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Abstract. We construct experimental economies, populated with human subjects, with a structure based on a nonlinear version of the New Keynesian Dynamic Stochastic General Equilibrium (DSGE) model. We analyze the behavior of firms' pricing decisions in four different experimental economies. We consider how well the experimental data conform to a number of accepted empirical stylized facts. Pricing patterns mostly conform to these patterns. Most price changes are positive, and inflation is strongly correlated with average magnitude, but not the frequency, of price changes. Prices are affected negatively by the productivity shock and positively by the output gap. Lagged real interest rate has a negative effect on prices, unless human subjects choose the interest rate, or firms sell perfect substitutes in the output market. There is inertia in price setting, firms integrate wage increases into their prices, and there is evidence of adaptive behavior in price-setting in our laboratory economy. The hazard function for price changes, however, is upward-sloping, in contrast to most empirical studies.

JEL: C91; C92; E31; E32

Keywords: Experimental Economics, DSGE Economy, Pricing Behavior, Menu Costs.

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1. Introduction

Any accurate model of the macro-economy must be able to generate the stylized facts that characterize empirical data. One important feature of the macroeconomy is the existence of consistent patterns in how firms set and update their prices over time. Motivated by the importance of micro-level pricing behavior for generating business cycles, a number of studies have documented clear empirical patterns in price setting decisions (for a survey see Klenow and Malin, 2010). In this paper, we consider which environments best reproduce a number of stylized facts about pricing. We explore the implications of different assumptions on the structure of the economy for the pricing decisions of individual firms. The environments we study all have the Dynamic Stochastic General Equilibrium (DSGE) structure, which is currently the workhorse paradigm for macroeconomic policy making.

We employ an experimental approach. The use of an experiment allows us to specify and vary the structure of the economy as desired, while permitting complete freedom for the individuals placed in the role of firms to make their pricing, production, and factor purchase decisions. The key difference between employing experimentation with human subjects, as we do here, and conducting simulations, is that we leave agents' decision making uncontrolled. For the questions of interest here, we do not wish to impose any structure exogenously on the strategies agents use. The experimental design consists of four different environments. Each environment differs from one of the others in terms of exactly one feature. This structure allows the effect of that one feature on pricing behavior to be isolated.

Our experimental economy is based on a New Keynesian DSGE model. In the DSGE framework, inertia in output prices can generate persistence of demand and supply shocks. In turn, macroeconomic events, such as shocks to demand, productivity, or monetary policy, affect pricing behavior of individual firms. There are four treatments, that vary in terms of frictions, which may potentially create price inertia, that are present in the economy. Pairwise comparisons of our treatments isolate the effect of the presence of monopolistic, rather than perfect, competition, as well as the existence of menu costs, in the output market. Another comparison between two treatments isolates the effect of discretionary interest rate setting versus strict adherence to a Taylor-type policy rule. Note that this treatment introduces another layer of uncertainty in the economy that could potentially change pricing behavior. Additionally, the shocks in the economy could be propagated in a different manner in the case of human central banker.

In our analysis, we compare pricing patterns in our data to those described in Nakamura and Steinsson (2008), Bils and Klenow (2004), and Klenow and Malin (2010), and test the hypotheses that the stylized facts they document appear in our data.[1] We then compare the behavior of the four environments. Specifically, we measure the average frequency and magnitude of price changes, and how these correlate with overall inflation. We evaluate whether positive changes are more frequent than negative changes, and by what percentage. We check how the frequency and size of price changes covary with inflation. We consider whether the hazard rate of price

[1] These studies use product-level data from the US.

changes is decreasing or increasing over time. The hazard rate of price changes indicates the probability of a price change, as a function of the length of time that the same price has been in effect.

In addition, we conduct some exploratory analysis on the data. We estimate the markup that producers charge. We analyze the effect of macro variables such as productivity, output gap, and interest rate on prices set by firms in our economy. We also evaluate how micro level variables influence prices, in particular how past prices, current wage costs, and past profitability affect the prices set by firms in different treatments. We also check whether the behavior of human central bankers is in line with the Taylor principle, i.e., the response of the nominal interest rate to inflation must be greater than 1 in the long-run.

The principal findings, which are presented in section four, are the following. Pricing patterns mostly conform to empirical stylized facts. Which treatment conforms most closely to field data depends on the specific variables considered. Most price changes are positive, with the percentage of positive changes remarkably close to that observed in field data. Inflation is strongly correlated with the average magnitude, but not the frequency, of price changes. The hazard function for price changes, however, is upward-sloping. This means that the likelihood that a firm changes its price in a period is greater the longer it has kept its price constant. This stands in contrast to most empirical studies, but is consistent with the DSGE model with menu costs (see e.g., Alvarez, Lippi, and Paciello, 2011).

Our data analysis yields a number of other basic relationships between macroeconomic variables, as well as between these variables and institutions that would be difficult to isolate in non-experimental economies. Menu costs reduce the variability of inflation. Prices are affected negatively by productivity shocks and positively by the output gap under most regression specifications. The lagged real interest rate has a negative effect on prices, unless the output market is very competitive. There is inertia in price setting, firms integrate wage increases into their prices, and there is evidence of adaptive behavior in price setting. Results regarding "central bankers" suggest that they set the nominal interest rates where they respond more than one-to-one with respect to changes in the inflation.[2]

2. Experimental Design

In this section, we describe the DSGE model that is the basis for the experimental design. Additional details about the implementation are described in the online appendices. The analysis of the macroeconomic data in the economy is reported in a companion paper (Noussair, Pfajfar, and Zsiros, 2013).

Subjects were all undergraduate students at Tilburg University. Four sessions were conducted under each treatment for a total of sixteen sessions. Six subjects participated in each session (three consumers and three producers), with the exception of sessions of the Human Central Banker treatment. In this treatment, there were 9 participants, three consumers, three producers, and three central bankers. No subject participated in more than one session. Only

[2] Engle-Warnick and Turdaliev (2010) also study the monetary policy decisions of inexperienced human subjects. They find that the sensitivity to inflation is, on average, close to or above 1 in their interest rate decisions.

one treatment was in effect in any session. The sessions consisted of $50-70$ periods,[3] and took on average roughly four hours. Participant earnings averaged 49.50 Euro (roughly 66 USD). The experiment was computerized and used the Z-Tree platform developed by Fischbacher (2007).

2.1. The DSGE model. The dynamic stochastic general equilibrium (DSGE) model is the workhorse of modern macroeconomic research and policy.[4] In the model, there are three types of agent: households, firms, and a central bank, who interact over an infinite horizon. Households choose labor supply, consumption, and savings to maximize the discounted present value of the utility of consumption and leisure. Firms choose the quantity of labor to employ, and output to produce, to maximize profits. The central bank sets the nominal interest rate to maximize a specific function of inflation and output.

Specifically, in each period, the representative consumer works, consumes, and decides on a saving level at each time t, in order to maximize the expected discounted value of her utility of consumption and leisure $u(C_t, (1-L_t))$ over an infinite horizon. The consumer solves:

$$\max E_t \sum_{i=0}^{\infty} \beta^i \left\{ \frac{C_{t+i}^{1-\sigma}}{1-\sigma} - \frac{L_{t+i}^{1+\eta}}{1+\eta} \right\}, \tag{1}$$

subject to the following budget constraint

$$P_t C_t + B_t = W_t L_t + (1+i_{t-1}) B_{t-1} + P_t \Pi_t, \tag{2}$$

where

$$C_t = \left(\int_0^1 c_{jt}^{\frac{\vartheta-1}{\vartheta}} dj \right)^{\frac{\vartheta}{\vartheta-1}}, \ \vartheta > 1. \tag{3}$$

ϑ is the elasticity of substitution in consumption in the Dixit-Stiglitz aggregator, P_t is the corresponding price index, C_t is consumption, L_t is labor supplied, i_t is nominal interest rate, B_t denotes savings, W_t is the market wage, β is the intertemporal discount factor, η is the inverse of the Frisch elasticity of labor supply, σ is the intertemporal elasticity of substitution in demand, and Π_t is the total profit of firms at t.

