Average profits. Observations (solid line), prediction (dashed line).

Figure 9 shows the evolution of the market production in the *PQ3* treatment. We see a significant negative trend after the first periods (rank order correlation $r = -0.77786$, $p = 0.000316$). Total production is above market size but close to the mixed strategy equilibrium prediction. Finally, Figure 10 illustrates that subjects did not always choose to produce full market demand (only in 28% of the cases).

Result 3. *In the triopoly treatment, the observed behaviour differs markedly from the equilibrium predictions, as can be seen in the different price distri-*

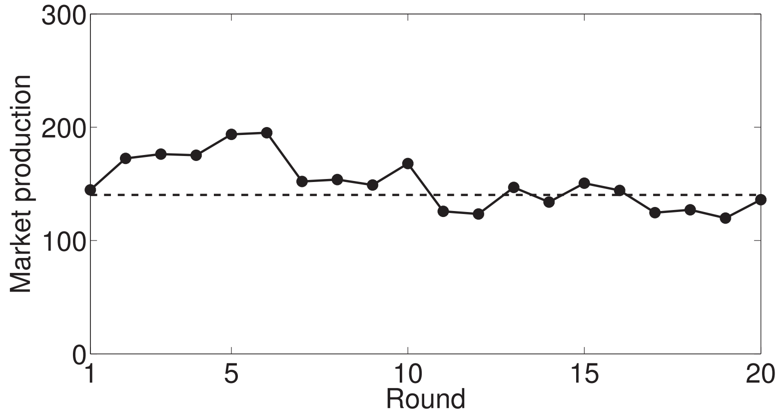


Figure 9: *PQ3* — Average market production. Observations (solid line), prediction (dashed line).

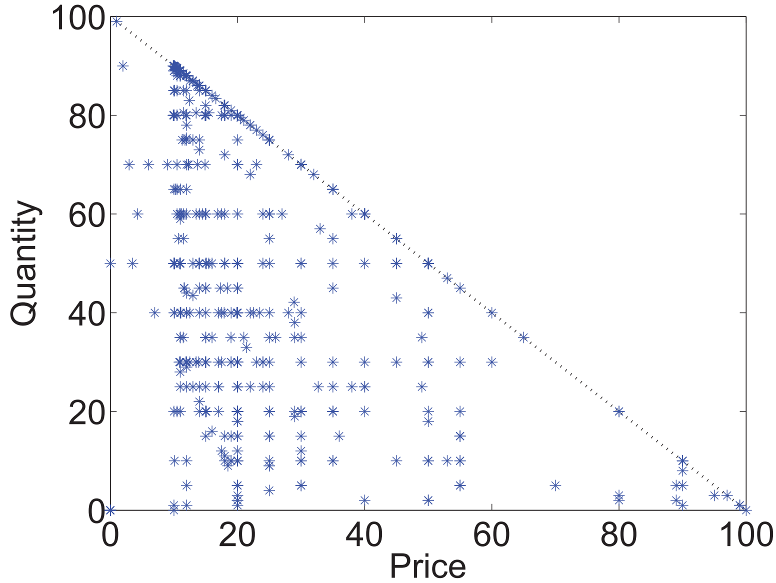


Figure 10: *PQ3* — PQ pairs. Observations (blue stars), prediction (dashed line).

bution. Production levels and average profits are close to the predictions.

5 Discussion with respect to the literature

For the very first time in experimental economics, we conducted an experiment with simultaneous price and quantity choice and linear demand. Similar studies of the PQ game have so far only involved non-linear demand. Brandts and Guillen (2007) analyse the PQ game in a dynamic setting with inelastic demand. Their results of markets with two and three firms show a price development coming close to the monopoly level. This can be explained by either collusion or bankruptcies. Davis (2011) conducts an experiment to evaluate the effect of advance production in Bertrand-Edgeworth duopolies. He concludes that the introduction of advance production reduces profits. This can be partially explained by the reduction of tacit collusion. Note that in economic terms, advance production is comparable to the costly production in the PQ game. Therefore, this finding relates to our duopoly treatment yielding lower levels of collusion and lower profits than a standard Bertrand experiment, see for example Dufwenberg and Gneezy (2000) and Muren (2000).

