Sequential Price Setting: Theory and Evidence from a Lab Experiment

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Abstract

In the Varian (1980) model of price competition, a change from simultaneous to sequential price setting dramatically changes equilibrium strategies and pay-offs, and in the unique symmetric equilibrium prices are pushed up to the monopoly price. In addition there exists an asymmetric equilibrium with lower average prices. Our main contribution is to test these predictions in the laboratory. Our experimental data strongly support the qualitative model predictions. However, there is a non-negligible fraction of players that set low prices in accordance with the asymmetric equilibrium, which is puzzling. We show that the puzzle to a large extent can be resolved by introducing competitive preferences in the model.

Keywords: Laboratory experiment; information frictions; price competition; sequential price setting; competitive preferences.

JEL: C91; D43; L13.

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1 Introduction

The timing of pricing decisions may impact prices markedly. When price setting is simultaneous, sellers have strong incentives to undercut each other, pulling prices down. However, if one of the sellers sets the price after the other sellers have set their prices, this may alter the price-setting incentives of the other sellers dramatically.

In order to investigate the role of sequencing in pricing games, we study a model with price competition based on Varian (1980), with the twist that one of the sellers sets its price after the other sellers have set their prices. As shown in Deneckere and Kovenock (1992), this twist fundamentally changes the equilibrium strategies and pay-offs, and in the unique symmetric equilibrium prices are dramatically higher than when prices are set simultaneously. Prices are actually pushed up to the monopoly price. In addition there exists an asymmetric equilibrium with lower average prices.

Although the effects of sequential pricing in the Varian model are particularly stark, the main mechanism is more general. Sellers in pricing models with search frictions face a trade-off between exploiting price-insensitive consumers and attracting price-sensitive consumers. Sequencing of the price setting decisions tilts this trade-off in the direction of exploiting price-insensitive consumers, as the price-sensitive consumers tend to be picked up by the price follower anyway. Due to its simple structure and strong predictions, the Varian model seems particularly well suited to test experimentally the behavioural effects of price sequencing in search models.

Reasonable empirical questions are whether sellers recognize and respond to the incentives of the model and what equilibrium sellers coordinate on, if they coordinate at all. Our main contribution is to test the model predictions in the laboratory. Our experimental data strongly support the qualitative model predictions. In particular we observe a significant rise in prices when going from simultaneous to sequential price setting, all else constant. However, a non-negligible fraction of players set low prices in accordance with the asymmetric equilibrium, which is puzzling. We show that the puzzle to a large extent can be resolved by introducing competitive preferences in the model.

In the Varian model, sellers set prices independently and simultaneously for a homogeneous product, and buyers are either informed about the prices or not. The informed buyers visit the seller with the lowest price, while the uninformed buyers visit sellers randomly. In equilibrium, sellers randomize over prices, and as the fraction of uninformed buyers goes to zero, the equilibrium price converges to zero. In this set-up, suppose one of the sellers, which we label the *entrant*, sets her price after observing the prices of other sellers (which we label the *incumbents)*, without these sellers being able to respond. In the unique symmetric equilibrium of the model, incumbents set their prices equal to the reservation price of the buyers, while the entrant undercuts this price. The result holds regardless of the number of sellers and the fraction of uninformed buyers (as long as there is at least one uninformed buyer in the market). Hence, if one seller is allowed to be a price follower, this may fundamentally change the role of competition, and lead to monopoly prices, notwithstanding that the equilibrium with simultaneous price setting may be arbitrarily close to the competitive outcome.

These theoretical results are confirmed by data. In particular, we observe a significant rise in prices when price setting is sequential, all else constant. That is, sequential price setting, with one seller being an entrant, pushes prices toward monopoly levels. Moreover, this observed price increase is independent of both the number of uninformed buyers and the total number of incumbents in the market, supporting the qualitative predictions of the unique symmetric equilibrium. Furthermore, we observe individual price postings quantitatively consistent with equilibrium play. That is, the entrants best respond in 87 percent of all games and in 91 percent of games in the latter half of the experiment, while the incumbents post prices that are part of a Nash equilibrium in 80 percent of all games and in 88 percent of the latter games.

Although individual choices are largely consistent with equilibrium play, average price-setting is nonethe-

$$F(p) = 1 - \left(\frac{1-p}{p} \frac{U}{SN} \right)^{1/(S-1)} \quad \text{with } p \in [p_0, 1].$$

In the unique symmetric equilibrium, prices posted by the incumbents and the entrant are insensitive to the number of incumbent sellers in the market and to the fraction of informed buyers.

In the asymmetric equilibrium, all players get the same payoff. The incumbents' payoffs are the same as in the symmetric equilibrium, while the entrant is worse off. However, if two (or more) incumbents *miscoordinate* (and both set $p = p_0$), they are worse off than in any of the equilibria.

2.3 Competitive preferences

As will be clear below, we do find that the participants in the experiment occasionally play the asymmetric equilibrium. Inspired by this, we explore the model when the agents have behavioural preferences. More specifically, we assume that the agents may have preferences over relative outcomes (competitive preferences). As will be clear below, this will be important for explaining our empirical results.

We consider a preference structure represented by the following utility function:

$$EU_i = E\pi_i - \frac{\alpha_i}{S-1}\sum_{j=1}^{S}\max[E\pi_j - E\pi_i; 0];$$

where π_i is profit (monetary pay-off), $\alpha_i \geq 0$ is a preference parameter, and the summation is over all sellers. In the following we label sellers with $\alpha_i > 0$ as behavioural sellers.[8]

The equilibrium in the game is summarized in the following proposition:

Proposition 2 *Suppose one or more of the incumbents are behavioural. With simultaneous price setting, the set of equilibria is independent of α. With sequential pricing, the following holds:*
a) The asymmetric equilibrium with non-behavioural preferences, in which one incumbent sets p_0 with probability 1, and the other incumbents as well as the entrant sets $p = 1$, is still an equilibrium.
b) The symmetric equilibrium with non-behavioural preferences, in which all incumbents set $p = 1$ and the entrant marginally undercuts is no longer an equilibrium.
c) Suppose all sellers are behavioural, with the same preference parameter α. Then there exists a unique symmetric equilibrium. In this symmetric equilibrium, the incumbents randomize. They set a high price $p = 1$ with probability $z > 0$, and a low price $p \leq p_0$ with probability $1 - z$, where

$$z = \left(\frac{p_0}{p_0 + \alpha/(S-1+\alpha)}\right)^{\frac{1}{S-2}}: \qquad (1)$$

If they set a low price, they randomize on an interval below p_0. If all incumbents set $p = 1$, the entrant marginally undercuts. Otherwise the entrant sets $p = 1$.

The proof is given in appendix $A.2$

where exactly one incumbent sets p_0 and the other sellers set $p = 1$ gives all sellers the same expected pay-off. It follows that the asymmetric equilibrium is still an equilibrium. Hence result *a)* follows.

Result *b)* is quite interesting. If at least one of the incumbents is behavioural, then the symmetric equilibrium with non-behavioural preferences where all incumbents set $p = 1$ is no longer an equilibrium. The reason is that if all incumbents play $p = 1$, a behavioural incumbent will be better off setting p_0, thereby obtaining the same monetary pay-off, and eliminating the pay-off difference between herself and the entrant.