Firms have a stochastic production technology, given by:

$$f_{jt}(L_{jt}) = A_t L_{jt}, \tag{4}$$

where A_t is a technology shock, which is common to all firms. It has the functional form

$$A_t = A + \nu A_{t-1} + \varsigma_t, \tag{5}$$

[3] While this experiment involves very lengthy sessions compared to most experimental studies, we felt that these long sessions were appropriate for two main reasons. The first is that the complexity of the experiment required subjects to spend more time on training and practice than in the typical experiment. The second is that, because we were interested in the dynamics of price setting behavior, and prices might not be changed for long spells, we felt that a long time series was necessary to accurately observe the patterns of price changes.

[4] For a detailed discussion of the model, see the books by Walsh (2003) and Woodford (2003).

where ς_t is independent white noise $\varsigma_t \sim N(0, \delta)$. The firms' objective is to minimize their expenditure for a certain level of production:

$$\min \frac{W_t}{P_t} L_{jt}, \tag{6}$$

subject to

$$c_{jt} = Z_t L_{jt},$$

where c_{jt} is the firm's level of production of the good that it produces.[5]

There is perfect competition in the labor market, and monopolistic competition (Dixit and Stiglitz, 1977) on the output market. The market power for producers in the output market follows from the elasticity of substitution in consumption in the Dixit-Stiglitz aggregator, represented by ϑ in equation (3).

The nominal interest rate in the economy (see, for example, Woodford, 2003) is set to minimize the loss function

$$\min L = (\pi_t - \pi^*)^2 + \lambda(x_t - x^*)^2, \tag{7}$$

where π_t is actual inflation, π^* is the inflation target, $x_t - x^*$ is the output gap, and λ is a parameter that indicates the relative weight of inflation and output in policy determination.

2.2. Departures from the DGSE model. The actual model implemented in the laboratory was a modification of the DSGE model described above. The changes we made were guided by concerns about what was feasible given the resources we had available.

The standard DSGE model has no explicit timing within each period. However the implementation in the laboratory requires that some decisions be taken before others. We cannot expect the consumers to submit the full schedules of their demand of final products and supply of labor contingent on all possible realizations of other relevant variables. Therefore, we had to make a number of decisions regarding the timing of activities within a period. Here we were guided by evidence about production processes in the field (real world). We assumed that the technology shock was observed before the labor market began to operate, with the effect that it reduced the uncertainty regarding the number of units produced. After the labor market closed,[6] production took place transforming labor into output. Then producers posted prices on the output market, and consumers had an opportunity to make purchases at the posted prices.

Discounting was implemented by reducing the induced value of consumption of each of the output goods, as well as the utility cost of labor supply, by $1 - \beta = 1\%$ in each period.

[5] This optimization problem could be reformulated in terms of profit maximization, where the objective of the firm is to maximize profit in each period.

[6] The labor market was implemented with a continuous double auction trading mechanism (Smith, 1962; Plott and Gray, 1990), where consumers and producers could exchange labor. A continuous double auction market is known to generate competitive outcomes, even with a small number of agents on each side of the market (Smith, 1982).

Creating a monopolistically competitive environment in the final good market necessitated a substantive departure from the model. Direct implementation of Dixit-Stiglitz preferences, as in equation (3), is not feasible in the laboratory. This is because it requires an infinite number of goods, which in turn requires an infinite number of producers. This is not possible to implement unless we resort to having artificial agents as producers. We pursue an alternative way to create imperfect substitutability between goods, where we impose a different utility valuation of goods across consumers. Using taste shocks with different drifts for each good-consumer match we are able to create an environment, where from the point of view of each consumer, each good has a different value,[7] and partial substitutability between goods is maintained. While producers have equal market power, its overall degree is ex-ante uncertain in this environment. Therefore, we use the data from the experiment to compare the implied elasticities of substitution with the estimates that are used in the literature to investigate the actual degree of market power.

In the experiment, each consumer was endowed with an induced valuation (Smith, 1982) for the following objective function:

$$u_{it}(c_{i1t}, c_{i2t}, c_{i3t}, (1 - L_{it})) = \beta^t \left\{ \sum_{j=1}^{3} \left(H_{ijt} \frac{c_{ijt}^{1-\theta}}{1-\theta} \right) - \alpha \frac{L_{it}^{1+\epsilon}}{1+\epsilon} \right\}, \tag{8}$$

where c_{ijt} is the consumption of the ith consumer of good j, and L_{it} is the labor i supplies, at time t. H_{ij} denotes the preference (taste) shock, which is specific to each consumer and good in each period, and follows the process:

$$H_{ijt} = \mu_{ij} + \tau H_{ijt-1} + \varepsilon_{jt}. \tag{9}$$

The white noise processes ε_{1t}, ε_{2t}, and ε_{3t} are independent, and $\varepsilon_{jt} \sim N(0, \zeta)$. The preference shocks follow an $AR(1)$ process.

2.3. Treatments. Table 1 gives a summary of the differences between the four treatments.

Treatment	Monopolistic competition	Human central banker	Menu cost for price change
Baseline	Yes	No	No
Menu Cost	Yes	No	Yes
Human CB	Yes	Yes	No
Low Friction	No	No	No

Table 1: Summary of treatments

The Baseline treatment was based on the model above, but with a number of differences,

[7] For example, for the first unit of good 1 consumer 1 will get a "high level" of utility, while consumer 2 will get a "medium level" of utility and consumer 3 will get a "low level" of utility. For the first unit of good 2 consumer 2 will get the "high level" of utility, while consumer 3 will get the "medium level" of utility and consumer 1 will get the "low level" of utility, etc.

which are detailed in Appendix B.[8] The three other treatments each differed from the Baseline treatment in one aspect.

The Menu Cost treatment was identical to Baseline, except that each firm incurred a small cost if it posted a price in the output market that was different from the price it posted in the immediately preceding period.

The Low Friction treatment differed from the Baseline treatment in that the output of all firms were perfect substitutes for each other. This means that from the viewpoint of consumers, all three goods are perfect substitutes at all times, regardless of prior consumption in the current period. Thus, in effect, the parameter ϑ in equation (3) is set to ∞ or in terms of our experimental implementation H_{ijt} was replaced with H_t in equation (8).

Lastly, the Human Central Banker treatment was different from the Baseline treatment in that human participants chose the interest rate in each period.[9] They received incentivized payments based on how close actual inflation from one period to the next was to the target rate of 3 percent.

Table 2 contains a summary of parameter values used in the experiment. The parameters of the model are taken from empirical estimates when possible, with each period t corresponding to one three-month quarter in the field. Exactly the same parameters were in effect in all treatments, except for the preference shock process in the Low Friction treatment.

β	θ	ϵ	α	τ	ν	A	δ	ζ	π^*	μ
0.99	0.5	2	15	0.8	0.8	0.7	0.2	1	0.03	$\begin{pmatrix} 95 & 62 & 37.8 \\ 38.2 & 93 & 64 \\ 33 & 59.6 & 97 \end{pmatrix}$

Table 2: Parameters

3. Hypotheses

We advance four sets of hypotheses. The first asserts that treatment differences exist. The second relates to the patterns of price setting. The third concerns the relationships between prices and macroeconomic variables. The fourth hypothesis relates to the behavior of human central bankers. We evaluate the hypotheses in section four.