We are also the first to consider the exact formulation of the underlying mixed strategy equilibrium prediction and compare it to the experimental outcomes. For the *PQ2* treatment, we find the mixed strategy equilibrium predicting average outcomes better than the Cournot or Bertrand solution. Although we find a dispersion of prices and a mixture of positive and negative profits, subjects' price and quantity choices do not match the predicted distribution of the mixed strategy equilibrium. For our treatment with three firms, price choices do not correspond to the mixed strategy equilibrium at all. In contrast to the equilibrium prediction, prices are significantly lower than in the duopoly treatment. Moreover, the frequency of market exits should increase with a higher number of firms. We find no evidence for this. The weak prediction power of the mixed strategy equilibrium in oligopoly games is also found in Brown-Kruse et al. (1994). They study a capacity constrained Bertrand-Edgeworth game and analyse the explanatory power of the mixed strategy equilibrium. Neither the classical theories of pure or mixed strategy Nash equilibria, nor the Bertrand-Edgeworth cycle or tacit collusion can explain all of the experimental results. Prices tend to fall in the first periods and then show a dispersion. This dispersion in prices can be better explained by the Bertrand-Edgeworth cycle theory than by mixed strategies. Overall, we argue that the mixed strategy equilibrium does not adequately describe the price choices made by the players in our experiment.

On the one hand, this finding fits with Palacios-Huerta and Volij (2008) who have shown that subjects inexperienced in real life tasks with mixed strategies fail to play even simple mixed strategies. On the other hand, the mixed strategy equilibrium incorporates unintuitive (high) price choices. Nevertheless, mixed strategy games may be studied using theory, as for example Dechenaux and Kovenock (2011) studied the game of Brandts and Guillen (2007).

Theory predicts that the average price is increasing in the number of firms (Gertner, 1986). Our results indicate the opposite, i.e. average prices are lower in the triopoly than in the duopoly setting. The finding that markets with more firms reveal stronger competition is well aligned with the experimental literature, see for example Dolbear et al. (1968) and Huck et al. (2004) for quantity competitions, Dufwenberg and Gneezy (2000) and Abbink and Brandts (2008) for price competitions as well as Brandts and Guillen (2007) for the PQ competition.

To explain actual price choices, we argue that subjects choose prices on a strategic basis rather than randomly from the mixed strategy equilibrium, or indeed another probability distribution. To support this, we differentiate subjects' price changes in the *PQ2* treatment from one round to the next in dependence of the outcome of the previous round. Figure 11 contrasts the price decisions of preceding round's winners and losers for this treatment. One can clearly see that preceding round's winners tend to increase their prices, whereas the majority of losers decrease prices. On average, winners increase their prices by 5.14 while losers decrease their prices by 7.22. A χ^2 test of independence - based on the absolute frequencies as shown in Table 4 - proves this finding to be highly significant ($p < 0.0001$). We conclude that prices are not drawn completely randomly but depend on the preceding round's outcome. In Table 5 we study this dependence using regression analysis. We estimate subjects' price choices in dependence of the previous round price choices. Moreover, we added a dummy, $LOSS$, that is 1 if the subject lost the previous round and 0 otherwise. We can see in Table 5 that preceding round losers *ceteris paribus* chose significantly lower prices than preceding round winners. The same reasoning holds for the triopoly treatment (see Figure 12 and Tables 6 and 7. From this we conclude that winning / losing the previous round has a major impact on the price choice of a participant, which in particular means that prices are not randomly chosen from a distribution. This result contributes to the learning direction theory (Selten and Stoecker, 1986 and Selten and Buchta, 1999). Subjects use

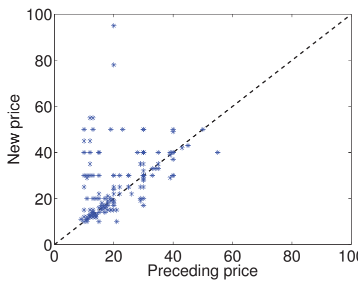
Table 4: *PQ2* — Price reactions (absolute frequencies).

	price increase	price decrease	no price change	$\sum$
preceding winner	76	53	20	149
preceding loser	13	111	25	149
preceding ties	6	10	66	82
$\sum$	95	174	111	380