Last, consider result *c)*. If all incumbents are behavioural, they will prefer to set a high price if the other incumbents set a low price, and a low price if all the others set a high price. Hence they will randomize and set the high price with probability given by (1). If they set a low price, there is a strictly positive probability that another incumbent also sets a low price. The standard undercutting-argument in the Varian model then applies, and the equilibrium distribution cannot have a mass point, say at p_0. If it had, a seller could discretely increase the probability of attracting the informed buyers by reducing the price marginally below p_0, thereby increasing its profit (recall that the entrant sets $p = 1$ in this case). This explains why there is a distribution below p_0 (however thin). Note that $z = 1$ when $\quad = 0$, and that z goes to $\frac{p_0}{p_0+1}$ when $\quad$ goes to infinity.

We want to explore heterogeneity in seller preferences. To that end, suppose sellers can be of two types: behavioural, with a strictly positive $\quad$ (the same for all the behavioural agents), or profit-maximizing, with $\quad = 0$. The probability that a randomly drawn seller is behavioural is denoted q. Both $\quad$ and q are common knowledge. Hence, each incumbent seller's beliefs are that the probability that each of the other incumbent sellers are behavioural is q, and that the draws are independent. We assume that the behavioural incumbents get a utility penalty if the entrant gets a higher monetary pay-off than themselves, but not if the other incumbents (who have the same choice set) do.

Corollary 1 *Suppose sellers differ in preferences as described above. In the unique symmetric equilibrium of the pricing game, behavioural incumbents set $p = 1$ with probability z, and a low price $p \quad p_0$ with probability $1 \quad z$, where*

$$z = \max \left(\frac{z \quad 1 + q}{q} ; 0 \right) \tag{2}$$

where z is given by (1).

The proof is given in the appendix. When the $z \quad 0$ constraint does not bind, the unconditional probability that an incumbent sets a high price is z, i.e., the same probability as when all agents are behavioural. The fact that only a fraction q of the incumbents are behavioural induces the behavioural agents to increase the probability of setting a low price proportionally.[9] If there are too few behavioural sellers, the behavioural sellers strictly prefer to set a low price, and do so with probability 1.

3 Experiment

The centerpiece of our design is to test the striking predictions regarding the effects of sequential pricing in the Varian-model framework. To do this we run separate sessions with simultaneous and with sequential price setting in accordance with the model above. That is, with sequential pricing one seller observes the other sellers' prices before it posts its own price. In the instructions to the experiment we used the term "Entrant" for the second mover and "Incumbents" for first movers. This is for convenience only. There is no difference between entrants and incumbents except for the sequencing of their price setting decisions. Sample instructions are available in appendix *C*.

[9] When $z > 0$ we have that $1 \quad z = \frac{1 \quad z}{q}$

Assuming = 0 and an inclination among participants to play the symmetric strategy, we have the following directional hypotheses:

1. Posted prices are higher when pricing is sequential compared to simultaneous for any share of uninformed buyers.
2. Posted prices with sequential pricing are insensitive to the number of uninformed buyers.
3. Posted prices with sequential pricing are insensitive to the number of incumbent sellers in the market.
4. Posted prices with simultaneous price setting are monotonically increasing in the number of uninformed buyers and monotonically decreasing in the number of sellers.

3.2 Implementation

In all treatments the same game is played 60 periods in succession. Small markets are formed randomly from ...xed matching blocks of 9 human sellers in each new period. Large markets are formed randomly from ...xed matching blocks of 18 human sellers in each new period. Unique subjects are used in each treatment. In small markets with sequential pricing each subject is the entrant (one of the two incumbents) in one (two) sequence(s) of 20 consecutive periods. In large markets each subject is the entrant (one of the ...ve incumbents) in one (...ve) sequence(s) of 10 consecutive periods. Subjects are randomly allocated to sequences at the beginning of the experiment. In the analysis we regard average behavior in a matching block over all 60 periods as an independent observation.

The number of matching blocks was determined in a pilot. With $\bar{\boldsymbol{p}}(\ )$ denoting the average posted price in treatment ( ), the pilot collected data on the treatment e¤ect $\bar{\boldsymbol{p}}(\boldsymbol{T}_{30}^{Y}$

each period, subjects received minimal feedback consisting of posted prices in the current market, own payoff from the current period, and own cumulative payoff. The protocol was implemented in zTree (Fischbacher 2007).

A total of 558 subjects participated in the experiment. In total $10{,}080$ pricing games were played, in which a total of $33{,}480$ prices were posted. On average subjects in the Norwegian sessions earned 26 USD while subjects in the Danish sessions earned 30 USD.[16]

4 Results

In what follows we present our results in four sections. The first section describe the time paths of play. The second section addresses the directional hypotheses under the assumption that the unique symmetric equilibrium is played assuming $= 0$ (no behavioural preferences). The third section opens up for asymmetric pure strategy equilibrium play and classifies behavior in terms of near equilibrium play using individual level data. The fourth section analyses the data assuming > 0.

4.1 Time paths of play

Figure 1

Figure 1: *Time paths of play.*

By eyeballing Figure 1 it appears that with simultaneous pricing and 15 and 30 uninformed buyers, prices approach from above to a level higher than the symmetric Nash prices, whereas with 60 uninformed buyers prices are close to the symmetric Nash from period one onwards. With sequential pricing, prices seem to approach the symmetric Nash equilibrium from below in the small market with 15 uninformed buyers, and in the large market with 30 uninformed buyers. In the small market with 30 uniformed buyers prices hover below the symmetric Nash. Finally, in the small market with 60 uninformed buyers prices seem to approach to a level somewhat below the symmetric Nash. In appendix ***B:***1 we lend support to these impressions by formally testing whether behavior is moving closer the Nash price in each matching block.

4.2 Treatment di¤erences

In our analysis of treatment e¤ects we follow a conservative approach and use the full data set. Appendix ***B:***2 contains parallel tests using data from the last half of the experiment (periods 31 60). Results