The first set of hypotheses relates to differences between treatments that are consequences of basic microeconomic relationships. In the Low Friction treatment the final products are perfect substitutes. Therefore, we expect that the market power of individual firms would be lower compared to a treatment with monopolistic competition, and thus the average markup would be lower. In the baseline theoretical New Keynesian DSGE model, there are no effects of menu costs on average markup, although the presence of nominal frictions produces time

[8] Appendices B, C, and D are available in online Supplementary Material at https://sites.google.com/site/dpfajfar/publications.

[9] At the beginning of each period, each of the three central bankers submits a proposed interest rate for the period. The median proposal became the interest rate in effect for the period. This procedure effectively implements the median voter's ideal point.

varying markups. There is also no reason to suppose a priori that human central bankers would have a consistent effect on markups. However, it might be expected that in the Menu Cost treatment, price changes would be less frequent compared to other treatments, because the firm pays a cost to change its price. Among the other treatments, there is no reason to suppose that the frequency of price changes would differ.

Hypothesis 1: Treatment differences (and non-differences)

(a) Hypothesis 1a: Average markups are lower under the Low Friction treatment than under the other three treatments.

(b) Hypothesis 1b: Average markups are equal in the Baseline, Human Central Banker and Menu Cost treatments.

(c) Hypothesis 1c: In the Menu Cost treatment, price changes are less frequent than in the other treatments.

(d) Hypothesis 1d: The frequency of price changes is equal in the Baseline, Human Central Banker and Low Friction treatments.

The second set of hypotheses originates in empirical stylized facts from the field. Klenow and Malin (2010) and Nakamura and Steinsson (2008) report that positive price changes are more frequent than negative changes in disaggregated data for the US. Klenow and Kryvtsov (2008) find that in their sample, also using US data, that inflation is only weakly correlated with the fraction of prices that change. The average size of changes, however, has a correlation with inflation of nearly 1. The time profile of the hazard rate of price changes has been debated in the literature. An upward sloping hazard rate would bring DSGE models more in line with the stylized facts about the behavior of inflation and output gap, see Sheedy (2010) and Alvarez et al. (2011). However, the empirical literature has mostly found that the hazard rate is not upward-sloping (see, e.g., Klenow and Kryvtsov, 2008 and Nakamura and Steinsson, 2008). Hypothesis 2 is that the empirical patterns described above would appear in our data.

Hypothesis 2: In the output markets, price changes between periods t and $t+1$ exhibit the following patterns:

(a) Hypothesis 2a: Positive price changes are more frequent than negative changes.

(b) Hypothesis 2b: The average absolute magnitude of price changes covaries strongly with inflation, but the frequency of price changes does not.

(c) Hypothesis 2c: The hazard rate of price changes is decreasing, that is, price changes are less likely, the longer the same price has been in effect.

The next hypothesis relates prices to macroeconomic variables in the economy. These are productivity, output gap, and wages. In a perfectly competitive product market, marginal revenue is equal to marginal cost, therefore if productivity increases, then prices have to decrease when wages are fixed. In a monopolistically competitive output market, similar logic drives prices to decrease as a consequence of increased productivity. However, the decrease is the smallest in the case of perfect competition on the market.[10]

Gali and Gertler (1999) and Gali, Gertler, and Lopez-Salido (2005) estimate the hybrid New Keynesian Phillips curve. Both papers find a positive and significant relationship between inflation and marginal cost. Gali and Gertler (1999) show that under certain conditions there is a log-linear relationship between the two variables. This implies a positive and significant relationship between the output gap and inflation in the US economy. Furthermore, the output gap is serially correlated. Therefore, we expect a positive sign of the lagged output gap on prices in our estimation, and a smaller effect under the Baseline than under the Low Friction treatment.[11] The empirical work discussed above serves as the basis for hypothesis 3.

Hypothesis 3: Price setting and macroeconomic variables

(a) Hypothesis 3a: Prices that individual firms charge are negatively correlated with productivity shocks.

(b) Hypothesis 3b: Prices that individual firms charge are positively correlated with the lagged output gap.

(c) Hypothesis 3c: Prices that individual firms charge are positively correlated with wages.

The fourth hypothesis concerns the behavior of the human central bankers. It is that their behavior follows the Taylor principle. The Taylor principle states that the response of the nominal interest rate to inflation must be greater than 1 in the long-run in order to guarantee determinacy (Woodford, 2003). The rationale for this hypothesis is both theoretical and empirical. Application of the principle is optimal in the New Keynesian framework, and central bank policies tend to satisfy the principle. Furthermore, the available evidence suggests that the principle is fairly transparent to typical experimental subjects in the role of central bankers in simple economies.

Hypothesis 4: Taylor Principle: Under the Human Central Banker treatment, interest rate policy follows the Taylor principle.

[10] Some empirical studies find negative estimates for the relationship between productivity and inflation. However, Cameron, Hum, and Simpson (1996) show that this negative relationship is due to a statistical bias from attempting to cointegrate stationary and non-stationary variables. They find no evidence for a connection between inflation and productivity, but do find a strong relationship between productivity growth and inflation, which is internally inconsistent, thus they claim it is implausible. There is also ambiguity about the direction of the causality between inflation and productivity. Ram (1984) finds that productivity changes have no Granger casual impact on inflation, but that inflation does have an impact on productivity. In line with economic theory, we expect a negative relationship between productivity and prices, because we can perfectly control for wage changes.

[11] Based on the discussion in the previous paragraph, the expected sign of the effect of changes in the macroeconomic variables on the probability of price change can be inferred. If a variable affects the magnitude of a price, then by definition it has to increase the probability of changing the price. However, these effects on the probability of price changes are smaller in case of menu costs, since firms have to pay an additional cost, and thus they are less likely to change prices.

4. Results

4.1. Markups and hypothesis 1a and 1b. Hypotheses 1a and 1b are mostly supported in the data. The costs of price changes, substitutability of the goods, and the manner in which policy is determined all affect average price markup levels. Low Friction generates the lowest markup among the four environments, and discretionary central banking does not have a systematic effect on markups compared to the use of a fixed Taylor rule. However, the presence of Menu Costs lowers average markups sharply. Result 1 summarizes how our results accord with Hypothesis 1a and 1b.

Result 1a: Average markups are lower under the Low Friction treatment than under the other three treatments.

Result 1b: Low Friction generates the lowest markup among the four environments. Average markups are similar in the Baseline and Human Central Banker treatments.

The markup that firms charge for their product is a measure of market power in a DSGE economy. To investigate the degree of market power in our experimental economies, we estimate the inverse demand function. This allows us to evaluate the level of monopolistic competition we have created with our experimental design across treatments and compare it to levels commonly assumed in the DSGE literature. We estimate the following inverse demand function:

$$\ln p_{jt} - \ln P_t = \frac{1}{\vartheta}(\ln C_t - \ln c_{jt}) + \varepsilon_t, \tag{10}$$

P_t is the average price and C_t is total consumption. We estimate $\frac{1}{\vartheta}$ using a panel data population average estimator with cluster-robust standard errors. $\frac{\vartheta}{\vartheta-1}$ is then the markup, according to the theoretical DSGE model. We can compare these elasticities with $\vartheta = 10$, corresponding to a markup of roughly 11%, which is a typical estimate in the DSGE literature (Fernandez-Villaverde, 2009). Table 3 shows the estimated, as well as the actual average, markups observed in the experiment. The average markup is measured as the actual profit per unit produced, divided by its price.