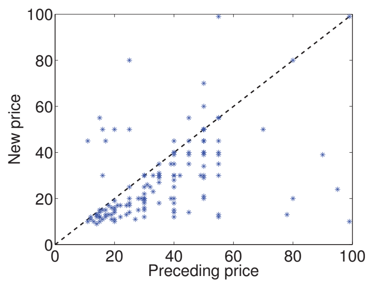
Table 5: *PQ2* — Regression results
Random-effects regression with price as dependent variable.
(Wald $\chi^2 = 84.52$, $p = 0.00$)

independent variable	coefficient	standard error	Z	$P > \|Z\|$
Constant	11.37124	2.33827	4.86	0.000
Preceding price	0.51121	0.05739	8.91	0.000
LOSS	−4.03411	1.83724	−2.20	0.028

the preceding round's outcome for their price choice. On average, winner's increase prices while losers decrease prices. The effect is stronger for losers. This result is in line with previous findings, see for example Neugebauer and Selten (2006) or Ockenfels and Selten (2005) for posted-offer markets and Bruttel (2009) for a Bertrand duopoly.



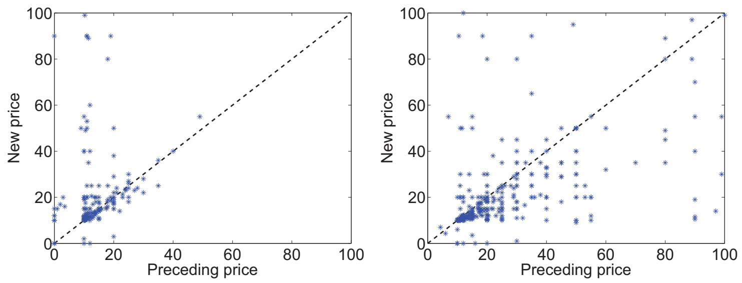
(a) Preceding round's winner



(b) Preceding round's loser

Figure 11: *PQ2* — Price reactions depending on the preceding round's outcome.

Result 4. *In both treatments, subjects respond to preceding round outcomes. On average, winners increase prices while losers decrease prices, with the absolute price by losers being stronger.*



(a) Preceding round's winner (b) Preceding round's loser

Figure 12: *PQ3* — Price reactions depending on the preceding round's outcome.

Table 6: *PQ3* — Price reactions (absolute frequencies).

	price increase	price decrease	no price change	$\sum$
preceding winner	91	63	27	181
preceding loser	58	220	51	329
preceding ties	1	0	2	3
$\sum$	150	283	80	513

To further support the idea of the learning direction theory, we simulate eight pairs of agents playing the mixed strategy equilibrium for the PQ duopoly game with our game parameters from the experiment. Using this data, we can precisely identify to what extent the pricing pattern we observe is a behavioural effect. A contrary explanation would be that winner's chose to increase prices more often than losers also in the mixed strategy equilibrium.

Proposition 1. *In the mixed strategy equilibrium of the simple PQ game,*

Table 7: *PQ3* — Regression results.
Random-effects regression with price as dependent variable.
(Wald $\chi^2 = 140.71$, $p = 0.00$)

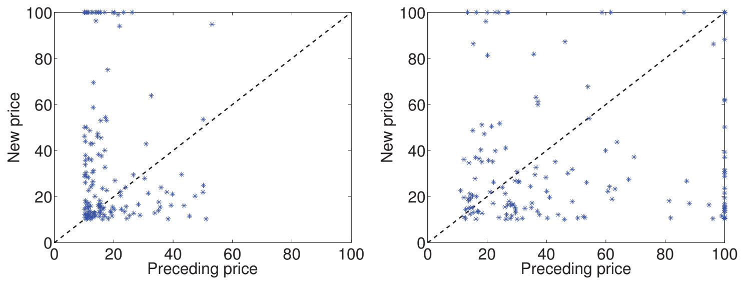
independent variable	coefficient	standard error	Z	$P > \|Z\|$
Constant	9.46346	1.14917	6.34	0.000
Preceding price	0.50441	0.04331	11.62	0.000
LOSS	−3.61119	1.59814	−2.26	0.024

Table 8: Price reactions (absolute frequencies for simulated agents).

	price increase	price decrease	no price change	$\sum$
preceding winner	97	55	0	152
preceding loser	50	102	0	152
preceding ties	0	0	0	0
$\sum$	147	157	0	304

preceding round winners will relatively more often increase their prices compared to preceding round losers. Preceding round losers will relatively more often decrease their prices compared to preceding round winners.