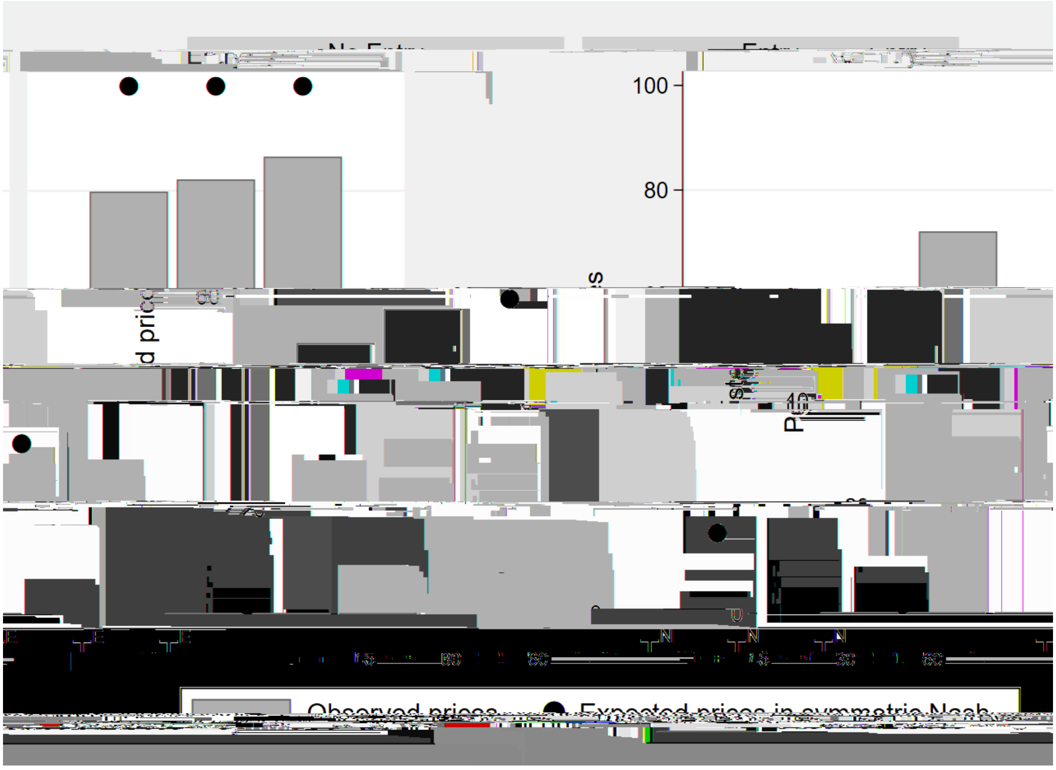

Figure 2: *Observed mean prices and expected prices in symmetric equilibrium*

Figure 2 summarizes the findings in Figure 1. There are substantial deviations from the symmetric equilibrium in all treatments. For treatments with simultaneous pricing, average prices lie 5–19 price points above the symmetric equilibrium, while they lie 14–20 price points below the symmetric equilibrium with sequential pricing. We find that the model predictions deviate from actual behavior when the competitive environment is close to Bertrand competition. This was expected. Similar results are obtained in earlier studies (e.g. Helland et al 2017), and are rationalized by the fact that the gains from playing the equilibrium strategy are very low while the potential gains from deviating if others also deviate are large.[18] With sequential pricing, the lower than equilibrium prices may to some extent be explained by the fact that the agents can only err on the downside relative to equilibrium behavior. More importantly however, the deviations between observed prices and equilibrium prices can also be due to asymmetric equilibrium play. We return to the latter below.

Judged as directional predictions, theory fares exceedingly well in the experimental data. First, prices are significantly higher when there is sequential pricing compared when there is not for any share of uniformed buyers: $\bar{p}(T^Y_{15}) - \bar{p}(T^N_{15}) = 28.8$; $\bar{p}(T^Y_{30}) - \bar{p}(T^N_{30}) = 24.6$; and $\bar{p}(T^Y_{60}) - \bar{p}(T^N_{60}) = 14.4$, with $p < 0.001$ for each comparison. The very low p-values indicate that the power calculation in our pilot succeeded.[19] We conclude that sequential pricing causes prices to move towards monopoly levels.

Second, there is no significant differences in prices over the share of uninformed buyers in markets with sequential pricing: $\bar{p}(T^Y_{30}) - \bar{p}(T^Y_{15}) = 2.3$, ($p = 0.573$); $\bar{p}(T^Y_{60}) - \bar{p}(T^Y_{30}) = 4.3$, ($p = 0.237$); and $\bar{p}(T^Y_{60}) - \bar{p}(T^Y_{15}) = 6.6$, ($p = 0.105$). As the share of uninformed buyers increases, there is a modest increase in observed prices. However, the observed increases are not significant at conventional levels,

[18] Helland et al. (2017) find that in simultaneous pricing duopolies, deviation from the symmetric equilibrium becomes less pronounced as the number of uninformed buyers increases. This pattern is consistent with a quantal response equilibrium in which errors become more costly as the number of uninformed decreases. We note that a similar pattern is observed in the triopolies of Figure 1.

[19] A detailed argument for this statement is found in Benjamin et al. (2018).

and far from significant at the stricter levels promoted by Benjamin et al. (2018) for new experimental findings (i.e., a significance threshold of 5/1000 rather than the conventional 5/100).

Third, there is no significant differences in prices over the small and the large markets with sequential pricing: $\bar{p}(L^Y_{30}) - \bar{p}(T^Y_{30}) = 5.9$, with $p = 0.181$. The null of identical price posting in small and large markets cannot be rejected at conventional levels.

Finally, we observe substantial and significant price increases as the number of uninformed buyers increases in markets without sequential pricing: $\bar{p}(T^N_{30}) - \bar{p}(T^N_{15}) = 6.5$; $\bar{p}(T^N_{60}) - \bar{p}(T^N_{30}) = 14.5$; and $\bar{p}(T^N_{60}) - \bar{p}(T^N_{15}) = 21.0$, with $p < 0.001$ for all comparisons. Theoretical and empirical CDFs of prices for our treatments without sequential pricing are displayed in appendix $B.3$. We note that the shape of the empirical CDFs agrees with the shape of the theoretical distributions, and that the empirical distributions obey the lower bound of the support (p_0) remarkably well.

4.3 Individual level analysis

Recall that observed average prices are below the symmetric equilibrium price in the games with sequential pricing (see Figures 1 and 2). Can this result be explained by asymmetric equilibrium play in which one incumbent sets $p = p_0$? Figure 3 displays the distribution of prices set by incumbents over all periods in treatments with sequential pricing. The dashed lines mark p_0. The picture is remarkably similar across all treatments: there is a large spike close to the monopoly price of 1, and a much smaller but still sizable distribution of prices in a small interval around p_0, and not many occurrences of price choices elsewhere. We take this picture to be broadly consistent with overall equilibrium play.

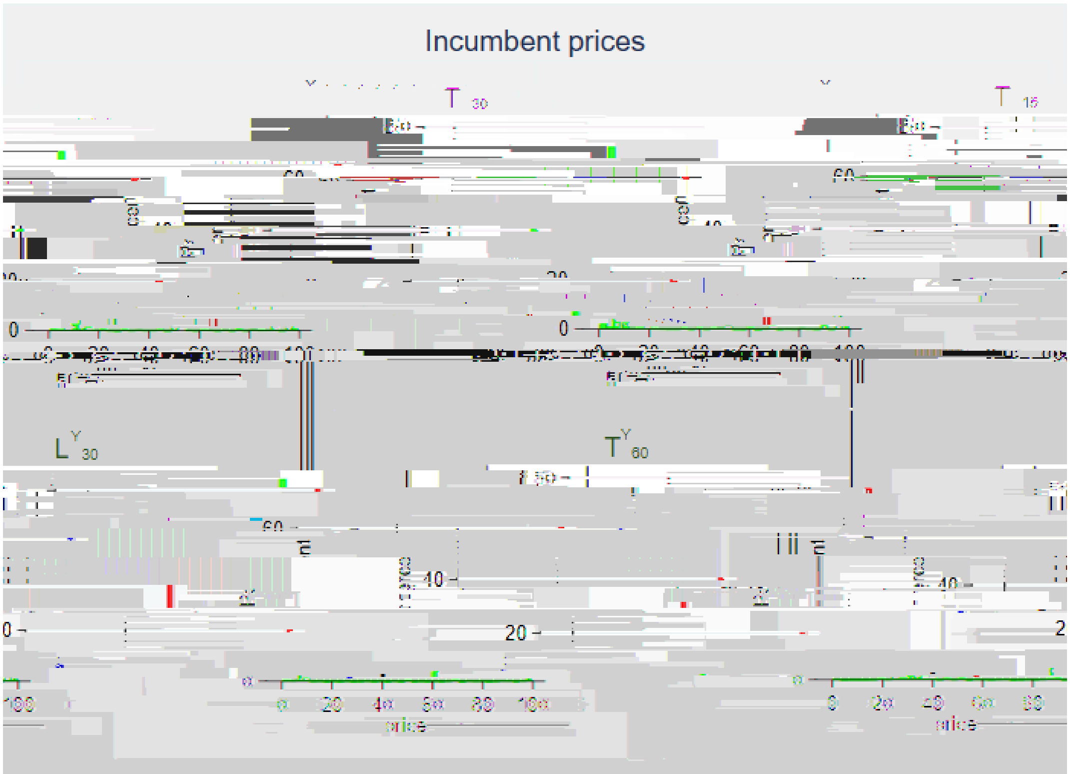

Figure 3: *Distribution of incumbent prices under sequential pricing.*

In what follows we use individual level data to classify decisions and games in our treatments with sequential pricing in terms of *near* Nash behavior, thereby providing direct evidence on the composition of aggregate prices. For the classification we assume play of pure strategies. This assumption is relaxed below, where we allow for mixed strategies.