	Baseline	Human CB	Menu Cost	Low Friction
Elasticity of substitution in demand, ϑ	4.27	4.58	16.40	31.73
Markup implied by ϑ	30.6%	27.8%	6.5%	3.2%
Observed average markup	37.5%	37.5%	22.1%	11.1%

Table 3: Estimated elasticities of substitution in demand and markups for each treatment.

The greatest value of the elasticity of substitution in demand (ϑ), and thus the lowest markup (3.2%), is found in the Low Friction treatment. The Menu Cost treatment has a markup roughly twice as great as the Low Friction treatment. Both the Baseline and Human Central Banker treatments have much lower values of ϑ than the Menu Cost and Low Friction treatments. Their markups are 30.6 % and 27.8%, respectively. The actual markup displays similar treatment differences as the estimates, though they are typically greater in magnitude. This shows that the presence of menu costs or perfect substitutability between products decreases the market power of firms, although the effect of menu costs is smaller.[12]

This exercise enables us to assess the level of market power created in our experiment. Our implementation of perfect substitution between products is indeed close to perfect competition, though the small number of sellers still gives them a bit of market power. The monopolistic competition environment results in a fair degree of market power.

4.2. Price Changes and Hypotheses 1c, 1d and 2.

Frequency of price changes. We next evaluate the remaining two statements in Hypothesis 1 (c and d) by focusing on the overall frequency of price changes.[13] Table 4 contains a summary of the incidence and direction of price changes in our economy as a percentage of the total number of opportunities to change prices. The percentages of increases and decreases, conditional on a price change occurring, are indicated in parentheses. In our experiment, firms change their prices in 74.5% of periods on average. As a comparison, for field data, Klenow and Kryvtsov (2008) calculate that the average monthly frequency of price changes is 36.2%, or equivalently 73.8% per quarter, (under the assumption of a constant hazard rate) for posted prices between 1988 and 2005.[14] While it may be questionable to directly compare these frequencies with our experimental data due to potential differences in the definition of a period, the percentages are close to those in our data if each of our periods is compared to one 3-month quarter. Indeed, the parameters of the economy were calibrated on the basis of one three-month quarter being equivalent to one period.

Treatment	Price changes (as a % of all cases)	Positive price changes (as a % of all cases)		Negative price changes (as a % of all cases)	
All	74.5	47.5	(64%)	27.0	(36%)
Baseline	85.9	52.1	(61%)	33.8	(39%)
Human CB	84.8	52.6	(62%)	32.1	(38%)
Menu cost	40.9	31.1	(76%)	9.8	(24%)
Low friction	86.3	53.9	(63%)	32.4	(37%)

Table 4: Summary of positive and negative price changes

[12] When studying the dynamics of the actual markup we find that it tends to exhibit a slight increase over time.

[13] In all of the analyses in this paper, only the first 50 periods of each session are used. We have also conducted all of our analyses separately for the first 20 periods, and for periods 30-50 of our sessions, in order to compare early and late periods. Some modest differences appear between these two subsets of data. Similar small differences appear between each subset and the pooled data from the entire session. The average magnitude of absolute price changes tends to increase over time. Regressions analysis shows that price inertia is more pronounced in early periods. See the Appendix B in the online Supplementary Material for details.

[14] Their estimation is based on monthly data from all products in the three largest metropolitan areas in the US, from monthly data for food and fuel products in all areas, and bimonthly data for all other prices. Their estimated weighted median frequency of monthly price changes is 27.3%.

There is virtually no difference between the Baseline, Human Central Banker and Low Friction treatments (the price changes in about 85% of possible instances). Standard non-parametric tests (Wilcoxon/Mann-Whitneym, Kruskal-Wallis and van der Waerden), using sessions as observations, show no significant differences in the frequency of price changes between these treatments. However, there are significant differences between the Menu Cost and each of the other treatments at about 3% significance level. In the Menu Cost treatment, firms change their prices 40.9% of the time, which is roughly half of the average percentage of instances that firms change their prices in the other treatments. Thus, the introduction of menu costs has a significant effect on the price setting behavior of firms.

Results 1c and 1d are part of the evaluation of hypothesis 1 that concerns treatment differences.[15]

Result 1c: In the Menu Cost treatment, price changes are less frequent than in the other treatments.

Result 1d: The frequency of price changes is equal in the Baseline, Human Central Banker and Low Friction treatments.

Vermeulen, Dias, Dossche, Gautier, Hernando, Sabbatini, and Stahl (2007) find that the degree of competition affects the frequency of price changes. The greater the degree of competition, the greater the frequency of price changes, especially decreases. Here, we also find the greatest frequency of changes in the Low Friction treatment, the most competitive condition, although it is not statistically different from the Baseline treatment.

Our findings with regard to the Hypothesis 2a are summarized as Result 2a.

Result 2a: Positive price changes are more frequent than negative changes.

Nakamura and Steinsson (2008) report that 64.8% of price changes are increases.[16] This percentage corresponds closely to our experiment, as can be seen in table 4, in the values given in parentheses. In our data, 64% of price changes are price increases, and 36% are decreases. The behavior in the Menu Cost treatment is once again significantly different from the other treatments at the 5 percent level. Under Menu Cost, 76% of price changes are increases, while only 24% are decreases. The percentages in the other three treatments are not significantly different from each other. One potential reason we observe more positive price changes is that in our experiment (as in the case of the U.S.) there was on average a positive rate of inflation.

Size of price changes. Table 5 gives a summary of the average, and average absolute, price changes in the experiment. The average absolute price change, indicated in the second column of data, is 16.2% over all treatments. The average price change, shown in the first column

[15] The frequency of the price changes is similar in early and late periods of the sessions. However positive price changes are more frequent in the beginning of the sessions than at the end. 70% of the price changes are price increases in the first 20 periods (for the first 20 periods), while only 58% are increases in the last 20 periods. Negative price changes occur more often late in the sessions.

[16] They use product-level price data, as employed to construct the CPI and PPI in the US.

of data, is 2.3%. These numbers suggest that price decreases are an important component of the price setting behavior of firms. The size of average and average absolute price changes is comparable to the empirical results of Klenow and Kryvtsov (2008), who report a 14% average absolute price change, and a 0.8% average price change.

Comparison between treatments reveals that the Menu Cost and Low Friction treatments are different from the other two treatments in their price-setting behavior. Average price changes range between $0.5-1.5\%$ in the Baseline, Human Central Banker, and Low Friction treatments. For the Menu Cost treatment, the average price change is approximately 4.5%. The average absolute price change is 22.3% and 15.8% in the Baseline and Human Central Banker treatments. In contrast, it is 8.8% and 11.0% in the Menu Cost and Low Friction treatments. Therefore, both the competitiveness of the market, and the introduction of a menu cost, affect the pricing behavior of firms. The introduction of a menu cost decreases, while monopolistic competition increases, average absolute price changes. However, the variability of inflation was lower in the Menu Cost treatment compared to other treatments (Noussair et al., 2013).[17]

Treatment	Average price changes in ECU (%)		Average abs. price changes in ECU (%)		Average pos. price changes in ECU (%)		Average neg. price changes in ECU (%)	
All	1.112	(2.28%)	7.890	(16.23%)	7.364	(15.15%)	-8.813	(-18.13%)
Baseline	0.239	(0.54%)	9.921	(22.27%)	8.404	(18.87%)	-12.260	(-27.53%)
Human CB	3.270	(4.52%)	11.421	(15.80%)	12.302	(17.02%)	-9.978	(-13.80%)
Menu Cost	0.407	(1.25%)	2.865	(8.81%)	2.530	(7.69%)	-3.901	(-12.00%)
Low friction	0.694	(1.49%)	5.113	(10.97%)	4.737	(10.16%)	-5.738	(-12.31%)