Proof. See A. □



(a) Preceding round's winner (b) Preceding round's loser

Figure 13: Price reactions depending on the preceding round's outcome (simulated agents).

Figure 13 and Table 8 summarise the price changes in the simulation. We find a great dispersion of prices. Following Proposition 1, we also find preceding round winner to increase prices relatively more often than preceding round loser and vice versa. We calculate that in this simulation, preceding round winners increase prices on average by 8.60 while preceding round losers decrease their prices on average by 8.60. We thus see that the effect of winning or losing on price changes is stronger than in our experiment. However, our regression results in Table 9 show that this effect is due to the random choice from the probability distribution rather than due to behavioural effects.[7]

[7]Note that we used the regression model for reasons of comparability only. For other

Table 9: Regression results (simulated agents).
Random-effects regression with price as dependent variable.
(Wald $\chi^2 = 1.23$, $p = 0.5416$)

independent variable	coefficient	standard error	Z	$P > \|Z\|$
Constant	32.13823	4.16788	7.71	0.000
Preceding price	0.07229	0.06910	1.05	0.296
LOSS	−0.99094	4.00447	−0.25	0.805

Comparing experimental results and simulation, we conclude that the difference between preceding round winners and losers seen in the experimental data is indeed caused by behavioural effects rather than by random strategy choices.

Result 5. *In the experimental data, players react directly to the outcome of a previous round, rather than drawing prices from a random distribution.*

In the duopoly treatment, our game yielded positive average profits in contrast to the equilibrium prediction of zero profit. On the one hand, we observe average prices exceeding the predicted expected price. On the other hand, we find production levels below the level of possible demand in both treatments. This resulted in a positive residual demand for the higher price firm in 27% of all rounds.[8] Both facts taken together may explain the occurrence of positive average profits. However, we are aware of the fact that in general, competition tends to be lower in economic experiments with fixed pairs of two than the theory predicts, see for example Muren (2000) for a Bertrand setting with quantity precommitment and Huck et al. (2004) for a Cournot setting.

Considering market production, we found that firms do not follow the equilibrium prediction of full production. In Zhang and Brorsen (2011), the PQ game is analysed with an agent-based model. Their game fits the rules of Brandts and Guillen (2007). The results of their simulation match the experimental results of Brandts and Guillen (2007), at least for the duopoly markets. For markets with more than two firms the agents fail to reach the efficiency of the human subjects. The inefficiency is caused by overproduction.

purposes, the regression model is not appropriate.

[8]In the rest of the rounds, the price of the high price firm was too high to guarantee any residual demand.

This relates to the fact that subjects do not always follow the equilibrium prediction of full production as was also observed in our experiment.

Finally, only two of our ten pairs in the duopoly treatment revealed collusion. For the remaining eight pairs we observe competitive behaviour with no tendency to cooperation or tacit collusion. This finding fits with Fonseca and Normann (2008) who study a capacity-constrained Bertrand-Edgeworth game. As in our experiment, subjects neither follow the mixed strategy equilibrium in their game nor agree on a certain price level. For our data, we have seen that the development of the AWP does not follow any trend. This result is, however, in contrast to Brandts and Guillen (2007) who expect a high level of collusion in our framework that should drive prices closer to the monopoly level. Their experimental design is similar to our setting except for four parameters: (i) the number of rounds was 50, (ii) they allowed for bankruptcies, (iii) marginal cost was $c = 50$ and (iv) they used an inelastic demand function ($D = 100$). They argue that subjects might take some time to collude, which is why they chose to analyse a repetition of 50 rounds. However, even in the first 20 rounds of their experiment, prices increased dramatically. We therefore would not expect our results to change, if we considered a higher number of rounds. Since we excluded bankruptcies, subjects could act more competitive in the first rounds. If we considered bankruptcies as a consequence for losses in the first rounds, subjects might refrain from competition ending up cooperating. Considering their marginal cost, we suggest that an increase in marginal cost reduces the bandwidth of possible (competitive) prices. This might make it easier for subjects to tacitly collude since the variety of competitive strategies was reduced as well. Studying the effect of marginal cost on willingness to cooperate in a further work therefore seems promising. Finally, for the difference in demand specification, we relate the high competition and the lower prices in our experiment to the fact that price undercutting is more attractive in this setting as it is aligned with a quantity expansion. However, note that the mixed strategy equilibrium is the same for both games.

