Frictions, persistence, and central bank policy in an experimental dynamic stochastic general equilibrium economy*

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Abstract. We construct experimental economies, populated with human subjects, with a structure based on a New Keynesian Dynamic Stochastic General Equilibrium (DSGE) model. Experimental methods provide an additional tool to study macroeconomic policy questions. They allow scope for agents' actual boundedly rational behavior and expectations to influence outcomes, while preserving the incentives and keeping the structure as close as possible to the DSGE model. We consider several specific research questions relating to the persistence of shocks, the behavior of human central bankers, and the pricing behavior of firms. We find that, in a setting where goods are perfect substitutes, there is little persistence of output shocks compared to treatments with monopolistic competition, which perform similarly irrespective of whether or not menu costs are present. Discretionary central banking is associated with greater persistence than automated instrumental rules. Interest rate policies of human discretionary central bankers are characterized by interest rate smoothing, the use of the Taylor principle, and lower output and welfare than under an automated instrumental rule. Patterns in price changes conform closely to stylized empirical facts.

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1. Introduction

New Keynesian dynamic stochastic general equilibrium (DSGE) models (see Clarida, Galí, and Gertler, 1999) are the principal paradigm currently employed for central bank policymaking. The popularity of these models lies in the rich and plausible dynamics they are able to generate, and their ability to allow policymakers to study the consequences of shocks, whether exogenous or policy-induced. Inclusion of wage or price stickiness generates short-term real effects (see, e.g., Christiano et al., 1999, 2004, 2005, and Chari, Kehoe, and Mcgrattan, 2000), and thus a meaningful and potentially beneficial role for central bank policy. With an appropriate specification of price frictions, important stylized empirical facts can be replicated (see e.g., Rotemberg and Woodford, 1997; Clarida, Galí, and Gertler, 1999; Christiano, Eichenbaum, and Evans, 2005; Smets and Wouters, 2007). A common method of introducing a price friction is to assume a menu cost (Barro, 1972, Mankiw, 1985, Ball and Mankiw, 1995, Rotemberg, 1982, Calvo, 1983), a cost that a firm must pay to change its price, in conjunction with monopolistic competition in the output market. The monopolistic competition ensures that firms earn profits, and thus that they have some discretion in the timing and magnitude of changes in the prices they set. These assumptions allow the DSGE model to conform to empirical data, while maintaining the classical assumptions of representative households and firms, who optimize and have rational expectations.

In this paper, we analyze the behavior of experimental economies, populated with human subjects, and with a structure similar to a New Keynesian DSGE model. The experimental economies conform as closely as possible to the structure of the nonlinear version of the model. Nevertheless, important differences remain, which are necessary to make the model implementable in the laboratory. The differences are described in section 2. Furthermore, we make no assumptions on agents' behavior. Instead, we give individuals monetary incentives to maximize the objective functions of the agents in the model, but allow scope for agents' boundedly rational behavior and expectations to influence outcomes. Our objective in this research is twofold. The first objective is general: it is to create an experimental environment, in which macroeconomic policy questions can be studied with a behavioral approach, to serve as a complementary tool to the methods currently employed. The second, more focused, objective of this study is to consider some specific macroeconomic research questions within our environment.

Stylized facts from empirical studies motivate the specific questions we consider. A first set of issues concerns how two particular frictions influence the persistence of shocks (Chari, Kehoe, and Mcgrattan, 2000; Jeanne, 1998). The frictions are (1) the presence of monopolistic rather than perfect competition, and (2) the existence of menu costs, in the output market. Specifically, we study whether a number of empirical stylized facts can be replicated in our experimental economies. Empirical vector autoregression (VAR) studies show that policy innovations typically generate an inertial response in inflation and a persistent, hump-shaped response in output after a policy shock (see, e.g., Christiano, Eichenbaum, and Evans, 1997; Leeper, Sims, Zha, Hall, and Bernanke, 1996). Moreover, hump-shaped responses in consumption, employment, profits, and productivity, as well as a limited response in the real wage, are robust findings. To match the empirical (conditional) moments of the data, as derived by structural VARs, nominal and real rigidities must be introduced. One way this has been done is through monopolistic competition and menu costs in the output market. Three of our experimental treatments isolate these specific rigidities in our economy. Our *Baseline* treatment differs from another treatment, *Menu Cost*, only in that in the latter, menu costs are present. Thus, we can isolate the effect of menu costs on shock persistence, while holding all else equal. We decided to implement a menu cost instead of the alternative of Calvo (1983) pricing, because the former has garnered more empirical support. The Baseline and the *Low Friction* treatments differ from each other only in that the output market is monopolistically competitive under Baseline and outputs are perfect substitutes under Low Friction. This allows us to study the effect of monopolistic competition, holding all else equal. Our treatments allow us to consider, within our setting, whether both frictions together produce more persistence than an identical economy in which the menu cost is absent, as well as than an economy in which both menu costs and monopolistic competition are absent. The experiment permits an additional potential source of friction and inefficiency, bounded rationality. The possibility exists that behavioral factors alone may cause slow market adjustment, and may be sufficient on their own to generate shock persistence, producing the stylized facts mentioned above.

A second set of issues considers the decision rules that human discretionary central bankers employ. The Taylor principle (Bullard and Mitra, 2002; Woodford, 2003c), a coefficient of responsiveness of interest rates to inflation of greater than one, has been widely advocated (Taylor, 1993, Rotemberg and Woodford, 1997, Schmitt-Grohe and Uribe, 2005). In the three treatments mentioned previously, the experimenter exogenously imposes the interest rate policy in the economy. The policy follows an instrumental inflation-targeting rule obeying the Taylor principle. However, in a fourth treatment, *Human Central Banker*, experimental subjects are placed in the role of central bankers. They are given incentives to target inflation but are free to set the interest rate in each period. While the appropriately chosen Taylor rule is effective in targeting inflation when economic agents are fully rational, it is unknown whether it would have the same effect in our economy (see Pfajfar and Žakelj, 2011). In our experiment, we consider two issues. The first is whether the interest rate policy of our subjects actually satisfies the Taylor principle. This is important because it ensures uniqueness, makes it easier to predict outcomes, and prevents coordination on an inferior equilibrium. The second issue is whether human central bankers are able to match or exceed the levels of GDP, welfare and employment, or to achieve more stability in inflation, than a simple instrumental Taylor rule.

The third set of issues we investigate concerns patterns in the pricing behavior of firms. Since pricing decisions are a key to generating persistence of policy-induced shocks, we investigate how these decisions were made in our experiment. We consider how well the experimental data conform to a number of accepted empirical stylized facts. We compare pricing patterns in our data to those described in Nakamura and Steinsson (2008), Bils and Klenow (2004), and Klenow and Malin (2010).[1] We measure the average frequency and magnitude of price changes,

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

and how they correlate with overall inflation. We evaluate whether positive changes are more frequent than negative changes, and by what percentage. We check whether the frequency of price changes covaries only weakly with inflation, while the size of prices changes covaries strongly. We consider whether the hazard rate of price changes is decreasing or increasing over time. We estimate the markup that producers charge, and check whether it decreases over time as in other experimental studies (Noussair et al., 1995, 2007). We also consider whether these patterns differ between treatments, and thus whether they are dependent on the presence of monopolistic competition or menu costs.

The experimental design, which is described in section two, employs many techniques developed and used in previous experiments that other authors have conducted.[2] Our subjects interact in both double auction (Smith, 1962) and posted offer markets (Plott and Smith, 1978; Ketcham, Smith, and Williams, 1984). Simultaneous input and output markets are operating, as in Goodfellow and Plott (1990), Noussair et al. (1995, 2007), Lian and Plott (1998), and Riedl and van Winden (2001). Saving possibilities create interdependencies between one period and the next, in a manner similar to Lei and Noussair (2002, 2007) and Capra, Tanaka, Camerer, Feiler, Sovero, and Noussair (2009). The incentives of our discretionary central bankers are similar to those studied by Engle-Warnick and Turdaliev (2010) and Roos and Luhan (2010). We implement menu costs in a manner with similarities to Wilson (1998). However, since we are guided by the structure of the New Keynesian DSGE model, we have added, when necessary, a number of new features to the economy. The structure of the economies is described in section two.

However, it is impossible to implement a model that fully conforms to the NK DSGE model in the laboratory. Several modifications, and imposition of assumptions on the timing of events, are required in order to make the model implementable in the laboratory. The modifications we made we were guided by the evidence in the empirical literature and by the functioning of field economies. The most important differences from the standard NK DSGE model relate to the existence of multiple agents, the explicit sequencing of events within a period, the structure of the demand side of the economy and the creation of the monopolistic competition, the positive level of savings, and demand uncertainty on the part of sellers. We describe each of these differences in the next section. Due to these modifications, we are not able to claim that we put the NK DSGE model under scrutiny in the laboratory. However, we believe that several of the changes outlined above could represent important avenues for further development of the theoretical DSGE model.

The principal findings, which are presented in section 4, are the following: (1) We find that in the setting where goods are perfect substitutes, there is little persistence of output shocks compared to treatments with monopolistic competition. The presence of menu costs does not significantly affect persistence. (2) Humans in the role of central banker generate considerably greater persistence of monetary policy shocks, lower persistence of output, lower output, and lower welfare than a simple automated instrumental Taylor rule. (3) Pricing patterns mostly

[2]See Duffy (2008) and Hommes (2011) for surveys of experimental macroeconomics.

conform to empirical stylized facts. Most price changes are positive, and inflation is strongly correlated with average magnitude, but not the frequency, of price changes. Menu costs reduce the variability of inflation. The hazard function for price changes, however, is upward-sloping, in contrast to most empirical studies.

We view the use of experiments as complementary to other empirical methods used in macroeconomics. Experimental methods allow researchers to create real, though synthetic, economies expressly designed to answer specific research questions. The structure of the economy is allowed to interact with the boundedly rational decisions of human agents to produce macroeconomic activity. However, many of the advantages of calibration exercises are preserved. Parameters such as production and cost functions, the timing and variance of shocks, and the number of producers and consumers, can be manipulated exogenously. Thus, the structure of the economy can conform to the model under investigation, causality can be imposed to distinguish between competing explanations for events or empirical patterns, and variables otherwise unobservable can be observed and precisely measured. Replication of an experiment is possible with multiple groups of randomly assigned subjects. This means that one can create many economies with the same underlying structure. This allows multiple observations to be gathered to enable proper statistical tests, and to allow the potential variability of outcomes to be studied. Furthermore, because subjects from the same population can be assigned to different experimental treatments, and the environment can be controlled, an experiment can be designed so that one or more institutional or environmental elements can be varied, ceteris paribus.

2. Experimental Design

This section is organized as follows. Subsection 2.1 presents the structure of the DSGE model that provides the basis for the experimental design, while subsection 2.2 describes the version implemented in the laboratory, so that the differences between model and experiment can be easily identified. Subsections 2.3 and 2.4 describe the differences between treatments and key aspects of the operational procedures, respectively.

2.1. The DSGE model. The dynamic stochastic general equilibrium (DSGE) model is the workhorse of modern macroeconomic research and policy.[3] 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 her expected discounted value of utility of

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

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, B_t denotes savings, W_t is the market wage, β is the intertemporal discount factor, and Π_t is the total profit of firms at t.

Firms have a stochastic production technology $g_{jt}(N_{jt}) = Z_t N_{jt}$, with $E(Z_t) = 1$. The firms' objective is to minimize their expenditure for a certain level of production:

$$\min \frac{W_t}{P_t} N_{jt}, \tag{4}$$

subject to

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

where N_{jt} is the labor hired by the firm j, and c_{jt} is the firm's level of production of the good that it produces.[4]

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, 2003a) is set to minimize the loss function

$$\min L = (\pi_t - \pi^*)^2 + \lambda (x_t - x_t^*)^2, \tag{5}$$

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. Experimental Implementation. 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 cognitive demands that could be imposed on the subjects and the resources we had available. The standard DSGE model has no explicit

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

timing within each period. However the implementation in the laboratory requires that some decisions be taken before others. The timing of activity is further discussed in section 2.2.7. The experiment was computerized and used the Z-Tree platform developed by Fischbacher (2007). We describe here the Baseline treatment. In subsection 2.3, we indicate the differences between the Baseline and the other three treatments.[5]

Consumers. There were $I = 3$ consumers and $J = 3$ firms indexed by i and j respectively. In the experiment, each consumer was endowed with an induced valuation (Smith, 1982) for the following objective function:

$$u_{it}(c_{i1t}, c_{i2t}, c_{i3t}, (1 - L_{it})) = \beta^t \left\{ \sum_{j=1}^{3} \left(H_{ijt} \frac{c_{ijt}^{1-\theta}}{1-\theta} \right) - \alpha \frac{L_{it}^{1+\epsilon}}{1+\epsilon} \right\}, \tag{6}$$

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:

$$H_{ijt} = \mu_{ij} + \tau H_{ijt-1} + \varepsilon_{jt}. \tag{7}$$

Here, ε_{1t}, ε_{2t}, and ε_{3t} are independent white noise processes, and $\varepsilon_{jt} \sim N(0, \zeta)$. As is standard in the DSGE literature, the preference shocks follow an $AR(1)$ process. Creating proper consumer incentives posed a methodological challenge. 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. However, 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, so we had to resort to other possible means to create imperfect substitutability between goods in the eyes of consumers. To do so, we added taste shocks with different drifts for each good-consumer match. Therefore, from the point of view of each consumer, each good has a different value, and partial substitutability between goods is maintained. As the degree of market power producers have in this environment is uncertain ex-ante, we use the data from the experiment to compare the implied elasticities of substitution with the one that are used in the literature.