Table 5: Average and average absolute price changes

Table 5 also presents the average positive and negative price changes of the experiment both in terms of experimental currency (ECU) and in percentage terms. The average positive price change is 15.2%, while the average negative price change is 18.1% in the experiment. In all treatments, except for Human Central Banker, the average magnitude of positive price changes is smaller than that of negative price changes. Thus, the experiment confirms the stylized fact that price decreases are greater than increases. However, the difference in the size of positive and negative price changes is not statistically significant in any treatment. Similarly, Nakamura and Steinsson (2008) also report that price decreases tend to be larger than increases. The median absolute size of price changes is 8.5%, the median size of price increases is 7.3%, and the median of price decreases is 10.5%.[18]

Price changes and inflation. Klenow and Kryvtsov (2008) decompose monthly inflation

[17] In Appendix, Table A4, we replicate Table 5 by showing median price changes, rather than mean values.

[18] Klenow and Malin (2010) discuss higher moments of the price change distribution. They report that the kurtosis of the distribution of price changes is 10.0 for posted prices, and 17.4 for regular prices. In our experiment, the distribution of all price changes has a kurtosis of 22.3. The kurtosis is 11.3 in the Baseline treatment, 17.4 in Human Central Banker, 119.4 in Menu Cost, and 33.1 in Low Friction. This heterogeneity confirms the differences in price setting behavior between treatments. The figures from the Baseline and Human Central Banker treatments are close to empirical findings. In the Menu Cost treatment there are more extreme price changes.

into the fraction of prices that change and the average size of those price changes. In their sample, they find that the correlation between the fraction of prices that change and the overall inflation rate is 0.25, which means that the fraction is not highly correlated with inflation. The average size of changes, however, has a correlation with inflation of 0.99, and thus comoves almost perfectly with inflation. In our data we find similar patterns. The fraction of prices changing is relatively stable and not highly correlated with inflation (0.10) in the pooled data from all treatments. However, the average magnitude of price changes has a higher correlation (0.53) with inflation. The Baseline and Human Central Banker treatments exhibit similar correlation between magnitude and inflation (≈ 0.5), while the Menu Cost and Low Friction treatments have much greater correlations of roughly 0.84 and 0.79, respectively. Generally, the Menu Cost treatment figures are the closest to the field data. There we can state the following result that corresponds to Hypothesis 2b:

> **Result 2b: The average absolute magnitude of price changes covaries strongly with inflation, but the frequency of price changes does not.**

Time Profile of Hazard Rate of Price Changes. The hazard function of price changes indicates the probability of a price change as a function of the length of time that the same price has been in effect. Intuitively, one might anticipate an upward sloping function (see Sheedy, 2010 and Alvarez et al., 2011), i.e. the longer a price has remained unchanged, the greater the probability it is changed in a given period, particularly if there is a positive underlying rate of inflation. However, different theoretical models and empirical results suggest the possibility of a flat or downward sloping hazard function. Klenow and Malin (2010) summarize the theoretical predictions for the hazard functions of different price-setting models. They show that the Calvo model assumes a flat hazard function, while the Taylor model predicts a zero hazard except at a single point in time, when the hazard is one. Furthermore, they point out that menu cost models can generate a variety of shapes. When permanent shocks are relatively more important, the hazard function tends to be upward-sloping, while transitory shocks tend to flatten or in some circumstances even yield a downward-sloping hazard function.

In the empirical literature, the general result is that hazard functions are not upward-sloping. Klenow and Kryvtsov (2008) find the frequency of price changes conditional on reaching a given age is downward sloping or constant if all goods are considered, depending on the exact specification. Nakamura and Steinsson (2008) estimate separate hazard functions for different classes of goods, and they find that hazard functions are downward sloping in the first few months and constant after that. Ikeda and Nishioka (2007), using Japanese CPI data find, contrary to previous empirical research, upward sloping hazard functions. They use a finite-mixture model and assume a Weibull distribution for price changes. They estimate increasing hazard functions for some products, and constant functions for others.[19]

[19] Ikeda and Nishioka (2007) estimate the hazard function for goods and for services separately. They assume a Weibull distribution, as we do here, but they estimate a model with heterogeneous types. Alvarez et al. (2011) derive a non-monotonic hazard function from their model. The shape of the function depends on the relative sizes of the observation costs and the menu costs in their model. Our model does not include observation costs.

Table 6 shows the differences between treatments in the duration of price spells, the number of periods that a firm's price remains unchanged. The average durations are 1.16, 1.18 and 1.16 in the Baseline, Human Central Banker and Low Friction treatments. The Menu Cost treatment has an average of 2.42, significantly different at 3% from any of the other treatments using a battery of non-parametric tests.

Treatment	Obs	Mean	Std. Dev.	Min	Max
All	2104	1.34	1.12	1	21
Baseline	612	1.16	0.45	1	4
Human CB	561	1.18	0.57	1	6
Menu cost	287	2.42	2.47	1	21
Low friction	641	1.16	0.56	1	8

Table 6: Descriptive statistics of price spells (number of periods price remains unchanged)

The slope of the hazard function can be evaluated for our data. We assume a hazard function of the following form:

$$\lambda_i(t|x_j) = \nu_i \lambda_0(t) weibull(x_{i,j}\beta), \tag{11}$$

where i indexes producers, j indexes observations, ν_i is a producer-specific random variable that reflects unobserved heterogeneity in the level of the hazard, $\lambda_0(t)$ is a nonparametric baseline hazard function, x_{ij} is a vector of covariates, and β is a vector of parameters. We assume that $\nu_i \sim Gamma(1, \sigma_\nu^2)$. As in Ikeda and Nishioka (2007), we assume a Weibull distribution in the hazard function, given by $weibull(x_{i,j}\beta) = x_{i,j}\beta \cdot h \cdot t^{h-1}$, where h is a parameter to be estimated. Under this distributional assumption, we can test explicitly whether the hazard function is upward sloping so that $h > 1$, downward sloping with $h < 1$, or constant with $h = 1$.

The independent variables in the regressions are the wage of the firm, amount of labor hired, lagged value of the firm's price, lagged value of its profit, lagged value of its unsold products, technology shock, lagged value of the real interest rate and lagged value of the output gap. Individual differences are captured by producer-specific dummies (ν_i). The hazard rate is estimated for the pooled data, for each treatment and also for each subject separately. The estimation results can be found in Table A1 in the Appendix. There are significant explanatory variables in the regressions. Wage, amount of labor hired, lagged value of unsold products, lagged profits, and a dummy for positive profit in the previous period, are significant in the regression for the pooled data from all treatments. The hazard functions in each treatment are upward sloping. When menu costs are present, average price spells are longer.[20] As shown in Table A1, the estimated values of h are about 2.5 in all treatments except under Menu Cost, where $h = 1.55$. All of these estimates are significantly greater than 1 at the 1% significance level, indicating a significantly increasing hazard rate. These results are in line with Ikeda and Nishioka (2007), though they differ from the findings generally reported in the literature.[21]

[20] Price spells can be found in Figure C1 in the Appendix C that can be found in the online Supplementary Material.