6 Concluding remarks

We have introduced a precise formulation of the mixed strategy equilibrium for the simple price-quantity game with linear demand and constant marginal cost. Using these insights, we are the first to present a systematic comparison of experimental outcomes with the underlying equilibrium prediction. Although some of our results are well-known characteristics of market experiments, our duopoly study incorporates three main contributions that had been not addressed by the existing literature. First, we proved that firms' pricing behaviour does not follow the mixed strategy equilibrium. Second, we calculated that average prices differ much more from the Cournot and Bertrand prediction than from the expected equilibrium prices in the *PQ2* treatment. Thus, the mixed strategy equilibrium provides a relatively good prediction for average prices in this treatment, but it fails to predict subjects actual distribution of price choices. Third, we could show that firms' responses to preceding round results differ from those that would be also observed in the mixed strategy equilibrium. By introducing a third firm, we found similar results. However, the observed behaviour contradicted the prediction of Gertner (1986) that the average price in the PQ game increases with an increased number of firms.

A typical caveat of oligopoly experiments with fixed pairs may be the existence of multiple equilibria. In repeated interactions, reputation effects may play a role and thus applying a random matching procedure would be a natural variation of our experiment. However, we find no indication for tacit collusion (revealed by increasing AWPs or firms taking turns) in our results with fixed pairs and thus do not expect our results to be dependent on the matching pattern.

Overall, our results provide a good basis for further analysis of experimental oligopolies with price-quantity competition. Experimental designs are no longer limited to deciding between using price or quantity competition in classic oligopoly markets but may include more realistic bivariate decisions on prices and quantities. In particular, games with endogenous timing as in Hamilton and Slutsky (1990) or endogenous choice of the decision variable as suggested by Tasnádi (2006) can be studied experimentally allowing for simultaneous price-quantity choices.

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A Proof of Proposition 1

Let us denote the price chosen by firm $i \in \{1, 2\}$ in round $t \in \mathbb{N}$ by p_i^t. Let us further denote the probability of an event X by $P(X)$ and the probability of an event X given that event Y occurred by $P(X|Y) = P(X \cup Y)/P(Y)$. Then Proposition 1 can be written in the form

$$\begin{aligned} P\left(p_i^t > p_i^{t-1} | p_i^{t-1} < p_j^{t-1}\right) > P\left(p_i^t > p_i^{t-1} | p_i^{t-1} > p_j^{t-1}\right) \ , \\ P\left(p_i^t < p_i^{t-1} | p_i^{t-1} > p_j^{t-1}\right) > P\left(p_i^t < p_i^{t-1} | p_i^{t-1} < p_j^{t-1}\right) \ . \end{aligned}$$

In order to simplify the calculation, we introduce the probability density function of prices in $[c, a)$ as the derivative of the distribution function given in (2):

$$f(p) = \frac{c}{p^2}\,, \quad p \in [c, a)\,.$$

We start by calculating the probability of winning a round $P(p_i^t < p_j^t) = P(p_i^{t-1} < P_j^{t-1})$:

$$P(p_i^t < p_j^t) = \int_c^a f(p_i^t)(1 - F(p_i^t))\mathrm{d}p_j^t = \frac{1}{2}\left(1 - \frac{c^2}{a^2}\right)\,.$$

Obviously, the probability of losing a round is identical to this probability and a tie only occurs if both players choose to exit the market and hence has a probability of c^2/a^2. Let us now calculate the probability of a winner decreasing their price:

$$\begin{aligned} P\left(p_i^t < p_i^{t-1} | p_i^{t-1} < p_j^{t-1}\right) &= \frac{P\left(p_i^t < p_i^{t-1} < p_j^{t-1}\right)}{P\left(p_i^{t-1} < p_j^{t-1}\right)} \\ &= \frac{\int_c^a f(p_i^t) \int_{p_i^t}^a f(p_i^{t-1})(1 - F(p_i^{t-1}))\mathrm{d}p_i^{t-1}\mathrm{d}p_i^t}{\frac{1}{2}\left(1 - \frac{c^2}{a^2}\right)} \\ &= \frac{1}{3}\left(1 - \frac{2c^2}{a(a+c)}\right)\,. \end{aligned}$$

Due to symmetry, this probability is equal to the probability of a loser increasing their price $P\left(p_i^t > p_i^{t-1} | p_i^{t-1} > p_j^{t-1}\right)$.