Consumers faced the budget constraint

$$\sum_{j=1}^{3} c_{ijt} p_{jt} + B_{it} = w_{it} L_{it} + (1 + i_{t-1}) B_{it-1} + \frac{1}{I} \Pi_{t-1}^{N}, \tag{8}$$

where c_{ijt} is the consumption of subject i of good j at time t, p_{jt} is the price of good j at

[5] Subjects were all undergraduate students at Tilburg University. Four sessions were conducted under each treatment. Six subjects participated in each session, with the exception of sessions of the Human Central Banker treatment, in which there were 9 participants. Average final earnings to participants were 43.99 euros. No subject participated in more than one session. Only one treatment was in effect in any session.

time t, w_{it} is the wage of subject i at time t, B_{it} is the saving of subject i at period t, Π^N_{t-1} is the total nominal profit of firms in period $t-1$, and $I = 3$ indicates the number of consumers in the economy. Π^N_{t-1} appears in the budget constraint, in accordance with the DSGE model assumption that the households own the firms. Therefore, at the end of each period in the experiment, the total profits of firms were transferred to, and divided equally among, the three consumers. We did not constrain savings to be on average zero as in the DSGE literature. We allow for positive levels of savings and give an initial amount of money to each subject in the experiment. We do so because saving is an important component of the intertemporal decision problems that each individual faces in the field.

Producers. In each period t, the payoff of firm j was given by:

$$\Pi^R_{jt} = (p_{jt}y_{jt} - w_{jt}L_{jt})\frac{P_0}{P_t}, \tag{9}$$

where Π^R_{jt} denotes real profits, p_{jt} is the price, y_{jt} is the quantity of good sold, w_{jt} is the wage payed, and L_{jt} is the labor purchased and employed by firm j in period t. P_t is the price level in period t, while P_0 is the price level in the initial period. Therefore, $\frac{P_0}{P_t}$ is a deflator that translates nominal profits into real terms. Firms were given incentives to maximize real profits as each p_{jt} has a nonnegligible effect on the overall price level P_t.

All firms were endowed with the same production technology, given by:

$$f_{jt}(L_{jt}) = A_t L_{jt}, \tag{10}$$

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

$$A_t = A + \nu A_{t-1} + \varsigma_t, \tag{11}$$

where ς_t is independent white noise $\varsigma_t \sim N(0, \delta)$. A_t follows an AR(1) process, as is standard in the DSGE literature. In each period, each firm j chose how much labor to employ, L_{jt}, and its product price, p_{jt}.

Labor market. The standard DSGE model assumes perfect competition on the labor market. This 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). The market was open for a fixed period of time, during which agents could submit offers to purchase and sell units. Offers were posted publicly. At any time, any trader could accept a quote submitted by an individual on the other side of the market. Trade in both the labor and the output markets took place in terms of an experimental currency, called ECU.

The cost of supplying labor was known only privately to consumers, while information on current productivity was private information for producers. The motivation for this departure from the standard NK DSGE model lies in previous evidence in the experimental literature, where it has been shown that convergence to competitive equilibrium in double auctions occurs faster when asymmetry in information is present (for a discussion on this see Smith, 1994). To further facilitate the convergence to the competitive equilibrium a relatively steep disutility function of labor was employed in the experiment.

Output market. On the product market, the three different goods were imperfect substitutes, due to the product specific H_{ijt} taste shocks of consumers. This ensured that each firm had some monopoly power in the market, as in the monopolistic competition assumed in the DSGE model. The market was organized as a posted offer market. Each producer sold her product in a separate market, and the three markets operated simultaneously. Producers set prices before observing the prices of their competitors. After prices were set, consumers could purchase the products on a first-come first-served basis. Products were consumed immediately upon purchase. Producers were required to bring their entire production to market. Unsold units could not be carried over to the next period. The main difference from a standard NK DSGE model on the producer side was that the demand for products was not known in advance. Producers can only learn the average demand they face over time.

Monetary policy. The nominal interest rate was exogenously set according to the Taylor rule,

$$i_t = \pi^* + \kappa(\pi_{t-1} - \pi^*) + \varrho_t, \tag{12}$$

where ϱ_t is i.i.d. and the parameters were set to $\kappa = 1.5$ and $\pi^* = 3\%$. This is a simplified version of the Taylor rule that found widespread support in the empirical literature.

Parameters. Table 1 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 (see Appendix A1).

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 1: Parameters

Each consumer was endowed with 1500 ECU of cash at the beginning of period 1 that could be used for purchases. In each period, each consumer was endowed with 10 units of labor. Producers had no initial endowment of labor or cash. However, they could borrow at the beginning of a period (interest free) in order to purchase labor, and thus were not cash-constrained.

Timing within a period. The experiment was divided into a sequence of periods. Each period corresponded to a time period t in the DSGE model. At the beginning of each period, producers observed the realization of their own productivity shock for the period. The labor market was then opened and operated for 2 minutes.[6] After the market was closed, production occurred automatically, transforming all of the labor that producers purchased in the period into output.

As mentioned previously, while the labor market was open, the cost of supplying labor was known only privately to consumers, while information on current productivity was private information for producers. For consumers, the history of the wages they received, the average wage in the economy, the quantity of labor they sold, the inflation rate, the interest rate, and the output gap were displayed while the market was in operation. For producers, the history of the wages they paid, the wages in the economy, the quantity of units of labor they hired, and the same macroeconomic variables as shown to consumers, were displayed.

After the labor market closed for the period, the product market opened. Producers simultaneously posted their prices. Subsequently, consumers received the posted prices and information on their current budget level, the interest rate, their valuations of each good, and the ratio of their marginal valuation and the posted price for each good. Before setting their prices, producers observed the actual labor they hired, the quantity of output that the labor produced, the total and average cost of production, and the interest rate. When posting prices, producers had access to the history of own sales, prices, labor expenses, profits, and a number of macroeconomic variables. After the consumers finished their purchases, the period ended. At the end of each period, consumers received information about their current earnings and the budget they would have available for the next period. Producers were informed of their profits, production, and sales.

In the NK DSGE model all of the above phases, with the possible exception of the realization of the shocks, occur at the same time. This is not feasible to implement in the laboratory, as we cannot expect the consumers to give the full schedules for their demand of final products and supply of labor contingent on all possible realizations of other relevant variables. Therefore, we had to make an assumption regarding timing. Here we were guided by evidence about production processes in the field. 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.

Timing of sessions and incentives. Each session took between 3 3/4 and 4 3/4 hours. A session consisted of instruction and two sequences of periods. After the instructions were read to subjects, which lasted approximately 45 minutes, the first sequence began. The first sequence consisted of 5 practice periods, and did not count toward the subjects' final payment. The next sequence, which constituted the experimental data retained for analysis, consisted of $50-70$ periods, and determined the final payment of the subjects. A random ending rule was used to end the session, with the final period drawn randomly from a uniform distribution. Subjects did not know the process used to end the session, but were told it would end randomly after period 50. The random ending rule ensured that a fully rational agent, with the payoff

[6] This was shortened to 1.5 minutes and then to 1 minute in later periods.

function given in equation (6) in each period, would be incentivized to maximize the objective function of equation (1).

Participants in the role of consumers received a monetary payment for the session, in Euros, in proportion to the sum of the values of (6) they attained over all periods. Valuations for output and costs of labor supply were expressed in terms of 100^{th}'s of a euro cent on subjects' screens. It is important to keep in mind that, in contrast to most other studies of experimental markets, the currency used for transactions, ECU, did not translate directly into the earnings that participants in the role of consumers received (see Lian and Plott (1998) for a similar implementation). There were, however, strong indirect incentives for consumers to maximize currency holdings, since currency was required to purchase the products that did yield value for them. ECU earned interest at rate i_t between periods t and $t+1$.

The savings that consumers held at the end of the session were converted from ECU to euros (1 euro = 1.44 US dollars at the time of this writing) in the following manner. We assumed that the experiment would continue forever, with the valuations and costs continuing the downward trend they followed during the session. We calculated how much a consumer would have earned if she made the best possible savings, labor sale, and product purchase decisions possible, given the savings she had at the end of the session. The average prices for labor and products over the course of the session were used for the calculation. The resulting euro earnings were awarded to the participant.[7]

Participants in the role of producers received a real monetary payment for the session, in Euros, in proportion to the sum of the values of (9) they realized over all periods. Although the ECU profit was removed from the firm's balance and added to the currency balance of the consumers at the end of each period, the profits were awarded to the participant on paper. These profits were translated into real monetary payments to the human participant in the role of the firm. This was required to create the same incentives and structure as in the theoretical model.

2.3. Treatments. Table 2 gives a summary of the differences between 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 2: Summary of treatments

The Human Central Banker treatment. Section 2.2 described the Baseline treatment. The Human Central Banker treatment was identical to the Baseline treatment, except that

[7]For consumers, payoffs equalled the sum of the values of equation (6) attained over the life of the economy, plus the payout based on final savings. For producers, the conversion rate from their profits in terms of ECU to euro was 100 ECU to 1 Euro.

three additional human subjects were placed in the role of central banker. Their task was to set the interest rate. Each of the central bankers submitted a proposed nominal interest rate simultaneously at the beginning of each period. The median choice was adopted as the interest rate for the current period. Central bankers were given incentives to attain an inflation rate as close as possible to 3% in each period. They were incentivized with the following loss function:

$$\text{Central Banker's Payoff}_{lt} = \max\left\{a - b(\pi_t - \pi^*)^2, 0\right\}, \tag{13}$$

where $a = 100$, $b = 1$ and $\pi^* = 3\%$. The conversion rate from payoffs to euro earnings was 1 to 100. Therefore, if the inflation rate was 3 % in a given period, then each central banker earned $100 \cdot \frac{1}{100} = 1$ euro in that period. This payoff function gives incentives to central bankers to minimize the loss function in equation (5) with $\lambda = 0$, and thus to engage in inflation targeting. At the time they made their choice, central bankers had the history of interest rates, inflation, and the output gap available on their screens.

The Menu Cost treatment. This treatment differed from Baseline only in that if a producer set a price in period t, which was different than the one he set in period $t-1$, he had to pay a menu cost equal to

$$M_{jt} = \omega p_{j,t-1} y_{jt}, \tag{14}$$

where

$$\omega = 0.025. \tag{15}$$

p_{jt} is the price that producer j chose in period t, and $y_{j,t-1}$ is the quantity of sales of producer j in the previous period. The calibration of the menu cost is based on Nakamura and Steinsson (2008). Producers who do not change their prices are not required to pay the cost. The menu cost is subtracted from the producers' nominal profit (in ECU) at the end of each period.

The Low Friction treatment. The Low Friction treatment was identical to the Baseline treatment, except for the specification of the utility function and the preference shock process for consumers. The payoffs for consumers in period t were given by

$$u_{it}(c_{i1t}, c_{i2t}, c_{i3t}, (1 - L_i t)) = \beta^t \left\{ H_t \frac{\left(\sum_{j=1}^{3} c_{ijt}\right)^{1-\theta}}{1-\theta} - \alpha \frac{L_{it}^{1+\epsilon}}{1+\epsilon} \right\}, \tag{16}$$

with the following identical preference shocks for all consumers:

$$H_t = \mu + \tau H_{t-1} + \varepsilon_t, \tag{17}$$

where $\mu = 120$, ε_t is an independent white noise process, and $\varepsilon_t \sim N(0, \zeta)$. The specification of the shocks ensured that consumers valued all three goods as perfect substitutes. In this paper, despite the small number of sellers, we view this situation as one close to perfect competition.[8]

[8] In experimental posted offer markets for perfect substitutes, convergence to Nash equlibrium price levels tends to occur, and collusion among sellers is rarely observed (see, e.g., Holt, 1995).

This assertion is supported in the sense that the average price markup in this treatment is low (see section 4.2)

The parameters of the economy were calibrated so that the welfare of consumers in the Low Friction and Baseline treatments was approximately identical, under certain assumptions.[9] As in the Baseline treatment, the institution on the product market was a posted offer market with a separate market for each firm's product.

3. Hypotheses

We advance three hypotheses here. They are evaluated in section four, which also contains an exploratory analysis of the data. The hypotheses are derived from empirical stylized facts from the field, from behavior of the theoretical DSGE model, and from previous experimental results. The first hypothesis concerns differences in the persistence of shocks between treatments. In the New Keynesian model, both menu costs and market power are required for a policy induced shock to exhibit an effect beyond the current period. On the other hand, productivity and taste shocks have persistent effects on output, inflation and interest rates. Thus, we hypothesize that inflation and output would be persistent in all treatments. Only in the Menu Cost treatment, would monetary policy shocks be persistent.

Hypothesis 1 - Persistence: Shocks to inflation (demand), and output (productivity) have persistent effects on themselves and all other variables in all treatments. Policy (interest rate) shocks have persistent effects on output and inflation in the Menu Cost treatment. These shocks do not have persistent effects in the Baseline, and Low Friction treatments.

The second hypothesis concerns the behavior of the human central bankers. It is that their behavior follows the Taylor principle. 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.[10]

Hypothesis 2 - Taylor Principle: Under the Human Central Banker treatment, interest rate policy follows the Taylor principle.