In the classification we follow a cautious path in allowing for a deviation of only 1 price point from true Nash behavior. As above, let $\boldsymbol{p}^E$ be the price posted by the entrant, $\boldsymbol{p}^I$ the price posted by an incumbent, $\boldsymbol{p}^I_{min}$ the lowest price posted by an incumbent, and $\boldsymbol{p}_0$ the indifference price in a market. Our definitions of near Nash behavior and near Nash equilibrium play for our chosen deviation threshold are then:

> *Entrant best response (EBR)*: Entrant's price $\boldsymbol{p}^E$ is defined as entrant best response if $\boldsymbol{p}^E \quad 99$ when $\boldsymbol{p}^I_{min} < \boldsymbol{p}_0 + 1$; or if $\boldsymbol{p}^I_{min} \quad 1 \quad \boldsymbol{p}^E < \boldsymbol{p}^I_{min}$ when $\boldsymbol{p}^I_{min} > \boldsymbol{p}_0 \quad 1$.
>
> *Incumbent Nash strategy (INS)*: Incumbents' price $\boldsymbol{p}^I$ is defined as an incumbent Nash strategy if $\boldsymbol{p}^I = \boldsymbol{p}_0 \quad 1$; or if $\boldsymbol{p}^I \quad 99$.
>
> *Symmetric Nash equilibrium outcome (SE):* The outcome of a game is counted as a symmetric Nash equilibrium (SE) if all incumbents post prices $\boldsymbol{p}^I \quad 99$ and the entrant plays best response.
>
> *Asymmetric Nash equilibrium outcome (AE)*: The outcome is counted as an asymmetric Nash equilibrium (AE) if at most one incumbent posts a price $\boldsymbol{p}^I = \boldsymbol{p}_0 \quad 1$, the other incumbent(s) post(s) prices $\boldsymbol{p}^I \quad 99$, and the entrant plays best response.
>
> *Miscoordination outcome (MC)*: The outcome of a game is counted as a miscoordination (MC) if more than one incumbent posts a price $\boldsymbol{p}^I = \boldsymbol{p}_0 \quad 1$, and the entrant plays best response.

Our choice of cut-off is, of course, debatable. In appendix ***B:***4 we run the analysis allowing for a more liberal deviation of 5 price points from Nash behavior. This leads to a classification with a moderate increase in near Nash behavior. However, the patterns of near Nash behavior (see below) are retained with the more liberal deviation threshold.

Figure 4 displays the propo5.012-1.495=J/F2295=J/F22959dnTd[(Figure)]TJ/F89.9626Tf31.8620Td[(4)]TJ/F409.964tc

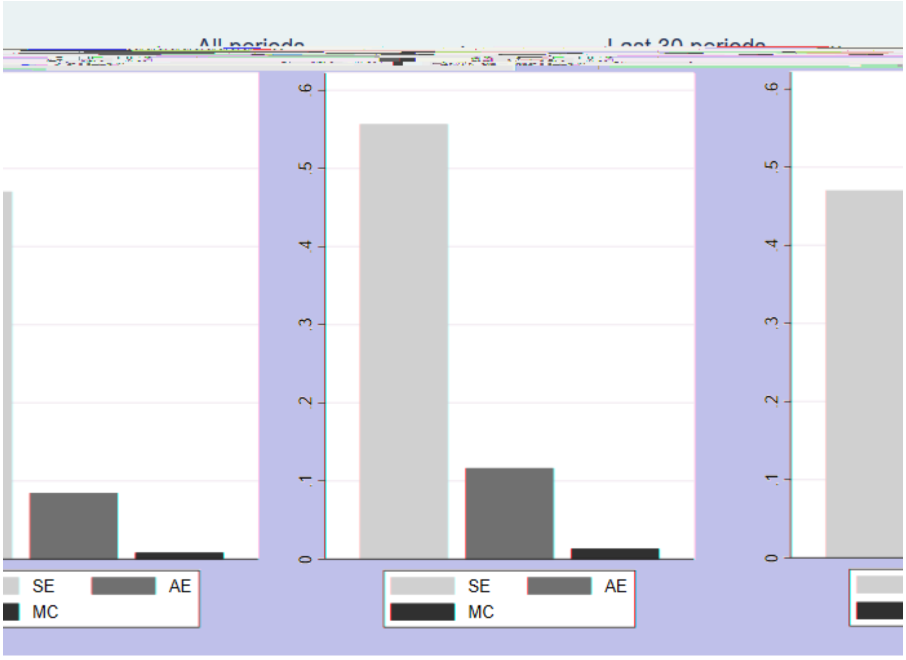

Figure 5:

In what follows we calibrate q and using observations from the latter half of the experiment only. To for behavioural incumbents goes a long way in rationalizing our observation that a substantial share of price choices are consistent with asymmetric equilibrium play.

5 Conclusion

In this paper we analyze sequential price setting in the Varian (1980) model framework. Compared with simultaneous pricing, a sequential price setting dramatically changes the incentives of the sellers and hence the equilibrium outcome of the price posting game. In the symmetric equilibrium of the model, which we expect rational income-maximizing agents to play, sequential pricing pushes prices toward monopoly levels. There also exist asymmetric equilibria in which prices do not increase.

We test the model's predictions in the laboratory. Our experimental data strongly supports the qualitative model predictions. In particular we observe a significant rise in prices of sequential pricing, all else constant. However, there is a non-negligible fraction of players that set low prices in accordance with the asymmetric equilibrium, which is puzzling. We show that the puzzle to a large extent can be resolved by introducing competitive preferences in the model. The reason is that incumbent sellers then have an incentive to set low prices in accordance with the asymmetric equilibrium, as this reduces the difference

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Appendix

Appendix overview

A Model Appendix

A.1 Simultaneous pricing

This section solves out the price dispersion equilibrium when there is no sequential pricing.

Let $^{n;N}(p_s; p_{-s})$ denote the (expected number of) buyers to a seller who sets the price p_s when the opponents' vector of prices is p_{-S}. Then $^{n;N}(p_S; p_{-S}) = N + U/S$ if p_S is the strictly lowest price and $^{n;N}(p_S; p_{-S}) = U/S$ if one of the opponents sets the strictly lowest price (if more than one seller set the lowest price, the informed buyers are divided equally between the sellers). Varian (1980) shows that the symmetric equilibrium entails a mixed strategy given by the c.d.f. $F(p)$ with support $p \in [p_0; 1]$.[24] A seller that sets $p = 1$ only sells to uninformed buyers, and obtains a profit of U/S. From the definition of a mixed-strategy equilibrium it follows that all prices in the support of F give rise to the same profits. Hence

$$(U/S + N(1 - F(p_s))^{S-1})p_s = U/S \tag{3}$$

The left-hand side shows the pay-off when setting a price p_s. Independent of the price, the seller will sell in expectation to U/S uninformed buyers. If it sets the lowest price, it will in addition sell to N informed buyers, and this happens with probability $(1 - F(p))^{S-1}$. The right hand side shows the expected pay-off when setting $p_s = 1$. Solving for $F(p)$ gives:

$$F(p) = 1 - \left(\frac{1-p}{p}\frac{U}{SN}\right)^{1/(S-1)} \quad \text{with } p \in [p_0; 1]. \tag{4}$$

Let p_0 denote the lowest price in the support of F. A seller that sets p_0 sets the lowest price with probability 1. From (3) it then follows that $p_0 = \frac{U}{U+SN}$. It follows directly that the expected posted price as well as the expected transaction price is a decreasing function of the fraction of informed to uninformed buyers N/U.