The probability of a price increase by a winner can be calculated as one minus the probability of a price decrease by a winner, because the winning price must be smaller than a and maintaining the exact same price level therefore has a probability of zero. Hence:

$$P\left(p_i^t > p_i^{t-1} | p_i^{t-1} < p_j^{t-1}\right) = \frac{2}{3}\left(1 + \frac{c^2}{a(a+c)}\right)\,.$$

The missing probability we need to calculate is the probability of a price decrease by a loser. This is not equal to one minus the probability of the price decrease by a loser, because a loser could have chosen a price equal to a and can therefore maintain their current price level. We calculate the probability through:

$$\begin{aligned}
P\left(p_i^t < p_i^{t-1} | p_i^{t-1} > p_j^{t-1}\right) &= \frac{P\left(p_i^t < p_i^{t-1}, p - i^{t-1} > p_j^{t-1}\right)}{P\left(p_i^{t-1} < p_j^{t-1}\right)} \\
&= \frac{\int_c^a f(p_i^{t-1}) F(p_i^{t-1})^2 \mathrm{d}p_i^{t-1} + (1 - F(a))F(a)^2}{\frac{1}{2}\left(1 - \frac{c^2}{a^2}\right)} \\
&= \frac{2}{3}\left(1 - \frac{2c^2}{a(a+c)}\right) .
\end{aligned}$$

All that's left to do is to verify the inequalities:

$$\begin{aligned}
P\left(p_i^t < p_i^{t-1} | p_i^{t-1} > p_j^{t-1}\right) &= \frac{2}{3}\left(1 - \frac{2c^2}{a(a+c)}\right) \\
&> \frac{1}{3}\left(1 - \frac{2c^2}{a(a+c)}\right) \\
&= P\left(p_i^t < p_i^{t-1} | p_i^{t-1} < p_j^{t-1}\right) ,
\end{aligned}$$

where the inequality holds because $1 - \frac{2c^2}{a(a+c)}$ is always positive for $a > c$. The second inequality can be shown straightforwardly as follows:

$$\begin{aligned}
P\left(p_i^t > p_i^{t-1} | p_i^{t-1} < p_j^{t-1}\right) &= \frac{2}{3}\left(1 + \frac{c^2}{a(a+c)}\right) > \frac{2}{3} > \frac{1}{3} \\
&> \frac{1}{3}\left(1 - \frac{2c^2}{a(a+c)}\right) \\
&= P\left(p_i^t > p_i^{t-1} | p_i^{t-1} > p_j^{t-1}\right) .
\end{aligned}$$

$\square$

Experiment 1: Instructions

Welcome to the experiment!

From now on, please stop any communication and read the following information with great care. Questions will be answered after reading the instructions individually at your place.

The following experiment deals with the sale of goods. During the experiment, you take over the role of a firm which decides on a sales price and a production quantity in a market.

- The experiment consists of 2 stages, which are played consecutively.
- At the beginning of the experiment, pairs of two firms are each randomly assigned to one of two markets.
- During the whole experiment, the assignment of the pairs is fixed.

Stage 1

In the **5 rounds** of the first stage, each of the two firms is situated as the only firm in one of the two markets.

- The consumer demand in each of the two markets is determined by:
  - **demand = 100 – sales price**
- You decide on your sales price and on your production quantity.
  - Your sales price has to be chosen **in 0.001 increments** from the interval **[0; 100] Taler**.
  - Your production quantity has to be chosen **in 0.001 increments** from the interval **[0; 100]**.
- Production results in production costs equal to **10 Taler** per unit produced.
  - Your total production cost are therefore: **your production quantity x 10**
- Your maximum production quantity depends on the sales price you have chosen:
  - **Maximum production quantity = 100 – your sales price**
- The payoff for each round is calculated by**: (sales price – 10) x production quantity**

Before your decision in each round of the first stage, you will find a what-if-calculator. You may insert various combinations of your sales price and your production quantity and calculate the corresponding payoff!