[9] This calibration was conducted in the following manner. The economy was simulated, assuming a markup of 11 percent, under the assumption that firms and consumers optimize for the current period. The resulting welfare is calculated and the initial shock parameters are chosen so that welfare in Low Friction is equal to that in Baseline.

[10] 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.

The third hypothesis concerns pricing patterns in the economy. We consider whether several stylized facts from the field, documented by Nakamura and Steinsson (2008), Bils and Klenow (2004), and Klenow and Malin (2010), appear in the experiment.

Hypothesis 3 - Pricing Behavior: In the output markets, price changes between periods t and $t+1$ exhibit the following patterns: (a) Positive price changes are more frequent than negative changes. (b) The average absolute magnitude of price changes covaries strongly with inflation, but the frequency of price changes does not. (c) The hazard rate of price changes is increasing, that is, price changes are more likely, the longer the same price has been in effect.

4. Results

This section is organized into five subsections. In subsection 4.1, we describe and illustrate some of the overall patterns in the data. In sections 4.2 and 4.3, we evaluate hypothesis one. We consider the extent to which our economies exhibit frictions, and whether there are treatment differences. We analyze price markups, compute contemporaneous and intertemporal correlations between macroeconomic variables, estimate a vector autoregression (VAR), and compare the resulting impulse response functions, to measure shock persistence. In section 4.4, we study the behavior of the human central bankers, and test hypothesis two. In section 4.5, we investigate firms' output pricing decisions, and test for the pricing patterns listed in hypothesis three.

4.1. Overall patterns and treatment differences in output, welfare and inflation. Figure 1 shows the real GDP of the economy in each treatment, averaged over the four sessions comprising the treatment. All treatments have similar GDP at the beginning of the sessions, until roughly period 10. The Baseline and the Human Central Banker treatments have comparable GDP until period 30. After period 30, the Human Central Banker treatment stabilizes at under 600 ECU, which is the lowest among all treatments. On average, GDP is similar under the Menu Cost and the Baseline treatments. This suggests that menu costs do not affect the real GDP of the economy. GDP is greatest in the Low Friction treatment, where it varies between 800 and 1000 ECU until period 36. Afterwards, period GDP drops and stabilizes at roughly 700 ECU.[11] However, this drop is solely a product of the shocks, which can be observed from the time path the simulated data under the Baseline treatment that is also shown in figure 1.[12]

The welfare in the economy is shown in Figure 2 for the four treatments. Welfare is defined as the sum of the utilities, as expressed in equation (6), of the three consumers in each period. Welfare is on average greatest under the Low Friction treatment. It is similar in the other three treatments, except for the last 20 periods, when Human Central Banker has the lowest welfare. Average welfare in the Baseline and Menu Cost treatments has a similar time profile. The overall pattern suggests that a frictionless economy is strictly preferable from a welfare point of

[11] There is no source of growth in the economy, so there is no reason for GDP to increase over time.

[12] The model is solved and simulated under the assumption that firms employ a 20% markup over costs.

view, and that our instrumental rule is performing better than human central bankers.[13]

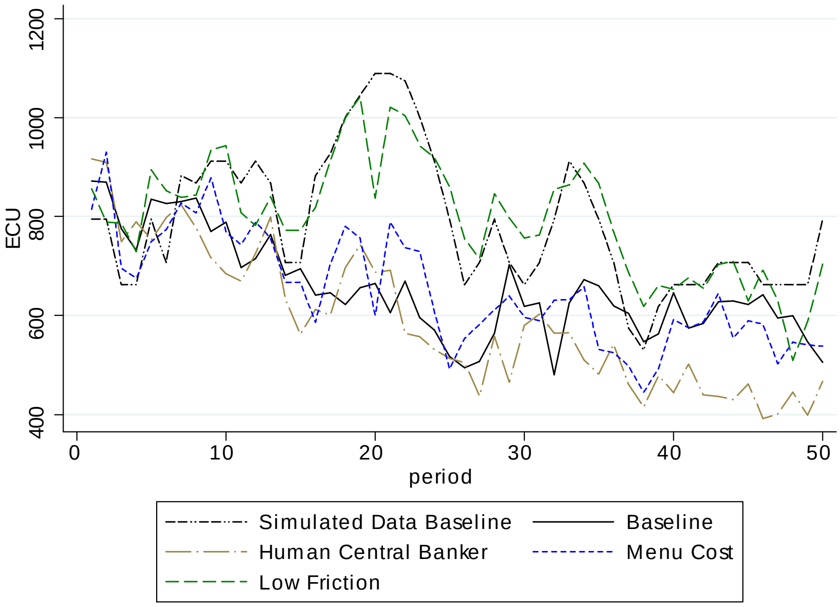

Figure 1: Real GDP across treatments

Nonparametric tests confirm the impression conveyed in the figures. Specifically, under the Low Friction treatment, we observe significantly higher employment, real GDP, and welfare, than in any other treatment. The Human Central Banker generates significantly lower welfare, real GDP and employment than any other treatment. There are no significant differences between the Baseline and Menu Cost treatments.

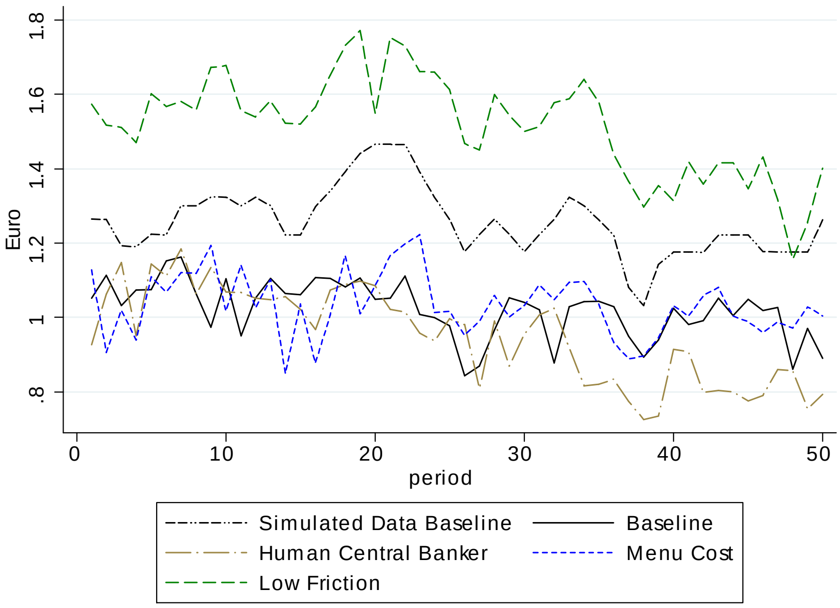

Figure 2: Welfare across treatments

[13]The Human Central Banker treatment performs significantly better than the simulated data for the Baseline treatment, mainly due to different markups in the two environments. A lower markup is associated with a greater quantity of output exchanged and therefore with higher welfare.

The average inflation rate is similar in all four treatments, ranging between −15% and +16%, except for three outlier periods. Nonparametric tests fail to reject the hypothesis that the level of inflation is the same between any pair of treatments. Comparing the variances of inflation between different treatments, however, indicates that the variance is the lowest in the Menu Cost, followed in turn by the Low Friction, Human Central Banker and Baseline treatments. All of the differences are statistically significant according to the Levene (1960) test.

Thus, from a welfare point of view, menu costs have an ambiguous effect. On one hand, they reduce inflation variance, which has positive effect on welfare (see Woodford, 2003b). On the other hand, the costs themselves are a deadweight loss to the economy, since they are deducted from producer profits and thus from consumer cash holdings. In the experiment, the two effects on welfare appear to roughly offset each other.

4.2. Frictions and Persistence of Shocks.

Markup. One measure of friction in a DSGE economy is the markup that firms charge for their product. In our experimental economies, we are able to estimate the inverse demand function implied by the Dixit-Stiglitz aggregator in the theoretical model, and use it as a measure of market power. This allows us to evaluate the level of monopolistic competition we have created with our experimental design and compare it to levels commonly assumed in the DSGE literature. We can thus consider differences, between treatments, in the level of friction the observed economic activity implies. We estimate the following inverse demand function:

$$\ln p_{jt} - lnP_t = \frac{1}{\vartheta}(\ln C_t - \ln c_{jt}) + \varepsilon_t, \tag{18}$$

P_t is the average price in period t and C_t is the total consumption in period t. 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 table reveals that the average markup observed in the economy is between 7−15% higher than the one implied by the estimations of the inverse demand functions. The Low Friction treatment has the highest value of the elasticity of substitution in demand (ϑ), and thus the lowest markup, 3.2%. 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. The estimated markup levels are 30.6 % and 27.8% respectively, in these treatments. 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 a menu cost is smaller. The markup tends to exhibit a slight increase over time.

This exercise enable us to assess the level of market power created with our implementations of monopolistic competition and perfect substitution between products. The latter is indeed close to perfect competition, though the small number of sellers still gives them a small amount of market power. The former environment results in a fair degree of market power.

Persistence and Correlations. We begin our analysis with the cross-correlations of output with other variables, in order to study the functioning of these economies and to compare them to the results from the field. We then examine the persistence of shocks using structural vector autoregressions.

variable	rho	Cross-correlation of output with							corr with
		t-3	t-2	t-1	t	t+1	t+2	t+3	i_t
Baseline									
GDP (Y_t)	0.504	0.190**	0.208**	0.162*	0.209**	0.102	0.134*	0.087	0.291***
real GDP (Y_t^r)	0.805	0.716***	0.751***	0.805***	1	0.802***	0.737***	0.696***	0.132*
real GDP gr. (Y_t^{rg})	-0.094	-0.049	-0.090	-0.290***	0.049	0.029	0.001	0.001	0.029
output gap (x_t)	0.757	0.574***	0.625***	0.698***	0.928***	0.721***	0.663***	0.627***	0.216***
total hours (L_t)	0.713	0.684***	0.670***	0.718***	0.828***	0.629***	0.612***	0.583***	0.176**
savings (B_t)	0.992	0.070	0.103	0.136*	0.144*	0.152*	0.158*	0.169*	0.032
real wages (W_t^{rr})	0.952	0.405***	0.388***	0.350***	0.350***	0.310***	0.254***	0.221***	-0.340***
prices (P_t)	0.875	0.109	0.089	0.065	0.027	0.003	0.012	0.000	0.302***
inflation (π_t)	0.467	0.227***	0.149*	0.235***	0.216***	0.206**	0.281***	0.274***	0.460***
prod. avg. markup	0.958	-0.344***	-0.314***	-0.264***	-0.236***	-0.227***	-0.205**	-0.176**	0.308***
welfare (u_t)	0.971	0.552***	0.543***	0.532***	0.537***	0.494***	0.448***	0.434***	0.030
Human Central Banker									
GDP (Y_t)	0.920	0.088	0.090	0.097	0.144*	0.120	0.131	0.151*	0.497***
real GDP (Y_t^r)	0.865	0.791***	0.810***	0.865***	1	0.864***	0.799***	0.776***	0.164*
real GDP gr. (Y_t^{rg})	-0.219	-0.105	-0.176**	-0.291***	0.195**	0.058	-0.010	-0.012	0.030
output gap (x_t)	0.771	0.638***	0.667***	0.746***	0.928***	0.763***	0.692***	0.671***	0.244***
total hours (L_t)	0.797	0.717***	0.738***	0.770***	0.863***	0.731***	0.692***	0.677***	-0.091
savings (B_t)	0.999	-0.054	-0.063	-0.056	-0.055	-0.048	-0.041	-0.039	0.107
real wages (W_t^{rr})	0.899	0.491***	0.466***	0.441***	0.462***	0.421***	0.362***	0.302***	0.004
prices (P_t)	0.990	0.011	0.007	0.011	0.014	0.036	0.049	0.062	0.418***
inflation (π_t)	0.218	0.162*	0.196**	0.193**	0.112	0.132*	0.097	0.039	0.136*
prod. avg. markup	0.951	-0.591***	-0.571***	-0.541***	-0.545***	-0.530***	-0.503***	-0.479***	-0.005
welfare (u_t)	0.945	0.615***	0.607***	0.613***	0.604***	0.578***	0.550***	0.525***	0.136*

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

Table 4: Cross-correlations for the Baseline and Human Central Banker treatments

Persistence of output shocks and cross-correlation with other variables. In tables 4 and 5, as is traditional in the RBC literature (see e.g. Cooley and Prescott, 1995), we report the cross-correlations of output with other macroeconomic variables in the experiment. These illustrate the functioning of the monetary policy transmission mechanism. Comparison of the magnitudes of the correlations in the second row of data for each treatment shows that persistence of real GDP is lowest in the Low Friction, and greatest in the Human Central Banker, treatment. The other two treatments produce a similar degree of persistence in real GDP.

The output gap and labor employed (which can be thought of as total hours worked) are highly correlated with output contemporaneously, as well as at all leads and lags. This can be observed in the fifth row of the data for each treatment in tables 4 and 5. The weakest cross-correlations occur in the Low Friction treatment. Savings are at best only weakly correlated with output. An exception is the Low Friction treatment, where highly significant countercyclical behavior is observed. The strongest correlation is between lagged savings and current output. The negative sign is rather unexpected as one might expect savings to be procyclical. Except in the Menu Cost treatment, real wages exhibit significant positive cross-correlation with output of $0.3 - 0.5$, similar values to those found in field data.