A.2 Proof of Proposition 2

We first want to show that with simultaneous pricing the set of equilibria is independent of .

First, consider an equilibrium for $= 0$. In the equilibrium allocation, everyone get the same expected payoff, and hence does not influence payoffs. Furthermore, a deviation is profitable with > 0 if and only if it is profitable with $= 0$. Hence the $= 0$ equilibria are still equilibria with > 0.

Suppose then that there exists an equilibrium for $\neq 0$ that is not an equilibrium for $= 0$. In this equilibrium the expected payoffs must differ between the agents (otherwise it would have been an equilibrium for $= 0$). Hence the equilibrium must by asymmetric. An agent can always set $p = 1$ and sell to the uninformed and get a monetary payoff of $\frac{U}{S}$. Consider an asymmetric equilibrium in which some agents get a strictly higher monetary payoff $'$. Let p' denote the infimum of the support of this agent, which then gives a pay-off of $'$. Then it must be optimal for the agent with a strictly lower pay-off to set $p' - \varepsilon$ for some ε and get a monetary payoff strictly higher than $\frac{U}{S}$, which contradicts equilibrium.

We will continue to show a)-c).

a) The asymmetric equilibrium gives the entrant and the incumbents the same expected payoffs. Hence the utility of deviating is as if $= 0$. Since the asymmetric equilibrium is an equilibrium with $= 0$, the claim follows.

[24] Varian (1980) also shows that $F(p)$ has no mass points so that ties are a measure zero event. mes(t)-327(t)24(i)-28(rh)-35()-Wo tg-352oh.9701Tf7-than2(s)r-27(a)

b) In the symmetric equilibrium for = 0, the entrant gets a higher monetary pay-o¤ than the incumbents. If all the other sellers set $p = 1$, an incumbent behavioural seller would like to deviate and set p_0, as that would eliminate the di¤erences in expected incomes without reducing the agent's monetary payo¤. Hence the symmetric equilibrium with = 0 is not an equilibrium if at least one seller has > 0.

c) Consider a seller in a symmetric equilibrium as described in the proposition. Suppose a seller sets $p = 1$. The probability that all the other sellers set $p = 1$ is z^{S-2}. The payo¤ if they do is $\frac{}{S-1}(+ N \quad) = \frac{}{S-1}N$, where $= U=S$. If one or more of the other incumbents set a low price, the payo¤ is . Hence the payo¤ if setting $p = 1$ is

$$U^1 = \quad z^{S-2}\frac{}{S \quad 1}N: \tag{5}$$

Suppose instead that the seller sets p low. The seller will get the same payo¤ if setting p^0 or randomizing below p^0. The probability that the seller sets the lowest price if setting p_0 is z^{S-2}. Hence it follows that the expected monetary payo¤ when setting a low price is (since the pay-o¤ is if $z = 1$)

$$^{l} = \quad (1 \quad z^{S-2})p_0 N \tag{6}$$

The entrant will set $p = 1$ and get an expected payo¤ of . Hence the utility if setting p low is (since all the other incumbents get the same payo¤ in expected terms)

$$\begin{aligned} U^2 &= {}^{l} \quad \frac{}{S \quad 1}(\quad {}^{l}) \\ &= \quad (1 + \frac{}{S \quad 1})(1 \quad z^{S-2})p_0 N: \end{aligned} \tag{7}$$

In equilibrium we must have that $U^1 = U^2$. It follows that

$$z^{S-2}\frac{}{S \quad 1}N = \quad (1 + \frac{}{S \quad 1})(1 \quad z^{S-2})p_0 N;$$

or

$$z^{S-2} = \frac{p_0}{p_0 + \quad =(S \quad 1 + \quad)}: \tag{8}$$

It follows that $z = 1$ when $= 0$, and that z goes to $\frac{p_0}{p_0+1}$ when goes to in…nity.

Finally, the distribution of prices below p_0 must be such that

$$[z + (1 \quad z)(1 \quad F(p))]^{S-2}pI + p\frac{U}{S} = \quad ^{l} \tag{9}$$

which gives

$$F(p) = \frac{1}{1 \quad z} \quad 1 \quad \frac{^{l}}{pI} \quad \frac{U}{SI}^{\frac{1}{S \quad 2}} \tag{10}$$

From (6) and (8) it follows that

$$^{l} = \quad \frac{p_0 I}{p_0(S + \quad) + }$$

Last, the incumbent that sets a price at the bottom of the support sells to $I + U=S$

The structure of the symmetric equilibrium is as above: with probability $z > 0$ a behavioural seller sets $p = 1$, and with the complementary probability a low price. If setting a low price, the seller randomizes on an interval $[p_{\min}; p_0]$ according to a distribution that has no mass points. The expected utility is the same for all prices in the support. Since $z > 0$, a non-behvioural incumbent seller always sets $p = 1$.

The probability that all the other incumbents are playing $p = 1$ is given by $(1 \quad q + qz)^{S-2} = \bar{z}^{S-2}$, where $\bar{z} = 1 \quad q + qz$. The expected utility for a behavioural seller if playing $p = 1$ is thus given by

$$U^1 = \quad \bar{z}^{S-2} \frac{}{S \quad 1} N: \tag{11}$$

which is equal to (5) with

B Data appendix

B.1 Dynamic regressions

We formally address the question of whether behavior is approaching Nash prices by running dynamic regressions inspired by Noussair et al. (1995,1997). The specification employed is the following:

$$p_{it} = \sum_{i=1}^{I} \beta_{1i} D_i (1/t) + \sum_{i=1}^{I} \beta_{2i} D_i ((t-1)/t) + \varepsilon_{it},$$

were p_{it} is posted price, $i \in [1, I]$ indicates block and $t \in [1, T]$ indicates period, with $I \in \{6, 8, 10\}$ and $T = 60$. The $((t-1)/t)$ terms take the value 0 in period 1, thus β_{1i} provides an estimate of p_{i1} for block i. As t grows the $((t-1)/t)$ terms approach 1 and the $1/t$ terms approach 0, thus β_{2i} is an estimate of the asymptote of p_{iT}. The idea is to test if β_{2i} is closer to the symmetric Nash equilibrium than β_{1i}.

Table B.1.1 provides regression results. The regressions are estimated with random intercepts for unique subjects, and corrected standard errors for correlation over panels (Prais-Winsten regression).