[21] We have also investigated differences between early and late periods of the sessions. The overall estimate of

Thus, we can reject Hypothesis 2c in favor of the following result:

Result 2c: The hazard rate of price changes is increasing.

4.3. Price setting, macroeconomic variables, and hypothesis 3. The statements in Hypothesis 3 receive mixed support in the data. Productivity shocks result in lower prices in the current period under all of our specifications, and thus there is strong support for hypothesis 3a. The support for a positive relation between lagged output and gap is considerably weaker, and there is no significant relationship between current wages and prices once other variables are taken into account.

Result 3a: Prices are negatively correlated with productivity shocks.

Result 3b: There is weak support for a positive correlation between prices that individual firms charge and the lagged output gap.

Result 3c: There is no significant correlation between prices that individual firms charge and wages (when controlling for other variables).

Table 7 displays regression results for the pooled data from all treatments. Separate regression results for each treatment are reported in the online Appendix C. To evaluate our hypothesis concerning the effects of macroeconomic variables on prices we specified the firm's price in period t as the dependent variable, and included productivity, the lagged output gap, and lagged real interest rate as independent variables. Moreover, we added firm-level variables such as the firm's price in the last period, the average wage it paid for a unit of labor, and its past profitability to consider price inertia and the effect of wages on price setting.[22] The estimation employs the linear dynamic panel-data GMM estimation developed by Arellano and Bover (1995) and Blundell and Bond (1998). The standard errors are clustered by session and obtained by bootstrap estimations with 1000 replications.

The productivity shock is the only macroeconomic variable that is significant and negative in all specifications in Table 7, which is in line with hypothesis 3a. The coefficient on productivity shocks is also negative and significant in all treatments when they are considered separately, except for the Human Central Banker treatment. The lagged output gap (x_{t-1}) is positive and significant in some models, but insignificant in models $3-5$ in Table 7. In fact, the estimated coefficient on the lagged output gap is positive and significant only in the Menu Cost treatment. However, this variable becomes insignificant when the interaction between lagged profits and a dummy of past positive profit is added. The sign of the variable is in line with our expectations,

h is larger in the first twenty periods of the sessions than in the last 20 periods. The same pattern is observed in the Baseline and Human Central Banker treatments. In the Menu Cost and Low Friction treatments, h becomes larger late in the sessions. Another interesting observation is that the coefficient of Π^{+}_{jt-1} is positive and significant in the most of the specifications in the late periods. This suggests that, late in the sessions, firms who had an increase in their profit in the past period are more likely to change their price, while early in the sessions, this pattern is not significant.

[22] Several variables are used to capture the past profitability of firms. See the note to Table 7 for a complete explanation.

p_{jt}	(1)	(2)	(3)	(4)	(5)	(6)	(7)
p_{jt-1}	0.8827***	0.8877***	0.8516***	0.8516***	0.8523***	0.8866***	0.8884***
	(0.0729)	(0.0669)	(0.0837)	(0.0836)	(0.0836)	(0.0677)	(0.0685)
w_{it}	0.0218	0.0237	0.0235	0.0231	0.0234	0.0236	0.0234
	(0.0284)	(0.0275)	(0.0279)	(0.0281)	(0.0282)	(0.0266)	(0.0274)
A_t	-6.8030***	-6.3637***	-7.2280***	-7.2502***	-7.0987***	-6.8342***	-7.4121***
	(2.0284)	(1.8955)	(2.2149)	(2.2121)	(2.1190)	(2.2121)	(2.3506)
x_{t-1}	0.0942*	0.0881**	-0.0037	-0.0032	-0.0096	0.1233*	0.1313**
	(0.0505)	(0.0440)	(0.0718)	(0.0711)	(0.0701)	(0.0667)	(0.0609)
i^R_{t-1}	-0.2261	-0.2204	-0.2333	-0.2331	-0.2326	-0.2232	-0.2729
	(0.1909)	(0.1852)	(0.1945)	(0.1945)	(0.1940)	(0.1938)	(0.1889)
Π^R_{jt-1}	0.0166	—	—	-0.0023	—	—	—
	(0.0356)	—	—	(0.0072)	—	—	—
D_1	—	6.1555	—	—	1.5355	—	—
	—	(4.6598)	—	—	(2.5631)	—	—
D_2	—	—	0.1142	0.1166	0.1122	—	—
	—	—	(0.0780)	(0.0810)	(0.0780)	—	—
D_3	—	—	—	—	—	1.3058	—
	—	—	—	—	—	(1.0942)	—
D_4	—	—	—	—	—	1.1653	—
	—	—	—	—	—	(1.3572)	—
D_5	—	—	—	—	—	—	0.2876
	—	—	—	—	—	—	(1.5388)
D_6	—	—	—	—	—	—	-0.854
	—	—	—	—	—	—	(0.7020)
D_7	—	—	—	—	—	—	4.4837
	—	—	—	—	—	—	(2.8642)
D_8	—	—	—	—	—	—	3.4833
	—	—	—	—	—	—	(5.5482)
$Cons.$	29.4603***	22.7210***	24.9356***	25.0267***	23.1319***	29.6074***	31.7737***
	(8.8499)	(5.6356)	(7.5684)	(7.5568)	(6.2969)	(9.7488)	(9.8564)
N	2806	2806	2806	2806	2806	2758	2758
χ^2	421	418	404	411	442	509	1104

Table 7: Regressions on prices (All treatments – pooled data). Notes: The linear dynamic panel-data GMM estimation developed by Arellano and Bover (1995) and Blundell and Bond (1998) is used for the estimation. Standard errors in parentheses. The standard errors are clustered by sessions and obtained by bootstrap estimations with 1000 replications. D_1 dummy measures whether the firm made profit in the previous period, and the effect of the amount of profit when positive profit was made in the previous period (D_2 dummy which is the interaction $D_1 \cdot \Pi^R_{jt-1}$). D_3 takes on a value of 1, if $p_{t-2} > p_{t-3}$ and $\Pi_{t-1} > 0$, and 0 otherwise. $D_4 = 1$ if $p_{t-2} < p_{t-3}$ and $\Pi_{t-1} > 0$, and 0 otherwise. D_5 is a dummy variable which equals to 1, when price increase in $t-2$ is followed by a profit increase in $t-1$. D_6 is a dummy variable which equals to 1, when price increase in $t-2$ is followed by a profit decrease in $t-1$. D_7 is a dummy variable which equals to 1, when price decrease in $t-2$ is followed by a profit increase in $t-1$. D_8 is a dummy variable which equals to 1, when price decrease in $t-2$ is followed by a profit decrease in $t-1$. */**/*** denotes significance at 10/5/1 percent level.

and the coefficient on the lagged output gap is greater in magnitude, but not significant, in the Low Friction treatment. Overall, there is some weak support for hypothesis 3b.

There is significant inertia in prices. A one ECU increase in price in the previous period results in an increase in price of about 0.85 ECU in the current period. However, its coefficient of 0.421 in the Low Friction treatment is half of the value in other treatments. Perfect competition in the output markets as in the Low Friction treatment appears to create more pressure on prices to adjust than in a monopolistically competitive market, leading firms to set prices more independently of past prices.

Lagged real interest rates are negative and significant in the Baseline and Menu Cost treatments, and positive and significant in the Human Central Banker and Low Friction treatments.

Wage enters positively and significantly in the Baseline, Human Central Banker and Low Friction treatments. Recall that wages represent the only cost of production in our economy. Firms do pass wage increases through to prices. The effect is largest (with a coefficient approximately 0.20) in the Low Friction treatment. Hence, each ECU average wage increase leads to a 0.20 ECU increase in prices.