The strength of the correlation between price level and output differs between treatments. In the Baseline and Human Central Banker treatments, there is no significant correlation, while in the Menu Cost and Low Friction treatments we observe a highly significant negative relationship. This is especially pronounced in the Menu Cost treatment, where cross-correlations reach values between -0.6 and -0.7. In the field, negative correlations of similar magnitude are typically observed. Kydland and Prescott (1990) argue that the negative contemporaneous relationship between output and prices suggests that supply shocks have prevailing effects over demand shocks. This is also the case in our experiment. Another factor that is intimately related to this correlation is price stickiness. As pointed out by Ball and Mankiw (1994), even if the demand shock is prevalent, it is possible to observe negative correlations if there are frictions in the price setting mechanism. This can explain the weaker cross-correlations in Menu Cost, compared to the three other treatments.

Correlations between interest rate and other variables. The correlations between nominal interest rates and other variables illustrate the influences on, and the effects of, monetary policy. There is some heterogeneity across treatments. Nominal GDP is positively correlated with interest rate in all treatments, except for Menu Cost. In the field data, positive correlation of similar magnitude to that in the Baseline treatment is typically observed. Positive correlations are also observed between interest rate and output gap in the Baseline and Human Central Banker treatments. In the remaining two treatments, these correlations are not significant. Nominal interest rate and real GDP growth are negatively correlated. The correlations are weakly significant in the Menu Cost and Low Friction treatments, but insignificant in the Baseline and Human Central Banker treatments. The correlation between interest rate and real wage is only significant (negatively) in the Baseline treatment. Price level and inflation

variable	rho	Cross-correlation of output with							corr with
		t-3	t-2	t-1	t	t+1	t+2	t+3	i_t
Menu Cost									
GDP (Y_t)	0.724	0.052	0.086	0.119	0.339***	0.107	0.116	0.066	-0.070
real GDP (Y_t^r)	0.770	0.706***	0.746***	0.770***	1	0.767***	0.734***	0.694***	-0.041
real GDP gr. (Y_t^{rg})	-0.339	-0.064	-0.033	-0.361***	0.217***	0.026	0.017	0.005	-0.150*
output gap (x_t)	0.627	0.539***	0.595***	0.637***	0.940***	0.661***	0.629***	0.585***	-0.124
total hours (L_t)	0.723	0.657***	0.654***	0.672***	0.827***	0.639***	0.658***	0.657***	0.079
savings (B_t)	0.987	0.098	0.091	0.087	0.093	0.104	0.105	0.092	-0.029
real wages (W_t^{rr})	0.227	0.081	0.072	0.048	0.115	0.162*	0.160*	0.155*	-0.090
prices (P_t)	0.987	-0.675***	-0.684***	-0.682***	-0.684***	-0.675***	-0.644***	-0.646***	-0.040
inflation (π_t)	0.308	0.249***	0.186**	0.192**	0.107	0.014	0.081	0.162*	0.245***
prod. avg. markup	0.805	-0.175**	-0.175**	-0.110	-0.086	-0.102	-0.142*	-0.204**	0.087
welfare (u_t)	0.827	0.465***	0.472***	0.489***	0.510***	0.479***	0.391***	0.353***	0.160*
Low Friction									
GDP (Y_t)	0.923	-0.196**	-0.220***	-0.219***	-0.116	-0.258***	-0.281***	-0.274***	0.240***
real GDP (Y_t^r)	0.610	0.515***	0.504***	0.610***	1	0.622***	0.529***	0.561***	-0.051
real GDP gr. (Y_t^{rg})	-0.312	-0.007	-0.100	-0.450***	0.355***	0.118	-0.024	0.098	-0.142*
output gap (x_t)	0.537	0.360***	0.356***	0.489***	0.938***	0.535***	0.428***	0.462***	-0.072
total hours (L_t)	0.413	0.460***	0.364***	0.393***	0.715***	0.317***	0.270***	0.335***	0.057
savings (B_t)	0.995	-0.196**	-0.195**	-0.210***	-0.193**	-0.188**	-0.189**	-0.182**	0.018
real wages (W_t^{rr})	0.503	0.144*	0.206**	0.284***	0.358***	0.248***	0.222***	0.231***	-0.027
prices (P_t)	0.999	-0.333***	-0.348***	-0.369***	-0.376***	-0.407***	-0.409***	-0.409***	0.206**
inflation (π_t)	-0.113	0.208***	0.179**	0.174**	0.201**	-0.015	0.038	0.087	-0.05
prod. avg. markup	0.853	0.044	0.082	0.105	0.178**	0.174**	0.095	0.081	-0.026
welfare (u_t)	0.882	0.541***	0.540***	0.551***	0.575***	0.533***	0.509***	0.513***	-0.050

$^*p < 0.05$, $^{**}p < 0.01$,$^{***}p < 0.001$

Table 5: Cross-correlations for the Menu Cost and Low Friction treatments. Note: See Appendix A for detailed definition of variables.

are significantly positively correlated with interest rate in the Baseline and Human Central Banker treatments. In the Low Friction treatment, the correlation is only significant for the price level. Under Menu Cost, it is significant only for inflation. The field evidence regarding these correlations is mixed, but usually found to be weaker in magnitude than in the Baseline treatment. Prices and wages tend to comove in the field, as well as in our experiment, except for the Baseline treatment.

The Phillips Curve. Cross-correlations between inflation and output, shown in the ninth row of the data for each treatment in tables 4 and 5, are only significant for lags of inflation. The only exception to this pattern is the Baseline treatment, which exhibits significant procyclical behavior for all leads and lags, but most strongly at t+2 and t+3. The cross-correlations between markup and output show quite a different pattern. In the Baseline and Human Central Banker treatments, the correlations are significantly negative, while in the Low Friction treatment they are significantly positive. In the former treatments, producers exploit their market power. This leads to a reduction in output. In Low Friction, however, this cannot occur due to fierce competition in the output market. As shown in table 3, the markups were indeed greatest under Baseline and Human Central Banker. In the Menu Cost treatment, the correlations are negative and only significant at long leads and lags. Generally, the cross-correlations are greater for leads than for lags of inflation. This is consistent with the fact that technology shocks are relatively more important for business cycle fluctuations than demand shocks. In all treatments, as shown in the last row of the data for each treatment in tables 4 and 5, the cross-correlations with welfare are positive and highly significant (between $0.5 - 0.6$).

	inflation						
gap	t-3	t-2	t-1	t	t+1	t+2	t+3
Baseline treat.	0.309***	0.323***	0.249***	0.268***	0.289***	0.192**	0.284***
Human CB treat.	-0.001	0.050	0.082	0.058	0.174**	0.171*	0.117
Menu Cost treat.	0.107	0.008	-0.073	0.041	0.145 *	0.131*	0.215**
Low Friction treat.	0.074	0.019	-0.047	0.195**	0.176**	0.189**	0.213***

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

Table 6: Correlations between inflation and output gap

To further study the relationship between inflation and output gap (see Yun, 1996) we consider the correlations between inflation and leads and lags of the output gap. The results are given in table 6. The greatest degree of persistence is observed for the Baseline treatment, which produces remarkably similar persistence patterns to those generated in the simulations, when 85% of firms change their price each period. Indeed, this is the actual frequency with which prices are changed under Baseline (section 4.5 analyzes price patterns in detail). Some persistence is also observed in the Low Friction treatment. In the remaining two treatments, we observe less persistence. Overall, the observed persistence in our experiment is not as pronounced as is usually observed in major developed economies (see e.g. Yun, 1996 for the US). Generally, the cross-correlations are greater for leads than for lags of inflation. This is again consistent with the fact that technology shocks are relatively more important for business cycle fluctuations than demand shocks.

4.3. VAR and impulse response functions. The most common methodology employed in empirical monetary economics to assess the persistence of shocks is to estimate a structural vector autoregression (SVAR) and to plot the impulse responses (IRFs). We follow this literature by estimating a trivariate VAR with two lags of output gap, inflation and interest rate. The appropriate identification scheme to use for our data is not obvious. In the literature, three options have attracted particular attention: Choleski decomposition, long run restrictions, and sign restrictions. However, they each have advantages and disadvantages. If we were to estimate the VAR using Choleski decomposition, we would fall into the trap described in Carlstrom, Fuerst, and Paustian (2009). They show that the IRFs can be severely muted if one assumes Choleski decomposition and the model actually does not exhibit the assumed timing. This critique does apply in the case of our experiment, where the demand, supply, and monetary policy shocks contemporaneously influence the realizations of inflation, output gap and interest rate. Therefore, Choleski decomposition is not an appropriate identification scheme. Long-run and sign restrictions have also been criticized (see, e.g. Faust and Leeper, 1997 and Chari, Kehoe, and McGrattan, 2008). Specifically, long-run restrictions tend to suffer from truncation bias, as finite order VARs are not good approximations of infinite order VARs. However, we believe that the truncation bias is less severe than the misspecified timing in the case of Choleski decomposition. Therefore, we report the impulse responses using long-run restrictions.[14]

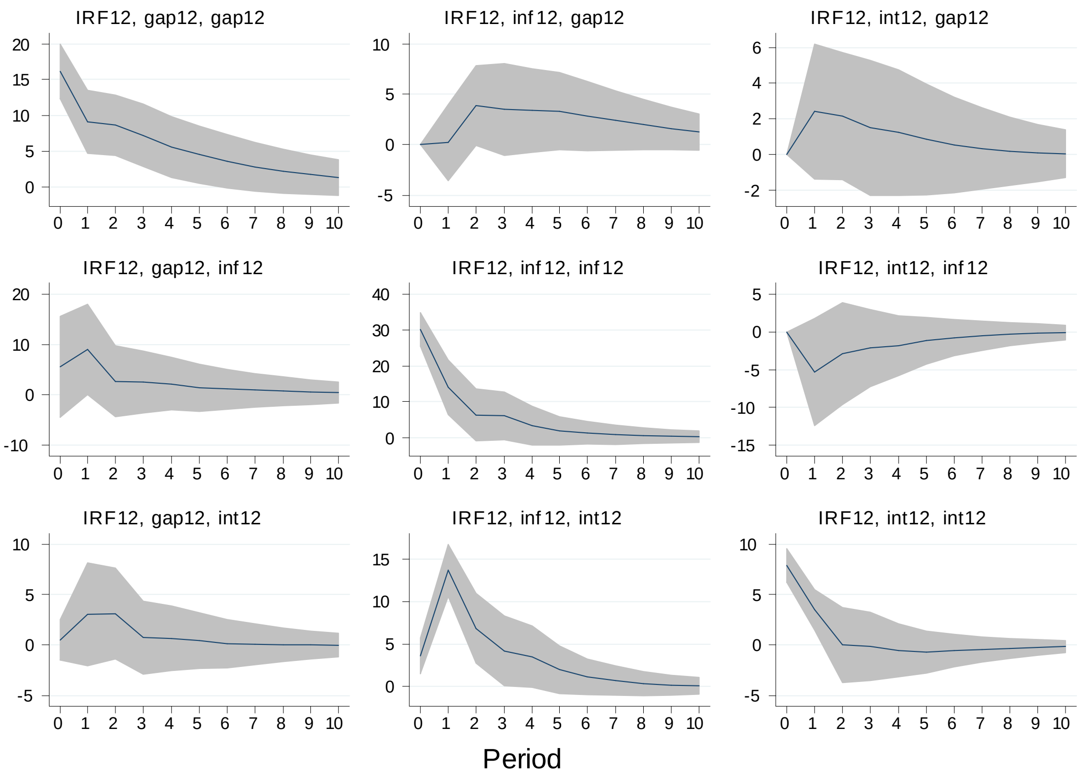

Figure 3: Impulse Responses for Baseline Treatment

Figures 3 - 6 display the IRFs of one representative session in each treatment (for comparison across sessions see Table A14 in Appendix). In the figures, orthogonalized impulse responses are plotted, and 95% error bands are calculated using bootstrap techniques. The label (IRFX, infX, gapX), for example, denotes the IRF for group X and the effect of inflation shock on output gap. For comparison we also estimated SVAR on the simulated data for the Baseline treatment (see figure A2 in the appendix). There are a number of regularities that are common to all treatments. A productivity shock induces a positive change in the output gap. Inflation reacts negatively to the productivity shock, though the reaction usually dissipates in a few periods. It thus appears that a positive productivity shock increases competition in the final product market. The effect of a productivity shock on interest rate is rather ambiguous. However, this is in line with the feature that our Taylor rule is set to respond only to inflation, and not to

[14] Restrictions that we implemented: no long run effects of demand shocks on output gap and interest rate and no long run effect of monetary policy shock on output gap.

the output gap. Except for the last reaction, which is usually found to be positive, the effects of the productivity shock correspond to stylized facts for major industrialized economies.