	T^N_{15}	T^N_{30}	T^N_{60}	T^Y_{15}	T^Y_{30}	T^Y_{60}	L^Y_{30}
β_{11}	91.2	90.5	69.7	63.8	91.1	69.9	72.1
β_{21}	49.8	51.5	73.4	78.8	83.8	88.5	99.5
β_{12}	75.6	65.7	81.6	70.3	68.8	71.6	65.6
β_{22}	47.0	55.7	74.2	86.8	78.6	85.0	90.3
β_{13}	64.1	69.5	79.9	50.0	96.2	51.7	63.5
β_{23}	49.5	61.3	75.1	72.3	90.8	90.2	83.0
β_{14}	82.8	59.0	82.1	39.6	64.7	84.4	67.0
β_{24}	48.2	54.8	70.6	91.3	76.5	87.7	89.5
β_{15}	64.2	77.2	78.7	79.4	69.1	42.7	62.6
β_{25}	52.7	62.5	75.0	75.8	84.1	80.3	83.6
β_{16}	54.2	73.8	72.4	72.8	94.5	70.6	58.1
β_{26}	52.1	60.0	68.9	92.7	71.7	89.7	95.0
β_{17}	90.4	65.4	56.6	65.1	77.8	84.2	
β_{27}	50.2	51.3	72.8	80.8	94.0	96.8	
β_{18}	88.5	84.7	76.3	64.6	79.0	91.3	
β_{28}	43.4	54.4	65.8	73.1	76.2	85.6	
β_{19}	.				74.3		
β_{29}	.				89.7		
β_{110}	.				69.6		
β_{210}	.				79.6		
$E(p^*)$	32.3	45.7	67.6	100	100	100	100

Table B.1.1 *Dynamic regressions: random intercepts for unique subjects and corrected standard errors for correlation over panels*

The overall picture is that behavior in matching blocks is approaching the symmetric Nash equilibrium in most treatments. This is illustrated in Table B.1.2. In the table a positive sign indicates that β_{2i} is closer to the symmetric Nash equilibrium than β_{1i}, the asterisks indicate significance levels of the observed di¤erences (at the ***1%, **5% or *10% levels respectively, using a ^{2} test of di¤erences in coe¢ cients). In $\boldsymbol{T}_{30}^{Y}$ 5 blocks move towards the symmetric Nash whereas 5 blocks move away from the symmetric Nash. In the other treatments either 7 out of 8 blocks, or all blocks, move towards the symmetric Nash. In general movements towards the symmetric Nash are frequent: 41 out of the 48 blocks move towards the symmetric Nash. Moreover, more than 1=2 of these movements are signi…cantly di¤erent from zero at conventional levels. Movements away from the symmetric Nash are infrequent: 7 out of 48 blocks move away from the symmetric equilibrium. Only 1=7 of these movements are signi…cantly di¤erent from zero at conventional levels.

*** +

Block	$\boldsymbol{T}_{15}^{N}$	$\boldsymbol{T}_{30}^{N}$	$\boldsymbol{T}_{60}^{N}$	$\boldsymbol{T}_{15}^{Y}$	$\boldsymbol{T}_{30}^{Y}$	$\boldsymbol{T}_{60}^{Y}$	$\boldsymbol{L}_{30}^{Y}$
1	+ ***	+ ***		+7 +			

***

	T^{N}_{15}	T^{N}_{30}	T^{N}_{60}	T^{Y}_{15}	T^{Y}_{30}
T^{N}_{30}	0.001				
	(-3.05)				
T^{N}_{60}	<0.001	<0.001			
	(-3.36)	(-3.36)			
T^{Y}_{15}	<0.001				
	-(3.36)				
T^{Y}_{30}		<0.001		0.534	
		(-3.55)		(-0.62)	
T^{Y}_{60}			<0.001	0.105	0.237
			(-3.36)	(-1.68)	(-1.24)
L^{Y}_{30}					0.181
					(-1.41)

Table B.2.2: *Wilcoxon rank sum tests using all periods. Exact p-values (test-statistics)*

Table B.2.3 provides the raw data for the Wilcoxon rank sum tests for periods 31 60. Average prices over periods 31 60 are provided for each block. Numbers are ranked in descending order in each treatment.

Block	T^{N}_{15}	T^{N}_{30}	T^{N}_{60}	T^{Y}_{15}	T^{Y}_{30}	T^{Y}_{60}	L^{Y}_{30}
1	44.2	52.8	65.7	70.3	72.5	82.0	81.4
2	45.0	53.1	68.8	80.6	72.9	84.5	86.4
3	48.3	56.0	72.2	83.5	76.7	87.6	89.1
4	48.5	59.1	72.9	85.1	78.5	89.6	92.6
5	50.2	62.0	74.6	85.8	78.9	89.8	94.8
6	51.1	62.9	75.9	89.8	79.7	91.1	98.3
7	51.4	63.8	76.5	92.8	90.1	93.4	
8	54.9	68.1	77.2	94.0	91.4	96.8	
9					91.7		
10					93.9		

	T^N_{15}	T^N_{30}	T^N_{60}	T^Y_{15}	T^Y_{30}
T^N_{30}	0.001				
	(-3.15)				
T^N_{60}	0.001	<0.001			
	(-3.36)	(-3.26)			
T^Y_{15}	0.001				
	(-3.36)				
T^Y_{30}	<0.001			0.460	
	(-3.55)			(0.80)	
T^Y_{60}			<0.001	0.328	0.173
			(-3.36)	(-1.10)	(-1.42)
L^Y_{30}					0.073
					(-1.84)

Table B.2.2: *Wilcoxon rank sum tests using periods 31-60. Exact p-values (test-statistics)*

B.3 Price distributions in treatments with simultaneous pricing

Figure B.3.1 ($t \in [1; 60]$) and B.3.2 ($t \in [31; 60]$) display the theoretical (i.e., the mixed Nash strategy in the unique symmetric equilibrium) and observed CDFs of our treatments with simultaneous pricing. We first note that empirical distributions obey the lower bound of the support (p_0) remarkably well. Secondly, we note that the shape of the empirical CDFs agrees with the shape of the theoretical distributions. Thirdly, eyeballing the distributions the appear very stable when comparing the whole experiment with the latter half of it. Finally, and consistent with the average prices documented in the main text, observed CDFs appear very close to stochastically first dominating the theoretical distributions.