Significant coefficients on past profit variables show evidence of adaptive behavior in price setting based on profit feedback in the Baseline, Menu Cost and Low Friction treatments. Past profit and the interaction between past profit and a positive past profit dummy are both significant and positive in the Baseline treatment. In the Menu Cost treatment, the D_5 dummy is significant and positive, which means that a firm adapts its behavior after a successful price increase in the recent past. Firms charge a 0.714 ECU higher price in period t if a past price increase in $t-2$ resulted in increased profit. Similar behavior is observed in the Low Friction treatment with a slightly smaller parameter value (0.54). This adaptive behavior is reversed in the Human Central Banker treatment, where firms significantly decrease their price after a successful price increase in the past or a greater previous period profits. Thus, hypothesis 3a is strongly supported, while 3b and 3c receive mixed support in the data.[23]

Probability of price changes. Table A3 in the Appendix contains the regression results with the probability of price change as the dependent variable. The online Appendix C reports the results for each treatment separately. It is possible to argue that prices should change in response to both a positive and negative productivity shocks. Thus, we include an additional independent variable, $\left|A_t^R\right|$, which measures the absolute magnitude of the productivity in time t compared to the steady state level of productivity. The lagged output gap and lagged real interest rate do not increase the probability of price changes except in the Baseline treatment, even though theoretical considerations and regression results on the magnitude of price changes suggest that price would increase.

A productivity shock has a negative effect on prices. The parameter for productivity is negative and significant in the pooled data as well as for the Human Central Banker and Menu

[23] We have also investigated potential asymmetries in the determinants of price setting between the beginning and the end of the sessions. Price inertia is stronger in the first 20 periods, while the productivity shock exerts a stronger impact around the end of the experiment compared to the beginning of the experiment. These results are available upon request from the authors.

Cost treatments alone. This result reveals that an increase in productivity decreases the probability of price changes and appears to occur because firms are averse to decreasing prices when they associate decreases in prices with decreases in profit. On the contrary, when productivity decreases, producers tend to increase prices, leading to a significant increase in the probability of a price change. However, the parameter on the absolute magnitude of the productivity shock is positive and significant in the pooled data. Thus a shock of greater magnitude increases the likelihood of changing the price. However, this variable is only significant in the pooled data and when firms have to pay a menu cost when they change prices. The negative and significant parameter of the D_1 dummy suggest that positive past profit makes firms less likely to change their pricing behavior in the pooled data, and in the Baseline treatment. In other treatments, this behavior is not observed. In the Low Friction treatment, none of the variables is significant except for the lagged dummy of price change. The parameter value for the lagged price change dummy suggests that a firm is more likely to change its price if the price was changed in the previous period. The presence of perfect substitution in the product market can explain why all of the dependent variables are insignificant.

4.4. Behavior of human central bankers, and hypothesis 4. Hypothesis 4 proposed that human central bankers' interest rate decisions satisfy the Taylor principle. We evaluate the hypothesis with the following regression:

$$i_t = \beta_1 i_{t-1} + (1 - \beta_1)(\beta_2 \pi_{t-1} + \beta_3 y_{t-1}) + \varepsilon_t \tag{12}$$

As in Table 7, the estimation employs the linear dynamic panel-data GMM estimator. We estimate two different specifications, one for individual decisions over interest rates (*ind*) and one for the actual interest rate (*group*) in the economy (recall that the interest rate implemented is the median choice of the subjects in the role of central bankers). The estimates of (12) are reported in Table 8.

	group	*ind*
i_{t-1}	0.9295***	0.9026***
	(0.0139)	(0.1331)
π_{t-1}	0.1517***	0.1431**
	(0.0115)	(0.0606)
y_{t-1}	-0.0170**	-0.0207*
	(0.0072)	(0.0120)
N	225	625
χ^2	5415.1	51.5

Table 8: Taylor-rule regressions. Notes: Two different specifications, one for individual decisions over interest rates (*ind*) and one for the actual interest rate (*group*) in the economy (the interest rate implemented is the median choice of the subjects in the role of central bankers). Coefficients are based on Blundell-Bond system GMM estimator. Standard errors in parentheses are calculated using bootstrap procedures (1000 replications) that take into account the potential presence of clusters in sessions. */**/*** denotes significance at 10/5/1 percent level.

The test of hypothesis 2 is whether β_2 satisfies the Taylor principle. The Taylor principle is that the response of the nominal interest rate to inflation must be greater than 1 in order to guarantee determinacy (Woodford, 2003). In our economy, determinacy is guaranteed if $\beta_1 + (1 - \beta_1)\,\beta_2 > 0$.[24] This condition is clearly satisfied in our case. β_2 in our case is 1.47, which is very close to 1.5, the coefficient originally proposed by Taylor, and β_1 is 0.90.[25,26] This indicates that Hypothesis 4 is supported.

Result 4: Under the Human Central Banker treatment, interest rate policy follows the Taylor principle.

Engle-Warnick and Turdaliev (2010) also study the monetary policy decisions of inexperienced human subjects. Their economy is a log-linearized variant of the standard DSGE model. They assume that the objective of the monetary policy is to minimize a loss function $E_t \sum_{t=1}^{\infty} \delta^{t-1}(\pi_t - \overline{\pi})^2$. They find that Taylor-type rules explain much of the variation of the interest rate decisions of subjects who successfully stabilize the economy. These subjects' (approximately 82% of all participants) behavior is consistent with interest rate smoothing, and the sensitivity to inflation is, on average, close to or above 1 in their interest rate decisions.

5. Conclusion

In this study, we construct a laboratory DSGE economy populated with human decision makers. The experiment allows us to create an economy with a structure similar to a standard New Keynesian DSGE economy, without making any assumptions about the behavior of agents. Different treatments allow us to study how the presence of menu costs and monopolistic competition affect firms' price-setting behavior.

Which of the treatment specifications conforms most closely to empirical stylized facts depends on the particular variables used in the comparison. Our results show that the stylized facts of pricing behavior documented in the field can be reproduced in a class of experimental economies, and are robust to a number of changes in the economic environment. These patterns may be general characteristics of production economies populated with human agents.

We considered whether a number of stylized empirical facts about pricing are observed in our economies. We find that price changes are frequent, occurring in 74.5% of possible instances, compared to 73.8% quarterly in US data. A majority of roughly 64% of price changes are increases, compared to 64.8% in the US data. In percentage terms, price changes are also similar to empirical estimates, and the ratio of magnitudes between the average positive and negative price change is similar. We find that the fraction of prices that change from one period to the next is not highly correlated with inflation, but the average magnitude of changes does exhibit a strong correlation with inflation. However, in contrast to most empirical studies, but

[24] The full set of conditions is given in Bullard and Mitra (2007).

[25] We also tested for a nonlinearity in policy. In particular, we considered whether there was an asymmetry in the sensitivity of interest rates to inflation, depending on whether inflation was above or below the target level of 3 percent. We found that there was no asymmetry of that form.

[26] Welfare is somewhat lower in the Human Central Bankers treatment. It is on average about 7% lower compared to the Baseline treatment.

in a manner consistent with the theoretical models of Sheedy (2010) and Alvarez et al. (2011), the hazard function of price changes is upward sloping. Menu costs, although calibrated in line with the estimations of Nakamura and Steinsson (2008), prove to be too high, and reduce the frequency of price changes considerably below the estimates from the field.

As expected, we find that price markups are lower, though still positive, when the products in the economy are perfect substitutes compared to other treatments that implement monopolistic competition. Among the latter treatments, we observe that markups are significantly lower and the elasticity of substitution in demand is greater when menu costs are introduced. The treatment with human central bankers does not significantly differ in terms of markups from the baseline specification with automated Taylor-type policy rules.