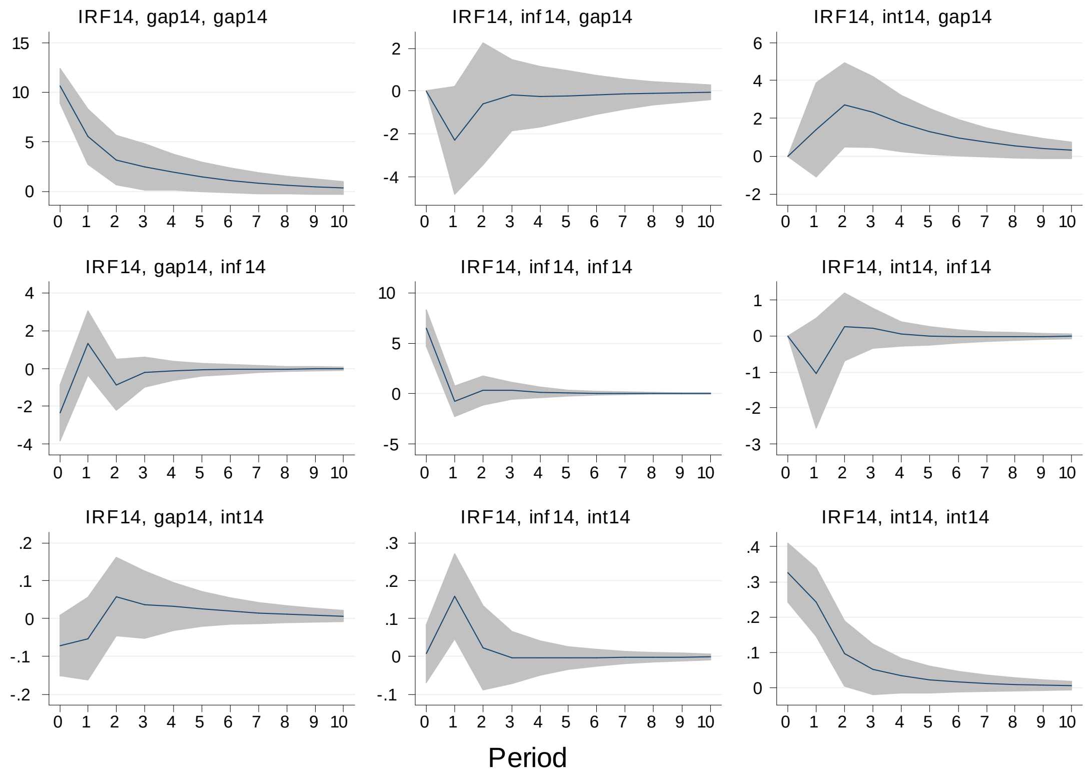

Figure 4: Impulse Responses for the Human Central Banker Treatment

The demand shock induces a reaction of inflation that is similar in sign. The persistence of this reaction varies substantially across treatments. It exhibits almost no persistence in the Low Friction treatment, while in other treatments, at least in some sessions, the shock lives for a few periods. In most sessions, the output gap reacts in the same direction as the demand shock, although in two sessions the reaction is opposite in sign and significant. The demand shock induces a change in interest rate that is similar in sign for most of the sessions. This is in line with the stabilizing objective of interest rates that are set in accordance with the Taylor principle. In the Human Central Banker treatment, all four sessions exhibit this property. This behavior is studied further in section 4.4.

The last shock that we study is the monetary policy shock. This shock is different in nature in our Human Central Banker treatment, compared to all other treatments, in which the interest rate was set according to the instrumental rule specified in (13).[15] In Human Central Banker, the monetary policy shock induces a change in interest rate that is similar in sign. The persistence of this shock varies considerably across sessions, but generally it is greater than in other treatments. Note that we have not exogenously embedded any persistence in the monetary

[15] We rounded the interest rate to the nearest one-tenth of one percent in the experiment. Therefore, the monetary policy shock in the Baseline, Menu Cost, and Low Friction treatments could be identified as the difference between the rounded interest rate and the rate implied by the Taylor rule.

policy shock. The Taylor rule we implemented does not exhibit interest rate smoothing and the objective function of the human central bankers does not penalize the interest rate variability.

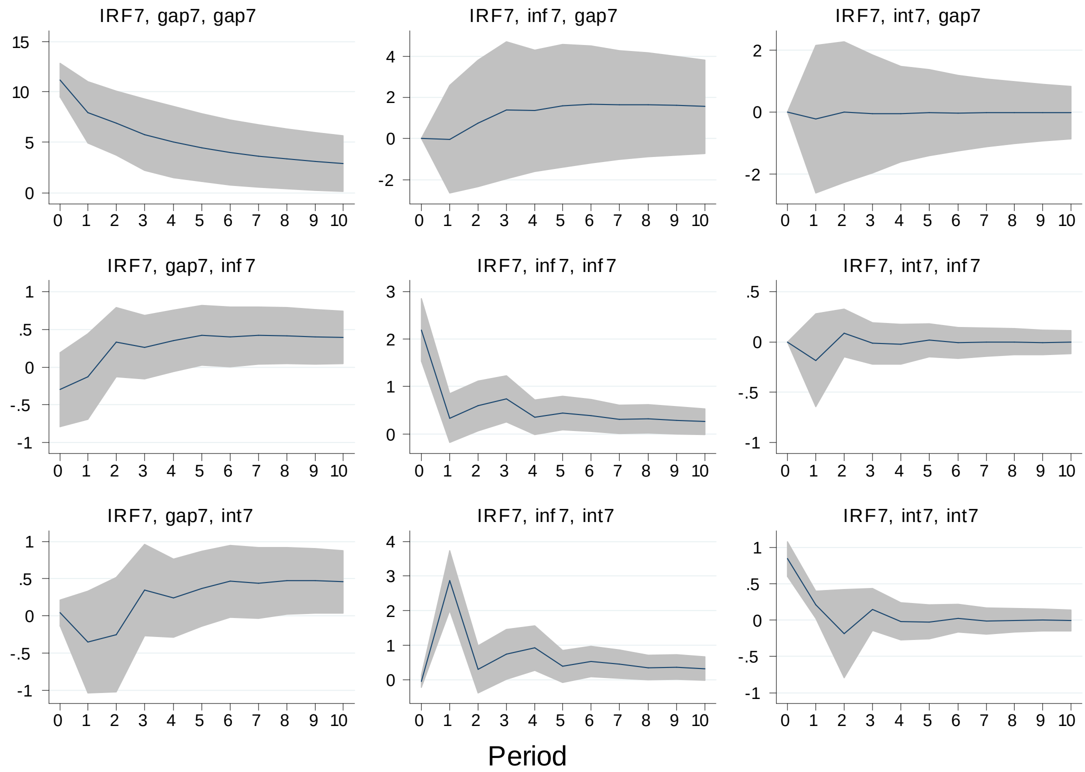

Figure 5: Impulse Responses for the Menu Cost Treatment

The persistence of output to monetary policy shocks has attracted a lot of attention in the literature in the last thirty years. In our experiment, a contractionary monetary policy has no persistent effect on the output gap in any treatment. In some cases it even increases the output gap, though not significantly. In our setup, the interest rate changes induce both substitution and income effects to the consumers, due to their accumulation of savings. Therefore, in principle, it is possible that higher interest rates increase output, although the evidence from empirical macroeconomics supports a negative effect. This difference may be also due to the fact that in the experimental economy, there are no effects of interest rate that go through the supply side. In all but three sessions, inflation reacts positively to the contractionary monetary policy shock, although this reaction is often not significant. A similar pattern is also commonly found in VAR studies of the monetary policy transmission mechanism, and is referred to as the price puzzle (Sims, 1992, Eichenbaum, 1992). The effect of a monetary policy shock on inflation and output gap displays the least persistence in the Low Friction treatment.

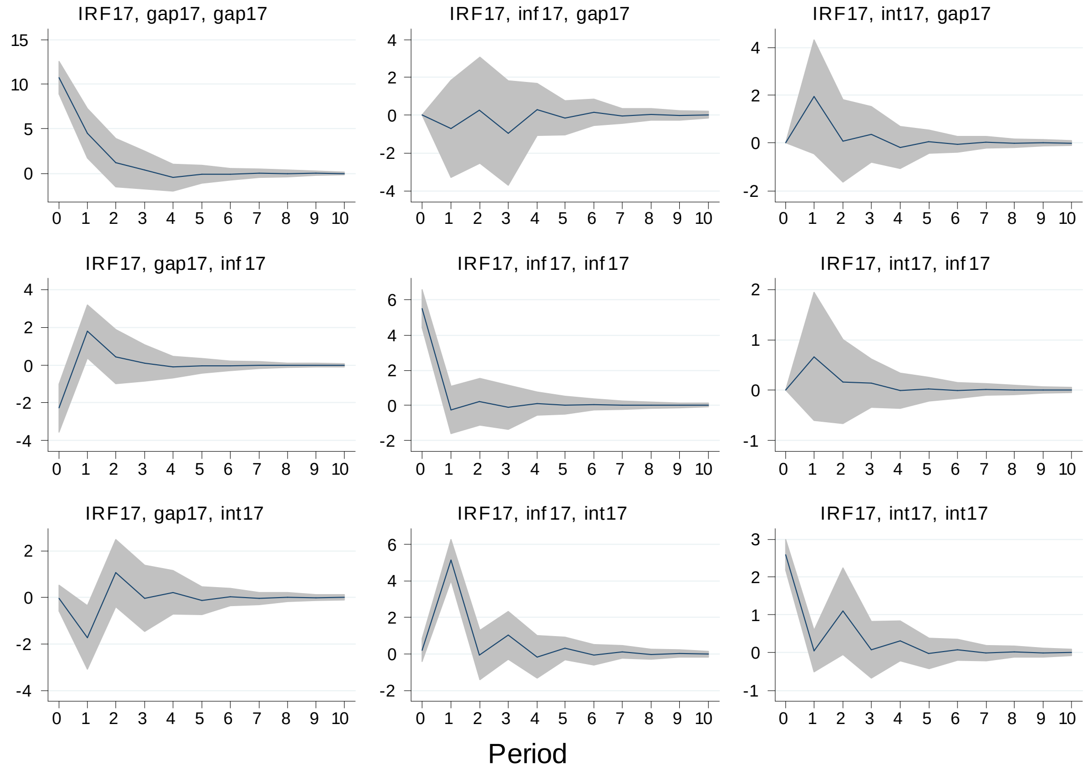

Figure 6: Impulse Responses for the Low Friction Treatment.

The effects of demand and supply shocks correspond, for the most part, to stylized facts. Figures 3 - 6 suggest similar persistence of shocks for output gap and interest rate in the Menu Cost and the Baseline treatments. Moreover, the Low Friction treatment exhibits a very low degree of persistence, and shocks rarely last more than one period. To compare the persistence of shocks between different treatments, we construct a simple test. We compute the number of periods for which output gap, inflation and interest rate deviate significantly from their long-run steady states as a result of a positive one-standard-deviation shock. The values are presented in table 7. We then compare these values between treatments using nonparametric tests, with each session as the unit of observation.

	# of periods (sig.)											
Treatment	output gap				inflation				interest rate			
Baseline	10	3	10	6	0	0	0	1	1	0	0	1
Human Central Banker	3	1	3	5	0	8	0	0	2	9	5	2
Menu Cost	10	10	4	2	1	6	1	0	0	1	1	1
Low Friction	1	2	2	1	0	0	0	0	0	0	0	0

Table 7: Persistence of Shocks

As mentioned above, we do not observe much persistence of monetary policy shocks on interest rates, except in Human Central Banker. The differences between this and the other three treatments are significant at the 5% level under standard nonparametric tests. The only significant difference regarding the effect of demand shocks on inflation is between the Menu Cost and Low Friction treatments (5% significance). For the output gap, the Baseline and Menu Cost treatments exhibit more persistence then the other treatments, indicating that Hypothesis 1 is not supported. The Baseline and Menu Cost treatments are significantly different from the other two treatments at the 5% level, using a Kruskal-Wallis test. The Baseline treatment is also significantly different from the Human Central Banker treatment at the 10% level. Estimations on the benchmark simulated data (see figure A2 in the appendix for the simulation of the Baseline treatment) find that the persistence of the productivity shock on the output gap is about 5 periods. This suggests that both the Human Central Banker and Low Friction treatments generate significantly lower persistence than the benchmark, while most of the sessions of the Baseline and Menu Cost treatments generate greater persistence of the output gap than the benchmark level.

The relative importance of shocks for the determination of interest rate, inflation and the output gap, can be measured with a variance decomposition exercise, using our VAR estimations. We find considerable differences between the Human Central Banker and the other treatments. The demand shock is the shock that explains the most variance of interest rate in the other three treatments. In the Human Central Banker treatment, however, interest rate smoothing explains a greater proportion of the variability of interest rates.

4.4. Behavior of human central bankers. Hypothesis 2 proposed that human central bankers' interest rate decisions satisfy the Taylor principle. We evaluate the hypothesis with the following regression:

$$i_t = \beta_1 i_{t-1} + (1-\beta_1)(\beta_2 \pi_{t-1} + \beta_3 y_{t-1}) + \varepsilon_t \tag{19}$$

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. 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 (19) are reported in Table 8.

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, 2003b). In our economy, determinacy is guaranteed if $\beta_1 + (1-\beta_1)\beta_2 > 0$.[16] 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. This indicates that Hypothesis 2 is supported. 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

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

	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. Note: 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.

there was no asymmetry of that form. In section 4.5, we evaluate the pricing patterns listed in hypothesis 3.

4.5. Price setting behavior of firms.

Frequency of price changes. We begin by focusing on the overall frequency of price changes. Table 9 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, on average, 74.5% of the time, firms change their prices in a period. 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.[17] 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.

There is virtually no difference between the Baseline, Human Central Banker and Low Friction treatments (the price changes in about 85% of possible instances). Non-parametric tests, 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 the 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.

[17] 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%.

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 9: Summary of positive and negative price changes

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.

Nakamura and Steinsson (2008) report that 64.8% of price changes are increases.[18] This percentage corresponds closely to our experiment, as can be seen in table 9, 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.