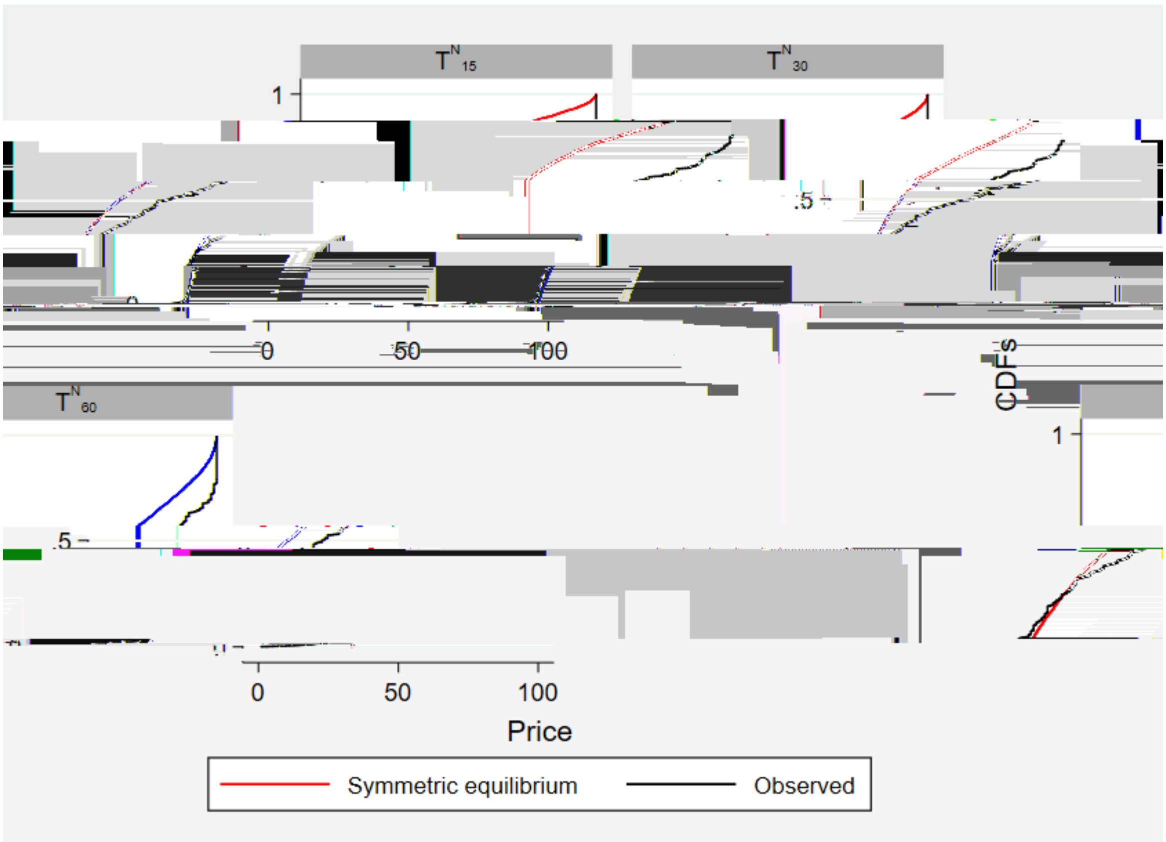

Figure B.3.1: *Nash and observed CDFs for reatments without sequential pricing, all periods*

Figure B.3.2: *Nash and observed CDFs for treatments without sequential pricing, periods 31-60*

B.4 Classifying near Nash behavior permitting 5 price points deviation

Figures B.4.1 and B.4.2 classi..es near Nash behavior using a more liberal threshold of 5 price points for near Nash behavior.

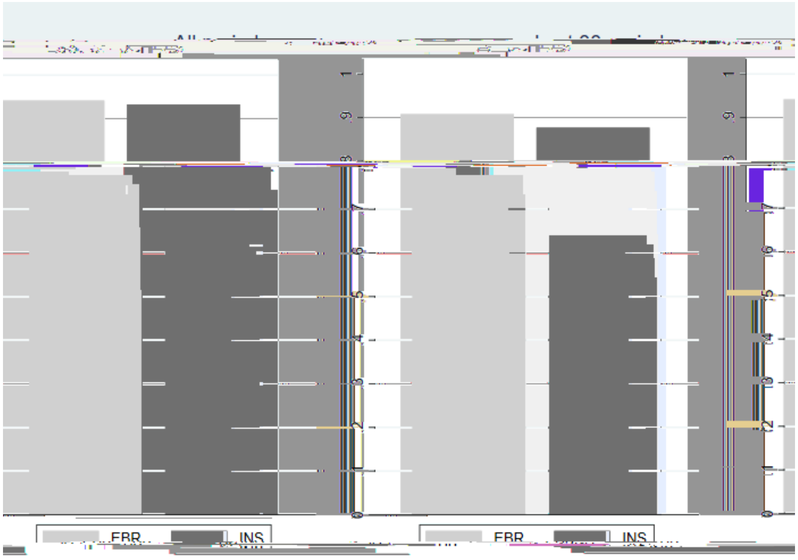

Figure B.4.1: *Fractions of individual price postings consistent with equilibrium strategies: entrant best response (EBR) and incumbent Nash strategy (INS). 5 price point deviation allowed.*

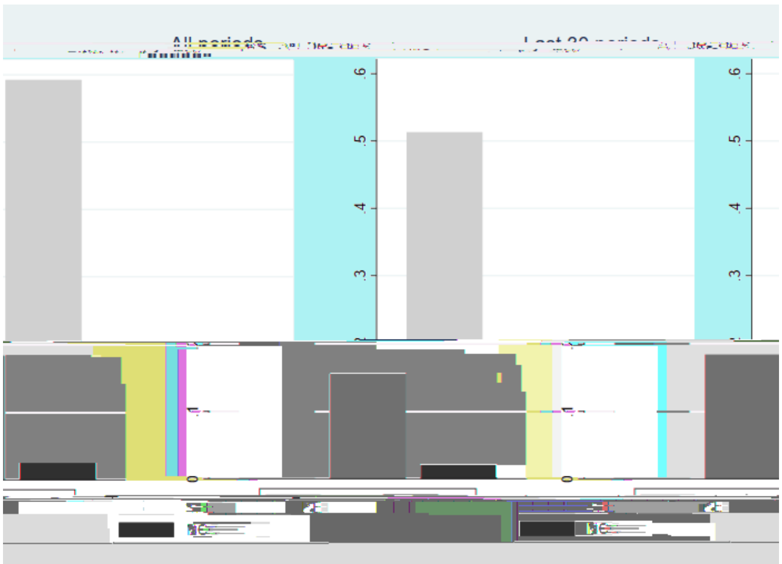

Figure B.4.2: *Fractions of markets consistent with: symmetric Nash equilibrium (SE), asymmetric Nash equilibrium (AE), and miscoordination (MC). 5 price point deviation allowed.*

Given cut-o¤ at 5 price points, entrants best respond in 90 percent of all games, and in 94 percent of games in the latter half of the experiment. Incumbents post prices that are part of a Nash equilibrium in 87 percent of decisions when all periods are considered, and in 93 percent of decisions in the latter half of the experiment. Observed behavior is consistent with the symmetric equilibrium being played in 51 percent of all games, and in 59 percent of games in the latter half of the experiment. Moreover, observed behavior is consistent with the asymmetric equilibrium being played in 16 percent of all games, and in 18 percent of games in the latter half of the experiment. Finally, observed behavior is consistent with miscoordination in a meagre 2 percent of all games, and in 3 percent of games in the latter half of the experiment.

So, when learning has presumably played out and behavior stabilizes, almost all entrants best response, almost all incumbents post prices that are part of a Nash equilibrium, and more than $3/4$ of observed behavior can be classified as equilibrium play, or attempts at equilibrium play that ended in miscoordination. Over the course of the experiment play of both the symmetric and the asymmetric equilibrium increases, though play of the symmetric equilibrium increases faster than that of the asymmetric equilibrium. Failures to coordinate on the asymmetric equilibrium are rare and do not increase much over the course of the experiment.

Table B.4.1 breaks down the classification on treatments. In the table the proportion of decisions (EBR, INS) and games (SE, AE, MC) falling in the different categories are noted for all periods ($t \in [1, 60]$) and for the last half of the experiment ($t \in [31, 60]$

For small market treatments (i.e., all treatments except $\boldsymbol{L}_{30}^{Y}$), data was collected in Oslo from 15th February 2019 to 6th March 2019, while data was collected in Copenhagen from 10th April 2019 to 6th June 2019. For the large market treatment, data was collected in Oslo on 11th November 2019, while data was collected in Copenhagen from 4th March 2020 to 9th March 2020. All sessions were conducted in English.

The fact that data was collected at two di¤erent locations has little impact on results, both economically and statistically. We substantiate this claim …rst by comparing the main results across locations for treatments $\boldsymbol{T}_{30}^{N}$, $\boldsymbol{T}_{30}^{Y}$, and $\boldsymbol{L}_{30}^{Y}$, and second by reproducing the main results when we drop all observations from session done in Oslo.

The following table summarizes means and standard deviations (between blocks) of prices across the two locations for treatments $\boldsymbol{T}_{30}^{N}$, $\boldsymbol{T}_{30}^{Y}$, and $\boldsymbol{L}_{30}^{Y}$.