Stage 2

In the **20 rounds** of the second stage, you make the same decisions as in stage 1. As a difference, both firms are now situated in the same market.

- You decide on your sales price in Taler and on your production quantity as in stage 1.
- If both firms decide on the same sales price, the demand is split equally.
  - Each obtains: **demand = (100 – sales price) / 2**
  - If one of the two firms has a production quantity which is too low to completely serve its proportion of the demand, a residual demand emerges which can be additionally served by the other firm.
- If the firms decide on different sales prices, the consumer buy first from the firm with the lower price:
  - **demand = 100 – low sales price**
  - If the firm with the lower sales price has a production quantity which is too low to completely serve the demand, a residual demand for the other firm can emerge.
  - **residual demand = (100 – sold quantity) – high sales price**
- the payoff for each round is calculated by: **sales price x sold quantity – 10 x production quantity**

At the beginning of the second stage, you will find a what-if-calculator. You may insert various combinations of sales prices and production quantities of both firms and calculate the corresponding payoffs!

At the end of the experiment, the sum of all round payoffs determines the total payoff for both firms.

(The exchange rate is: **1500 Taler = 1 Euro**.)

Experiment 2: Instructions

Welcome to the experiment!

From now on, please stop any communication and read the following information with great care. Questions will be answered after reading the instructions individually at your place.

The following experiment deals with the sale of goods. During the experiment, you take over the role of a firm which decides on a sales price and a production quantity in a market.

- The experiment consists of 2 stages, which are played consecutively.
- At the beginning of the experiment, pairs of three firms are each randomly assigned to one of three markets.
- During the whole experiment, the assignment of the groups is fixed.

Stage 1

In the **5 rounds** of the first stage, each of the three firms is situated as the only firm in one of the three markets.

- The consumer demand in each of the three markets is determined by:
  - **demand = 100 – sales price**
- You decide on your sales price and on your production quantity.
  - Your sales price has to be chosen **in 0.001 increments** from the interval **[0; 100] Taler**.
  - Your production quantity has to be chosen **in 0.001 increments** from the interval **[0; 100]**.
- Production results in production costs equal to **10 Taler** per unit produced.
  - Your total production cost are therefore: **your production quantity x 10**
- Your maximum production quantity depends on the sales price you have chosen:
  - **Maximum production quantity = 100 – your sales price**
- The payoff for each round is calculated by**: (sales price – 10) x production quantity**

Before your decision in each round of the first stage, you will find a what-if-calculator. You may insert various combinations of your sales price and your production quantity and calculate the corresponding payoff!

Stage 2

In the **20 rounds** of the second stage, you make the same decisions as in stage 1. As a difference, all three firms are now situated in the same market.

- You decide on your sales price in Taler and on your production quantity as in stage 1.
- If all three firms decide on the same sales price, the demand is split equally.
  - Each obtains: **demand = (100 – sales price) / 3**
  - If one or more of the three firms has a production quantity which is too low to completely serve its proportion of the demand, a residual demand emerges which can be additionally served by the other firms.
- If the firms decide on different sales prices, the consumer buy first from the firm with the lowes price:
  - **demand = 100 – lowest sales price**
  - If the firm with the lowest sales price has a production quantity which is too low to completely serve the demand, a residual demand for the firm with the second lowest sales price can emerge. Finally, a residual demand can emerge for the firm with the highest sales price.
  - **residual demand = (100 – sold quantity) – second lowest sales price**
  - If two firms charge the second lowest price, demand is split equally (as described above).
- The payoff for each round is calculated by: **sales price x sold quantity – 10 x production quantity**

At the beginning of the second stage, you will find a what-if-calculator. You may insert various combinations of sales prices and production quantities of all three firms and calculate the corresponding payoffs!

At the end of the experiment, the sum of all round payoffs determines the total payoff for both firms.

(The exchange rate is: **1500 Taler = 1 Euro**.)

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