Size of price changes. Table 10 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 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. Nakamura and Steinsson (2008) also report statistics regarding the magnitude of positive and negative price changes separately. The median absolute size of price changes is 8.5%, the median size of price increases is 7.3%, and the median of price

[18] They use product-level price data used to construct the CPI and PPI in the US.

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 10: Average and average absolute price changes

decreases is 10.5%. Table 10 also presents the average positive and negative price changes of the experiment both in terms of 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.[19]

Price changes and inflation. Klenow and Kryvtsov (2008) decompose monthly inflation into the fraction of items with price changes 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.

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, 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

[19] Klenow and Malin (2010) discusses 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.

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, depending on the relative importance of transitory and permanent shocks to marginal costs. Permanent shocks, which accumulate over time, tend to yield an upward-sloping hazard function, while transitory shocks tend to flatten or even produce 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 if all goods are considered. When they exclude decile fixed effects, the hazard rates become constant. 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 period. Ikeda and Nishioka (2007), using Japanese CPI data, contrary to previous empirical research, find 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.

Table 11 shows the differences between treatments in the duration of price spells. The average durations are 1.17, 1.16 and 1.15 in the Baseline, Human Central Banker and Low Friction treatments. The Menu Cost treatment has an average of 2.41, significantly different at 3 % from any of the other treatments.

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 11: 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:

$$\lambda_i(t|x_j) = \nu_i \lambda_0(t) weibull(x_{i,j}\beta), \tag{20}$$

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 $weibull(x_{i,j}\beta) = x_{i,j}\beta \cdot p \cdot t^{p-1}$, where p is a parameter to be estimated. Under this distributional assumption, we can test explicitly whether the hazard function is upward sloping so that $p > 1$, downward sloping with $p < 1$, or constant with $p = 1$.

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 A11 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, (see Figure A.3 in the Appendix). As shown in Table A11, the estimated values of p are about 2.5 in all treatments except under Menu Cost, where $p = 1.55$. 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 differ from the findings generally reported in the literature. As shown by Sheedy (2010) increasing hazard functions create additional persistence in the economy.

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 whether the assumptions of menu costs and monopolistic competition are essential to create the frictions required to make the economy conform to empirical stylized facts. The experiment allows the possibility that the behavior of human agents alone creates the requisite friction.

All of the results depend on whether we have been able to create a well-functioning economy, from which meaningful data can be extracted. This means that the complexity of the economy is not so great as to be beyond the capabilities of the participating human agents. The data provide clear evidence that economies with this level of complexity are amenable to experimentation. None of our subjects lost money overall or consistently made poor decisions. The empirical patterns and treatment differences lend themselves to intuitive ex-post explanations, though many of these would not have been anticipated ex-ante. Thus, in our view, experiments, in conjunction with traditional empirical methods, can increase our understanding of how a macroeconomy operates.

Comparison of our Baseline and Menu Cost treatments allows us to consider the effect of the addition of menu costs on the economy, holding all else equal. We find that the existence of monopolistic competition, in conjunction with the behavior of human agents, generates additional persistence in output, which is similar whether or not menu costs are present. However, the presence of menu costs is not enough to generate persistent effects of a monetary policy shock on output and inflation. Levels of GDP and welfare are not substantially different with or without menu costs. Nevertheless, menu costs do have an effect on pricing. Average markups are smaller under menu costs, perhaps as a result of greater forward-looking considerations in price setting, and thus menu costs inhibit the exercise of market power. Sellers, when facing a menu cost, appear to seek to guarantee sales over multiple future periods, by setting relatively low prices. While menu costs do not affect the level of inflation, they reduce its variability. The benefit from this lower variability appears to offset the direct deadweight loss of the cost itself, and results in an insignificant net effect on welfare.

Comparing the Baseline and Low Friction treatments allows us to analyze the differences between settings corresponding to perfect substitutability of goods and to monopolistic competition. Low Friction is characterized by greater output, employment, and welfare, as well as smaller price markups than Baseline. The Low Friction treatment generates virtually no persistence of shocks, in contrast to Baseline. Bounded rationality of agents does not create persistence of shocks under perfect substitutability of goods.

In the environment where all firms' outputs are perfect substitutes, consumers' purchase and firms' output pricing decisions are straightforward. Consumers simply buy at the lowest price, and thus face a one-dimensional problem. Producers face a situation, in which charging too high a markup can result in large losses, and thus there is powerful feedback reinforcing convergence to competitive pricing. This means that productivity shocks must be immediately passed through to output prices for producers to avoid losses. This competitive behavior is conducive to high output, welfare, and employment levels.

Under monopolistic competition, on the other hand, consumers face a multi-dimensional problem. They must compare the difference between the marginal utility and price of each of the goods, and choose the one yielding the greatest surplus. Reoptimization is required for each individual purchase, since the marginal utility of each good changes with each purchase. For producers, there is a relatively smooth tradeoff between price and sales, unlike the all-or-nothing tradeoffs under perfect competition. The parameters of the tradeoff under monopolistic competition depend in a complex manner on the other firms' prices, as well as on the shocks to preferences for each of the goods. In light of such complexity, boundedly rational agents might resort to rules of thumb or be reluctant to make changes in behavior, as long as their current strategies seem to be working reasonably well. This inertia in decision making can cause slow adjustment and thus shock persistence. Such inertia is less costly under monopolistic competition than in the environment where final goods are perfect substitutes, where it can lead to large losses.

Humans, when given the role of discretionary central bankers in our experiment, tend to employ the Taylor principle. They make relatively large adjustments in interest rates in response to a deviation of inflation from the target level. Interest rate shocks, when they result from human central bankers' decisions, show considerable persistence, despite the absence of explicit incentives for central banks to have them do so. This treatment also generates considerably lower persistence of output compared to the Baseline. Though typically applying the Taylor principle, our Human Central Bankers achieved lower levels of GDP and welfare than those attained under a simple instrumental rule. This can be seen in a comparison of the Baseline and Human Central Banker treatments. As illustrated in figures 1 and 2, the decrease in welfare occurs late in the life of the economies, when individuals are relatively experienced. This means that the low output and welfare are not long-term consequences of initial decisions taken during a learning process. Rather, they appear to reflect a slow policy response to price increases late in the sessions. Producers, as they gain experience, attempt to increase the wedge between output and input prices. In the Baseline treatment, the instrumental rule responds strongly to output price increases by raising interest rates. This encourages consumers to save rather than consume, putting downward pressure on prices. Producers respond to this by lowering prices. The Human Central Bankers react less effectively to such price increases, and this is reflected in the greater persistence of policy shocks and price inertia relative to Baseline.

We also 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, the hazard function of price changes is upward sloping.

In designing our experiment, we felt that we were required to make some changes to the DSGE model to make it feasible to implement as a functioning economy with human agents. In our view, such practical considerations could provide avenues for future extensions of the theoretical model. One is the explicit inclusion in the model of the timing of events within each period, modeling the output market as operating after production, which in turn occurs after the labor market clears. A second is to induce pricing power in the output market in a more realistic manner than to assume Dixit-Stiglitz aggregation. The third is to allow realizations of supply and demand, and by extension, those to shocks to demand and productivity, be private information to those who experience them. The fourth is to allow average savings to be positive. These changes would also make the model conform more closely to field economies.

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A. Appendix

Appendix A1 lists definitions for some of the aggregate variables used in the text. Appendix A2 contains the initial values of the shocks in the Low Friction treatment. Appendix A3 includes some supplementary tables containing estimation results and descriptive statistics. Appendix A4 is a reprint of the instructions for the Human Central Banker treatment. The instructions for each of the other three treatments is a subset of those given here. The differences are described in Appendix A5.

A.1. Initial value of shocks. The initial value of the A_t productivity shock is $A_0 = 3.5192$. The initial values of the preference shocks in all of the treatments except for Low Friction are

$$H_{1,t=0} = [475.0125, 190.0593, 165.4321]$$

for the first consumer,

$$H_{2,t=0} = [310.0125, 464.0593, 298.4321]$$

for the second consumer, and

$$H_{3,t=0} = [189.0125, 319.0593, 485.4321]$$

for the third consumer.

The initial values of the preference shocks in the Low Friction treatment are

$$H_{1,t=0} = [600.0125, 599.0593, 600.4321]$$

for the first consumer,

$$H_{2,t=0} = [600.0125, 599.0593, 600.4321]$$

for the second consumer, and

$$H_{3,t=0} = [600.0125, 599.0593, 600.4321]$$

for the third consumer.

A.2. Calculation of aggregate variables. The inflation rate at period t is computed with the following equation

$$\pi_t = \frac{\sum_{j=1}^{J} p_{jt}}{\sum_{j=1}^{J} p_{jt-1}}, \tag{21}$$

where p_{jt} is the price of good j at time t.

GDP, real GDP and real GDP growth are calculated at each period according to the following equations

$$Y_t = \sum_{j=1}^{J} y_{jt} p_{jt}, \tag{22}$$

$$Y_t^r = \sum_{j=1}^{J} y_{jt} p_{j1} \tag{23}$$

$$Y_t^{rg} = \frac{\sum_{j=1}^{J} y_{jt} p_{j1}}{\sum_{j=1}^{J} y_{jt-1} p_{j1}}, \tag{24}$$

where p_{jt} is the price of good j at time t and y_{jt} is the quantity of good j in period t.

The output gap is given by

$$x_t = \frac{\sum_{j=1}^{J} y_{jt} p_{j1} - \sum_{j=1}^{J} y_{jt}^P p_{j1}}{\sum_{j=1}^{J} y_{jt}^P p_{j1}}, \tag{25}$$

where $y_{jt}^P = \overline{A}_{jt} \overline{L}_{jt}$ is the potential level of production of firm j, $\overline{L}_{jt}$ is the optimal level of work and $\overline{A}_{jt}$ is the average productivity shock.

Finally, aggregate wages and aggregate real wages are determined by the equations below

$$W_t^R = \frac{1}{I} \sum_{i=1}^{I} w_{it}, \tag{26}$$

$$W_t^{RR} = \sum_{i=1}^{I} \frac{w_{it}}{1 + \pi_t}, \tag{27}$$

where w_{it} is the wage of subject i at period t.

Variable	Obs	Mean	Std. Dev.	Min	Max
interest rate (i_t)	958	5.662898	10.47261	0	50
inflation (π_t)	958	2.45458	13.50272	-68.55409	134.0426
output gap (x_t)	958	-20.22278	19.4485	-93.12498	33.0037
GDP (Y_t)	958	1895.601	2297.108	4.5	26002
real GDP (Y_t^r)	958	655.4251	200.3036	48	1186
real GDP growth (Y_t^{rg})	957	2.009392	37.52016	-89.89899	923.3333
labor hired (L_{jt})	2874	4.573069	1.847017	0	11
prices (p_{jt})	2874	48.60571	86.88744	0.1	1500
profits (Π_{jt})	2874	40.45601	176.4472	-4191.352	1270.8
products produced (y_{jt})	2874	15.5588	6.694012	0	41
sales	2874	14.27105	6.808245	0	39
unsold products	2874	1.287752	2.955584	0	26
wages (w_{it})	2854	102.0619	136.4999	0.1	4402
$w_{it} - W_t^R$	2854	1.650817	94.39867	-592.1738	3994.167
markup	2845	0.2675641	0.2277611	-0.577922	0.993205
w_{it}/P_t	2854	2.691143	6.496245	0.0220833	291.5232

Table A1: Descriptive statistics - pooled

Variable	Obs	Mean	Std. Dev.	Min	Max
interest rate (i_t)	242	8.387603	14.23122	0	50
inflation (π_t)	242	3.199414	21.653	-68.55409	134.0426
output gap (x_t)	242	-21.06752	20.26428	-93.12498	19.80921
GDP (Y_t)	242	1746.554	2100.203	4.5	26002
real GDP (Y_t^r)	242	626.8748	177.518	48	1012.8
real GDP growth (Y_t^{rg})	242	4.051115	62.87422	-89.89899	923.3333
labor hired (L_{jt})	726	4.414601	1.706865	0	9
prices (p_{jt})	726	44.53085	84.10343	0.1	1500
profits (Π_{jt})	726	62.94251	89.06482	-142.9054	707.3257
products produced (y_{jt})	726	14.96143	6.184845	0	38
sales	726	13.46143	6.086324	0	31
unsold products	726	1.5	3.160423	0	26
wages (w_{it})	722	79.61597	63.59612	0.1	511.8
$w_{it} - W_t^R$	722	-0.3438827	13.17343	-127.0192	203.0308
markup	722	0.3748539	0.2600075	-0.53	0.9932051
w_{it}/P_t	722	2.097963	0.8725777	0.0220833	5.7375

Table A2: Descriptive statistics - Baseline treatment

Variable	Obs	Mean	Std. Dev.	Min	Max
interest rate (i_t)	225	5.881333	9.865943	0	50
inflation (π_t)	225	2.63949	12.08882	-32.10526	98.8399
output gap (x_t)	225	-26.71141	21.79813	-75.66798	16.94264
GDP (Y_t)	225	2431.577	3665.547	84.8	17190
real GDP (Y_t^r)	225	568.6938	222.4741	166	1062.8
real GDP growth (Y_t^{rg})	224	1.113884	22.10198	-48.84354	81.49638
labor hired (L_{jt})	675	4.134815	1.710819	0	10
prices (p_{jt})	675	72.29393	146.6704	4.5	1100
profits (Π_{jt})	675	71.41323	122.2867	-438.3405	1270.8
products produced (y_{jt})	675	14.08296	6.291079	0	39
sales	675	12.45037	6.279717	0	36
unsold products	675	1.632593	3.065284	0	23
wages (w_{it})	671	95.51334	104.7708	5.5	374.925
$w_{it} - W_t^R$	671	-0.4317104	17.45936	-159	172.1429
markup	670	0.3754929	0.2372643	-0.577922	0.9666333
w_{it}/P_t	671	2.137723	0.9887657	0.1001001	14.86667