	Oslo		Copenhagen	
	Mean	St.dev.	Mean	St.dev.
$\boldsymbol{T}_{30}^{N}$	57.0	3.4	58.3	4.9
$\boldsymbol{T}_{30}^{Y}$	82.2	7.0	82.1	7.4
$\boldsymbol{L}_{30}^{Y}$	92.9	6.4	85.8	5.1

Table B.5.2: *Location result comparison.*

B.6 Subject heterogeneity

There are substantial di¤erences in how often subjects in the role of incumbent sellers set the high price. Figure B.6.1 reports frequencies of incumbents' ratio of high price to low price across treatments. The price ratio is calculated as $\frac{\hat{p}_{high}}{\hat{p}_{low}}$, where $\hat{p}_{low}$ and $\hat{p}_{high}$ are frequencies of observed prices $\boldsymbol{p} = \boldsymbol{p}_0$ 1 and $\boldsymbol{p}$

C Instructions appendix

In this appendix we give some samples of instructions used in the experiments.

C.1 Instructions for treatment $T_{30}^{\mathbf{N}}$- With simultaneous pricing, 30 uninformed

Sellers

In each market sellers post prices between 0 and 100 ECU with up to three decimal points.
Each seller posts his or her own price *without knowing* the price posted by the other sellers.

Buyers

After all the sellers have posted their prices, the robot buyers make their decisions on whom to buy their unit from.
There are two types of robot buyers: Informed and Uninformed.
In the experiment there are 70 Informed robot buyers and 30 Uninformed robot buyers.
Informed robot buyers *always* buy from the seller with the lowest price.
If one seller has the lowest price he or she gets all the 70 Informed robot buyers.
If two sellers have the lowest price each of them get 35 Informed robot buyers.

Examples

In the tables below we provide three examples of posted prices, purchases by robot buyers, and pro…ts.

Example 1	Seller	Seller	Seller
Sellers post prices simultaneously	2;000 ECU	97;000 ECU	1;999 ECU
Informed and Uninformed buyers make purchases			
Number of Uninformed buyers	10	10	10
Number of Informed buyers	0	0	70
Pro…t to each seller	10 2;000 = 20;000 ECU	10 97;000 = 970;000 ECU	(10 + 70) 1;999 = 159;920 ECU

Feedback

After each period there is a feedback screen. This screen provides information about the posted prices of all three sellers, your number of sales to Informed and Uninformed robot buyers, your pro…ts in the current period, and your accumulated pro…ts.

Earnings

After the last period is completed, your payo¤s in ECU are converted to NOK at the stated exchange rate. Your earnings in NOK will be paid in cash as you exit the lab.

Timely decisions

In the experiment you get an allocated time to make your decisions. If you use more than the allocated time, a blinking red message appears in the upper right hand side of the screen. The message reads "Please make a decision". It is important that participants don't use more than the allocated time, since the experiment will not proceed until everyone in a particular decision stage have made their decisions.

Are there any questions?

C.2 Instructions for treatment T_{30}^{Y}- With sequential pricing, 30 uninformed buyers, and 3 sellers

> *This is an economics experiment, administered by the department of economics at the school.*
>
> *In economics experiments deception is* never *used. This means that any information you are provided with in the experiment is* correct.
>
> *Experiments by other departments at the school may use deception. Whenever they do, you are told so.*

Instructions

Welcome! You are participating in an experiment ...nanced by the Department of Economics at BI and the Norwegian Research Council.

It is important that you do not talk to any of the other participants in the room until the experiment

o.ol

Sellers

Two of the sellers in a market are Incumbents while the third seller is an Entrant.
In each market sellers take decisions as follows:
First the two Incumbent sellers post prices between 0 and 100 ECU with up to three decimal points.
Each Incumbent posts his or her own price *without knowing* the price posted by the other Incumbents.
Then the Entrant observes the prices posted by the two Incumbents and posts his or her own price between 0 and 100 ECU with up to three decimal points.

Buyers

After all the sellers have posted their prices, the robot buyers make their decisions on whom to buy their unit from.
There are two types of robot buyers: Informed and Uninformed.
In the experiment there are 70 Informed robot buyers and 30 Uninformed robot buyers.
Informed robot buyers *always* buy from the seller with the lowest price.
If one seller has the lowest price he or she gets all the 70 Informed robot buyers.
If two sellers have the lowest price each of them get 35 Informed robot buyers.
If three sellers have the lowest price each of them get 23 Informed robot buyers while the last Informed robot buyer is distributed randomly to one of the three sellers.
Uninformed robot buyers make purchase decisions without regard to the prices posted in the market.
In particular, each seller will get an equal share of the uninformed robot buyers *independently* of the price he or she posts.
That is, each seller gets 10 Uninformed robot buyers independently of the price he or she posts.

Periods and matching

The experiment consists of a series of 60 periods, divided into three sequences of 20 periods each.
Each subject will be an Incumbent in two of the sequences and an Entrant in one of the sequences.
The sequence in which you are the Entrant is determined randomly.
In each new period a new market consisting of two Incumbents and one Entrant is formed randomly from participants present in the lab.
It is therefore highly unlikely that you will be in a market together with the same two participants twice in a row.

Pro…ts

Sellers face no cost when selling an item and each robot buyer has a maximal willingness to pay of 100 ECU.
The pro…t of the seller in any given period equals his/her posted price times the total number of buyers he/she gets.

Examples

In the tables below we provide three examples of posted prices, purchases by robot buyers, and pro…ts.

Example 1	Incumbent	Incumbent	Entrant
Incumbents post prices simultaneously	2;000 ECU	97;000 ECU	
Entrant observe incumbent prices and posts his/her own price			1;999 ECU
Informed and Uninformed buyers make purchases			
Number of Uninformed buyers	10	10	10
Number of Informed buyers	0	0	70
Pro…t to each seller	10 2;000 = 20;000 ECU	10 97;000 = 970;000 ECU	(10 + 70) 1;999 = 159;920 ECU

Note: The number of uninformed buyers a seller gets is 10 and is not in‡uenced by the prices of the sellers

Example 2	Incumbent	Incumbent	Entrant
Incumbents post prices simultaneously	8;000 ECU	79;000 ECU	
Entrant observe incumbent prices and posts his/her own price			8;000 ECU
Informed and Uninformed buyers make purchases			
Number of Uninformed buyers	10	10	10
Number of Informed buyers	35	0	35
Pro…t to each seller	(10 + 35) 8;000 = 360;000 ECU	10 79;000 = 790;000 ECU	(10 + 35) 8;000 = 360;000 ECU

Note: Two of the sellers both o¤er the lowest price. They share the 70 Informed robot buyers equally.

Example 3	Incumbent	Incumbent	Entrant
Incumbents post prices simultaneously	85;500 ECU	4;125 ECU	
Entrant observe incumbent prices and posts his/her own price			98;000 ECU
Informed and Uninformed buyers make purchases			
Number of Uninformed buyers	10	10	10
Number of Informed buyers	0	70	0
Pro…t to each seller	10 85;500 = 855;000 ECU	(10 + 70) 4;125 = 330;000 ECU	10 98;000 = 980;000 ECU

Feedback

After each period there is a feedback screen. This screen provides information about the posted prices of all three sellers, your number of sales to Informed and Uninformed robot buyers, your pro…ts in the current period, and your accumulated pro…ts.

Earnings

After the last period is completed, your payo¤s in ECU are converted to NOK at the stated exchange rate. Your earnings in NOK will be paid in cash as you exit the lab.

Timely decisions

In the experiment you get an allocated time to make your decisions. If you use more than the allocated time, a blinking red message appears in the upper right hand side of the screen. The message reads "Please make a decision". It is important that participants don't use more than the allocated time, since the experiment will not proceed until everyone in a particular decision stage have made their decisions.

Are there any questions?