Prices are affected negatively by increased productivity, and positively by the output gap, unless monetary policy is set by human subjects. Lagged real interest rates have a negative effect on prices, except when human subjects choose the interest rate, or there is perfect competition in the output market. Price-setting behavior depends significantly on past prices, with the effect weakest when the output market is characterized by perfect competition. Wage cost increases affect prices significantly and positively, except when menu costs are present, and the effect is the strongest when there is perfect competition in the output market. Therefore, production costs are found to be a more important determinant of prices in treatments where we observe lower markups. We find evidence of adaptive behavior in price-setting; firms charge higher prices after a positive profit in the previous period, or after a successful price increase in the past, when menu costs are present.

When human subjects set the interest rates, the behavior of price setting changes significantly, although the basic stylized facts regarding the frequency of updating, proportion of price decreases, and average markups, remain the same. The behavior of human subjects in the role of central bankers is in line with the Taylor principle.

Two stylized facts that we have not been able to reproduce in our data are a downward-sloping hazard rate for price changes, and an absence of an effect of menu costs on the average markup. The upward-sloping hazard rate is intuitive in our environment, in which the central bank tried to adhere to a positive inflation target. With nominal wage costs that tend to increase over time, and competitors that can also change the prices they are charging, a firm's output price may depart considerably from its optimal level when not changed for some time. The relatively small markup under menu costs may reflect the reluctance to update prices in the face of increasing wage costs. Firms may adjust their prices too late as their markup shrinks. When they do adjust prices, they may be unwilling to do so by a sufficient amount to be able to maintain a high markup for a sufficient number of future periods, as they fear charging too high a price relative to competitors.

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Appendix

A. Additional Tables

Hazard ratio	Pooled	Baseline	Human CB	Menu cost	Low friction
p_{jt-1}	1.0000	1.0014***	0.9992*	1.0234**	0.9982
	(0.0004)	(0.0005)	(0.0005)	(0.0109)	(0.0043)
w_{it}	1.0007*	0.9981**	1.0013	0.9796***	1.0023
	(0.0004)	(0.0009)	(0.0009)	(0.0062)	(0.0015)
A_t	1.0262*	0.9684	0.9632	1.1983***	1.0226
	(0.0154)	(0.0289)	(0.0290)	(0.0521)	(0.0249)
y_{jt}	0.9311	1.3261**	0.8368	0.5055***	0.9904
	(0.0616)	(0.1497)	(0.1113)	(0.1074)	(0.1355)
x_{t-1}	1.0000	1.0040	1.0002	0.9994	1.0020
	(0.0015)	(0.0025)	(0.0029)	(0.0050)	(0.0035)
i^R_{t-1}	0.9986	0.9990	0.9921**	1.0024	0.9991
	(0.0016)	(0.0023)	(0.0032)	(0.0087)	(0.0033)
$y_{jt} - c_{jt}$	0.9777**	0.9516**	0.9875	0.9374**	0.9745
	(0.0112)	(0.0188)	(0.0238)	(0.0300)	(0.0343)
Π_{jt-1}	1.0008**	0.9996	1.0011**	0.9994	0.9994
	(0.0004)	(0.0007)	(0.0005)	(0.0018)	(0.0019)
Π^+_{jt-1}	0.6807***	0.6219***	0.7798	0.6565**	0.7041
	(0.0639)	(0.1028)	(0.1491)	(0.1379)	(0.1521)
h	2.3518***	2.6535***	2.5452***	1.5581***	2.7462***
	(0.0361)	(0.0706)	(0.0720)	(0.0648)	(0.0717)
N	2029	599	543	272	615
χ^2	29	23	17	43	22

Table A1: Parametric hazard rate regressions Notes: Standard errors in parentheses. */**/*** denotes significance at 10/5/1 percent level.

inflation	All	Baseline	Human CB	Menu Cost	Low friction
fraction	0.1043	0.0463	0.1751	0.2672	0.1434
size	0.5348	0.5522	0.4768	0.8489	0.7987

Table A2: Correlation of size and fraction with inflation

Prob. of price change	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
w_{it}	0.0003	0	0.0004	0.0005	0.0005	0	0	0
	(0.0011)	(0.0001)	(0.0012)	(0.0012)	(0.0012)	(0.0001)	(0.0001)	(0.0001)
L_{jt}	0.0118	-0.0045	0.0049	0.0028	0.0029	-0.0051	-0.004	-0.0039
	(0.0345)	(0.0062)	(0.0422)	(0.0448)	(0.0437)	(0.0069)	(0.0066)	(0.0056)
A_t	-0.4214***	-0.0491**	-0.4189***	-0.4854***	-0.4108***	-0.0506*	-0.0562**	—
	(0.1183)	(0.0227)	(0.1423)	(0.1386)	(0.1375)	(0.0263)	(0.0254)	—
$\|A_t^R\|$	—	—	—	—	—	—	—	0.0610**
	—	—	—	—	—	—	—	(0.0287)
$p_{jt-1} - \overline{p}_{t-1}$	—	0.0314	—	—	—	0.0301	0.0289	0.0297*
	—	(0.0206)	—	—	—	(0.0205)	(0.0208)	(0.0160)
x_{t-1}	—	—	0.0019	0.0035	0.0013	0.0002	0.0006	0.0001
	—	—	(0.0036)	(0.0035)	(0.0034)	(0.0008)	(0.0007)	(0.0005)
i_{t-1}^R	—	—	-0.0071	-0.0077*	-0.0072	-0.0003	-0.0004	-0.0005
	—	—	(0.0048)	(0.0046)	(0.0048)	(0.0007)	(0.0007)	(0.0005)
$y_{jt-1} - c_{jt-1}$	—	—	—	0.0509**	—	—	—	—
	—	—	—	(0.0205)	—	—	—	—
Π_{jt-1}^R	—	—	—	0.0009*	0.0005	0	—	—
	—	—	—	(0.0005)	(0.0005)	(0.0001)	—	—
D_1	—	—	—	—	—	—	-0.0640**	-0.0560**
	—	—	—	—	—	—	(0.0257)	(0.0245)
$Cons.$	—	0.9057***	—	—	—	0.9173***	0.9969***	0.7710***
	—	(0.0636)	—	—	—	(0.0974)	(0.0956)	(0.0414)
N	2757	2758	2757	2757	2757	2758	2758	2758
χ^2	14	13	14	24	14	12	23	16

Table A3: Regression on the probability of price change - All treatments. Notes: The fixed effect panel logit model is used for analyzing the probability of price changes. The standard errors in parentheses are clustered by sessions and obtained by bootstrap estimations with 1000 replications. D_1 dummy measures whether the firm made profit in the previous period. */**/*** denotes significance at 10/5/1 percent level.

Treatment	Median price changes in ECU (%)		Median abs. price changes in ECU (%)		Median pos. price changes in ECU (%)		Median neg. price changes in ECU (%)	
All	0.000	0.00%	2.000	6.98%	2.000	6.67%	-2.000	-7.59%
Baseline	0.200	1.16%	2.000	7.92%	2.000	7.14%	-3.000	-9.62%
Human CB	0.200	1.01%	1.300	8.00%	1.900	7.14%	-1.000	-8.33%
Menu cost	0.000	0.00%	2.000	6.25%	2.000	6.06%	-3.000	-7.14%
Low friction	0.100	0.68%	1.900	5.88%	2.000	6.13%	-1.600	-5.56%

Table A4: Median price changes