Table A3: Descriptive statistics - Human CB treatment

Variable	Obs	Mean	Std. Dev.	Min	Max
interest rate (i_t)	239	2.847099	6.155897	0	50
inflation (π_t)	239	1.795545	6.003486	-17.4482	57.41525
output gap (x_t)	239	-19.6395	17.74195	-79.0022	23.82888
GDP (Y_t)	239	1273.082	352.0875	382.1	2522.5
real GDP (Y_t^{rg})	239	637.9925	181.1477	153.8	1041.8
real GDP growth (Y_t^r)	239	1.567379	24.91149	-76.46159	240.3121
labor hired (L_{jt})	717	4.490934	1.90383	0	11
prices (p_{jt})	717	32.52204	13.16851	14	82
profits (Π_{jt})	717	14.72283	310.0241	-4191.352	571.7784
products produced (y_{jt})	717	15.23291	6.866657	0	41
sales	717	14.03487	6.651766	0	39
unsold products	717	1.198047	2.661508	0	18
wages (w_{it})	710	93.42234	208.1062	42.0875	4402
$w_{it} - W_t^R$	710	7.49169	187.3672	-592.1738	3994.167
markup	706	0.2214447	0.1661604	-0.2387387	0.7734902
w_{it}/P_t	710	3.44522	12.90085	0.9142857	291.5232

Table A4: Descriptive statistics - Menu cost treatment

Variable	Obs	Mean	Std. Dev.	Min	Max
interest rate (i_t)	252	5.521825	9.281046	0	50
inflation (π_t)	252	2.199243	8.907355	-30.66667	36.19048
output gap (x_t)	252	-14.17133	15.80603	-68.55325	33.0037
GDP (Y_t)	252	2150.587	1749.849	510	7763.4
real GDP (Y_t^r)	252	776.8143	157.5383	285	1186
real GDP growth (Y_t^{rg})	252	1.263909	23.20006	-60.20236	210.5263
labor hired (L_{jt})	756	5.194444	1.882797	0	11
prices (p_{jt})	756	46.62262	42.42065	14	200
profits (Π_{jt})	756	15.62714	61.37043	-448.2118	188.8246
products produced (y_{jt})	756	17.75926	6.818769	0	39
sales	756	16.89815	7.286307	0	39
unsold products	756	0.8611111	2.864354	0	20
wages (w_{it})	751	137.6601	119.9132	45.125	430
$w_{it} - W_t^R$	751	-0.0928188	15.1116	-129.2857	116.25
markup	751	0.1009667	0.1585665	-1.811667	0.4517544
w_{it}/P_t	751	3.042976	0.5650854	1.8	9.840625

Table A5: Descriptive statistics - Low friction treatment

Variable	Obs	Mean	Std. Dev.	Min	Max
wage (w_{it})	2876	99.23777	130.5316	0	1520
leisure ($1 - L_{it}$)	2877	5.425791	1.38231	0	10
work (L_{it})	2877	4.574209	1.38231	0	10
savings (B_{it})	2877	39549.66	245908	0.0383689	3638128
sumsavings $\left(B_t^S\right)$	959	118653.7	540950.5	525.0417	4646720
utility (u_{it})	2869	2741.456	1292.135	-6013.475	7054.952
consumption (c_{1it})	2877	4.687522	4.384988	0	32
consumption (c_{2it})	2877	5.014251	4.073576	0	26
consumption (c_{3it})	2877	4.575252	4.015571	0	25
consumption (c_{it})	2877	14.27702	7.295907	0	57
consumption ($c_{it}p_{jt}$)	2877	631.5149	1078.006	0	24874

Table A6: Descriptive statistics - Pooled

Variable	Obs	Mean	Std. Dev.	Min	Max
wage (w_{it})	726	69.99287	62.84536	0	660.25
leisure ($1 - L_{it}$)	726	5.585399	1.230758	3	10
work (L_{it})	726	4.414601	1.230758	0	7
savings (B_{it})	726	69565.22	379341.9	0.0383689	3638128
sumsavings $\left(B_t^S\right)$	242	208695.7	796986	543.2195	4646720
utility (u_{it})	726	2438.292	1161.722	-142.8506	6247.739
consumption (c_{1it})	726	4.097796	4.048679	0	22
consumption (c_{2it})	726	5	4.242641	0	26
consumption (c_{3it})	726	4.363636	3.552949	0	18
consumption (c_{it})	726	13.46143	7.167784	0	44
consumption ($c_{it}p_{jt}$)	726	582.1847	1144.688	0	24874

Table A7: Descriptive statistics - Baseline treatment

Variable	Obs	Mean	Std. Dev.	Min	Max
wage (w_{it})	675	79.45976	115.0242	0	1200
leisure ($1 - L_{it}$)	675	5.865185	1.509973	1	10
work (L_{it})	675	4.134815	1.509973	0	9
savings (B_{it})	675	81898.04	312248.7	0.3426774	2798072
sumsavings $\left(B_t^S\right)$	225	245694.1	719631.2	595.8868	4323971
utility (u_{it})	667	2352.707	1305.954	-6013.475	6143.891
consumption (c_{1it})	675	4.302222	4.013765	0	21
consumption (c_{2it})	675	4.325926	3.411513	0	21
consumption (c_{3it})	675	3.822222	4.124665	0	21
consumption (c_{it})	675	12.45037	6.915459	0	46
consumption ($c_{it}p_{jt}$)	675	810.5256	1684.545	0	12160

Table A8: Descriptive statistics - Human CB treatment

Variable	Obs	Mean	Std. Dev.	Min	Max
wage (w_{it})	720	73.29934	75.34377	0	1132.25
leisure ($1 - L_{it}$)	720	5.504167	1.182856	1	10
work (L_{it})	720	4.495833	1.182856	0	9
savings (B_{it})	720	2605.616	2875.418	0.4359367	13970.76
sumsavings $\left(B_t^S\right)$	240	7835.598	6594.705	525.0417	26677.59
utility (u_{it})	720	2513.825	1063.925	-4752.119	6753.636
consumption (c_{1it})	720	4.183333	4.062071	0	28
consumption (c_{2it})	720	5.826389	3.986643	0	23
consumption (c_{3it})	720	4.05	3.255935	0	16
consumption (c_{it})	720	14.05972	6.029417	0	37
consumption ($c_{it}p_{jt}$)	720	423.8192	182.6202	0	1576.9

Table A9: Descriptive statistics - Menu cost treatment

Variable	Obs	Mean	Std. Dev.	Min	Max
wage (w_{it})	755	169.7777	192.6954	0	1520
leisure ($1 - L_{it}$)	756	4.805556	1.366785	0	10
work (L_{it})	756	5.194444	1.366785	0	10
savings (B_{it})	756	8098.946	18932.72	2.232203	146401.8
sumsavings $\left(B_t^S\right)$	252	24296.84	42794.93	2994.799	260551.8
utility (u_{it})	756	3592.364	1211.448	649.9122	7054.952
consumption (c_{1it})	756	6.078042	4.976288	0	32
consumption (c_{2it})	756	4.869048	4.396271	0	22
consumption (c_{3it})	756	5.951058	4.616296	0	25
consumption (c_{it})	756	16.89815	8.097678	1	57
consumption ($c_{it}p_{jt}$)	756	716.8622	723.9243	17.2	5311

Table A10: Descriptive statistics - Low friction treatment

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_{t-1}^R	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)
p	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
BIC	2713.9	622.3	643.3	669.5	619.1
*p<.10,		**p<.05,		***p<.01	

Table A11: Parametric hazard rate regressions

dur	Freq.	Percent	Cum.
1	1738	82.6	82.6
2	230	10.93	93.54
3	71	3.37	96.91
4	25	1.19	98.1
5	13	0.62	98.72
6	9	0.43	99.14
7	5	0.24	99.38
8	3	0.14	99.52
9	3	0.14	99.67
10	3	0.14	99.81
11	1	0.05	99.86
12	1	0.05	99.9
19	1	0.05	99.95
21	1	0.05	100
Total	2104	100	

Table A12: Price spells

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 A13: Correlation of size and fraction with inflation

Shock\Effect on		# of periods (sig.) output gap				inflation				interest rate			
output gap	Baseline	10	3	10	6	0	0	0	0	0	3	0	0
	Human Central Banker	3	1	3	5	10	0	0	0	8	0	0	4
	Menu Cost	10	10	4	2	0	0	0	2	0	0	2	1
	Low Friction	1	2	2	1	1	0	0	0	10	0	0	0
inflation	Baseline	0	0	0	0	0	0	0	1	0	0	0	0
	Human Central Banker	0	0	0	0	0	8	0	0	9	0	0	0
	Menu Cost	0	0	0	0	1	6	1	0	0	0	0	1
	Low Friction	0	0	0	1	0	0	0	0	7	0	0	0
interest rate	Baseline	0	0	0	0	1	1	1	1	1	0	0	1
	Human Central Banker	0	5	0	0	10	10	1	1	9	5	2	2
	Menu Cost	0	0	0	0	1	2	1	1	0	1	1	1
	Low Friction	0	1	0	1	1	1	1	1	0	0	0	0

Table A14: Persistence of shocks

A.3. Tables.

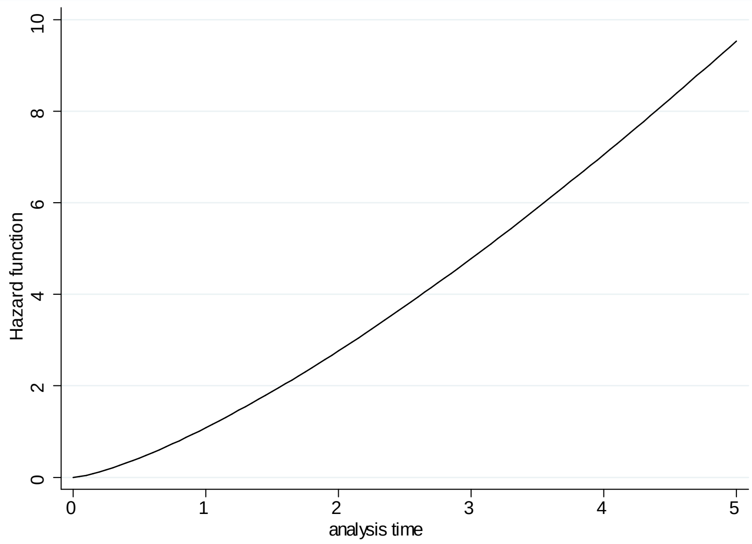


Figure A1: Hazard rate of price changes for Menu cost treatment

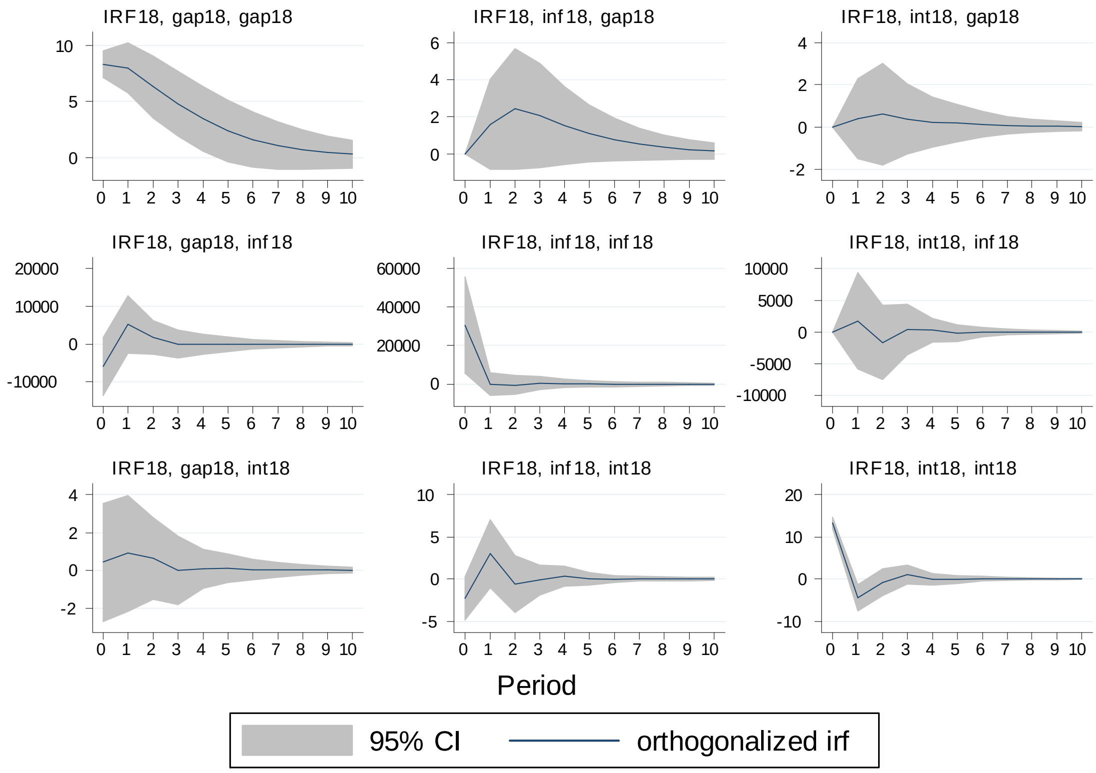


Figure A2: Impulse Responses for Baseline Treatment (Simulated Data)

A.4. Instructions. This section contains the instructions of the experiment. Each subject received the same instructions during the experiment. The instructions were given to each subject as a paper handout, and an experimenter read them aloud at the beginning of each session. The instructions reprinted here were used in the Human Central Banker treatment.

OVERVIEW. You are about to participate in an experiment in the economics of market decision making. The instructions are simple and if you follow them carefully and make good decisions, you can earn a considerable amount of money which will be paid to you in cash at the end of the experiment. Trading in the experiment will be in terms of experimental currency units (ECU). You will be paid, in Euro, at the end of the experiment.

The experiment will consist of a series of at least 50 periods. You are a consumer, a producer, or a central banker, and will remain in the same role for the entire experiment. If you are a consumer, you can make money by selling labor and buying products. If you are a producer, you can make money by buying labor and selling products that you make with the labor. If you are a banker you can make money by trying to get the inflation rate as close to possible to a target level. Whether you are a consumer, a producer, or a central banker is indicated at the top of the instructions.

SPECIFIC INSTRUCTIONS FOR CONSUMERS.

Selling labor. At the beginning of each period, you will have the opportunity to sell your labor for ECU. You will see the screen shown on the next page.

You can sell units of Labor for whatever wage you are able to get for them. To sell a unit, you use the table in the middle of the upper part of your screen entitled “Labor market”. There are two ways to sell a unit:

1. You can accept an offer to buy labor that a producer has made: To do this, look in the column labeled “offers to buy”, and highlight the wage at which you would like to sell. Then click on the red button labeled “sell”.

2. You can make an offer to sell, and wait for a producer to accept it. To do so, enter a wage in the field labeled “Your offer”, and then select “Offer to sell” to submit it to the market. Your offer will then appear in the column labeled “Offers to sell”. It may then be accepted by a producer. However, it is also possible that it may not be accepted by any producers before the current period ends, since they are free to choose whether or not to accept an offer.

When you do not wish to sell any more units in the period, please click the “Stop Selling” key.

You must pay a cost, in Euro, for each unit you sell. The table in the upper left part of the screen, called “Your cost to sell labor” tells you how much you have to pay for each unit of labor you can sell. The numbers are given in units of 1/100th of a cent, so that a cost of 400, for example, is equal to 4 cents. Each row of the table corresponds to a unit that you are selling. The first row is for the first unit you sell in the current period, the second row is for the second unit, etc... The second column of the table tells you how much it costs you to sell each unit. The numbers in the table will decrease by 1% from one period to the next.

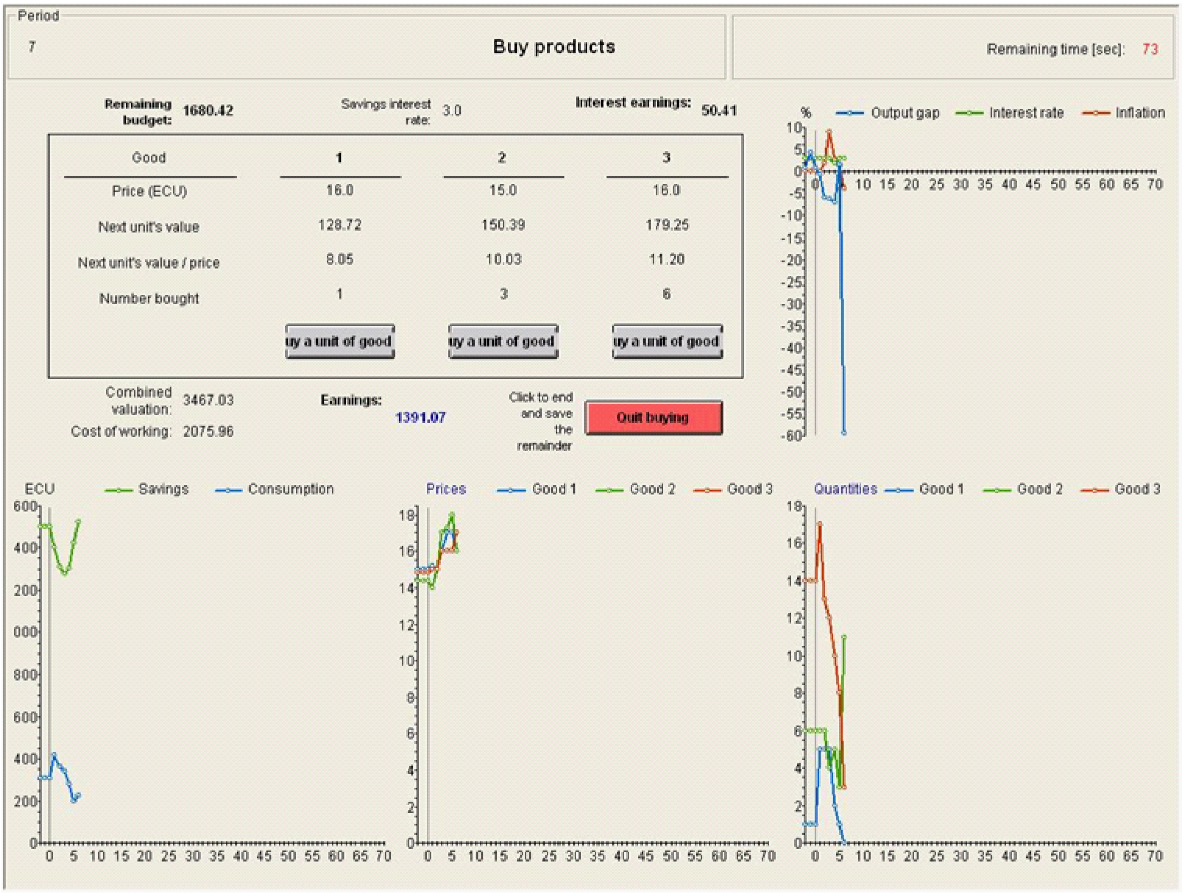
Buying products. After selling labor in each period, you will have the opportunity to buy products by spending ECU. The screen on the next page will appear to allow you to do so.

In the upper left part of the screen, there is a table which will help you make your purchase decisions. There are three goods, 1, 2, and 3, which each correspond to a column in the table. The row called "price" gives the current price per unit, in ECU, that the producer making the unit is currently charging for it.

The next row gives the "Next unit's value per ECU". This calculated in the following way. Your value for the next unit is the amount of money, in Euro, that you receive for the next unit you buy. As you buy more units within a period, your value for the next unit you buy will always be less than for the last unit you bought of the same good. Your values will change from one period to the next. They will randomly increase and decrease from one period to the next, but on average, they will decrease by 1% per period.

The numbers in the "Next unit's value per ECU" row give the value for the unit, divided by the price that the producer selling the unit is charging. The last row in the table shows the number of units of each good that you have purchased so far in the current period.

To make a purchase of a unit of good 1, click on the button labeled "buy a unit of good 1". To make a purchase of a unit of good 2 or 3, click on the button corresponding to the good you want to buy. When you do not want to purchase any more units of any of the three goods, click the button labeled "Quit buying".



Saving money for later periods. Any ECU that you have not spent in the period is kept by you for the next period. It will earn interest at the rate shown on at the top of your screen next to the label "Savings interest rate". That means, for example, if the interest rate is 2%, and you have 100 ECU at the end of the period, it will grow to 102 ECU by the beginning of the next period.

Note that saving ECU for later periods involves a trade-off. If you buy more products now, and save less ECU, you can earn more, in Euro, in the current period, but you have less ECU spend in later periods. If you buy fewer products now, you make fewer Euro in the current period, but you have more ECU to spend in later periods and can earn more Euro then. In a given period, you cannot spend more ECU than you have at that time.

Your share of producer profits. You will also receive an additional payment of ECU at the end of each period. This payment is based on the total profit of producers. Each consumer will receive an amount of ECU equal to 1/3 of the total profit of all three producers. How the profit of producers is determined will be described in the next section. You might think of this as you owning a share in each of the producers so that you receive a share of their profits.

How you make money if you are a consumer. Your earnings in a period, in Euro, are equal to the valuations of all of the products you have purchased minus the unit cost of all of the units of labor that you sell.

For example, suppose that in period 5 you buy two units of good 1 and one unit of good 3. You also sell three units of labor in the period. Your valuation, that is, the amount of Euros you receive, for your first unit of good 1 is 400, and your valuation for the second unit of good 1 is 280. Your value of the first unit of good 3 is 350. These valuations can be found on your "Buy Products" screen in the row called "Your valuation for the next unit. The cost of your first, second and third units of labor are 50, 100, and 150. Then, your earnings for the period equal

$$400 + 280 + 350 - 50 - 100 - 150 = 730 = 7.3 \text{ cents}$$

Note that the ECU that you paid to buy products and those that you received from selling labor are not counted in your earnings. The ECU you receive from selling labor, saving, and producer profit is important, however, because that is the only money that you can use to buy products.

Your Euro earnings for the experiment are equal to your total earnings in all of the periods, plus a bonus at the end of the game that is described in section 6.

SPECIFIC INSTRUCTIONS FOR PRODUCERS.

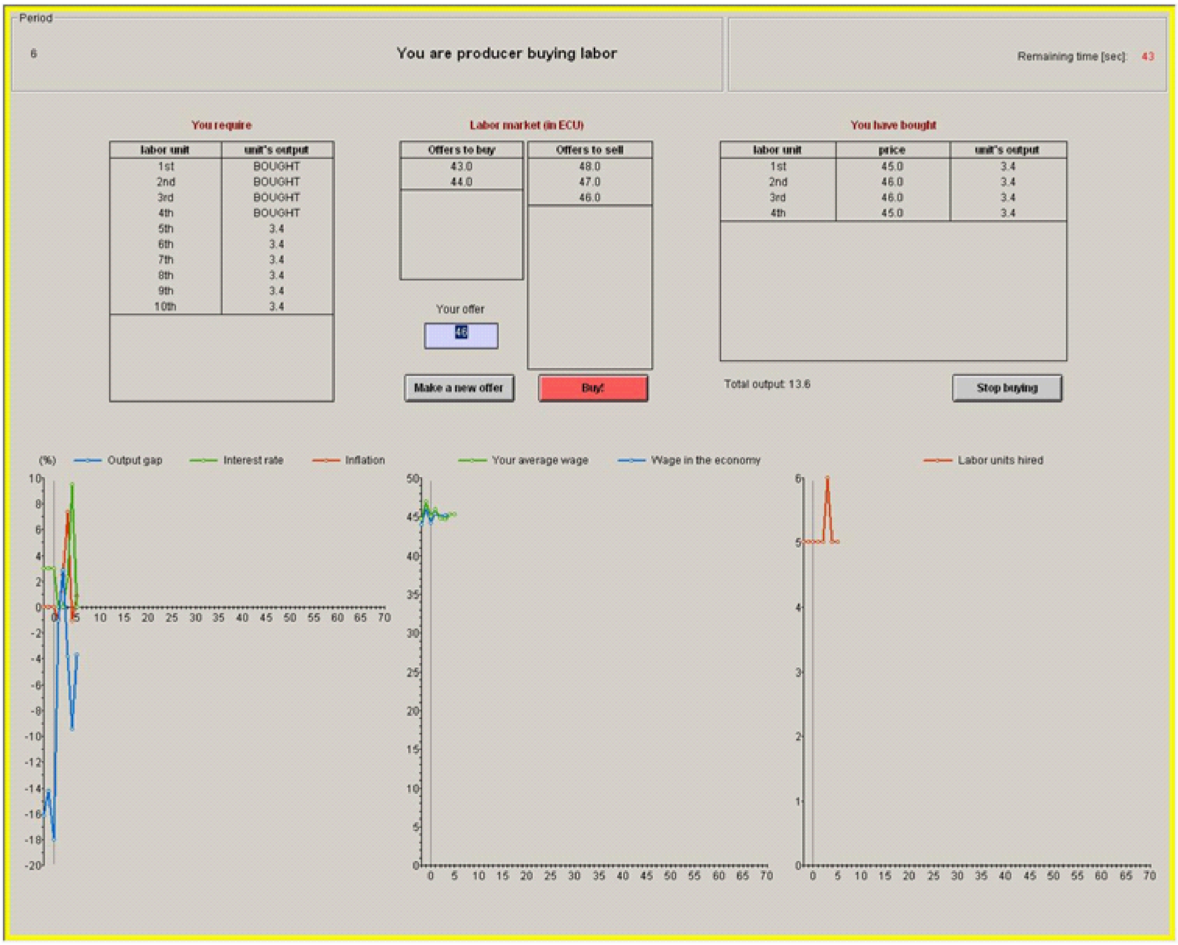
Buying labor. At the beginning of each period, you will have the opportunity to buy labor with ECU. You will see the following screen.

You can buy units of Labor for whatever wage in ECU you are able to get them for. To buy a unit, you use the table in the middle of the upper part of your screen entitled "Labor market". There are two ways to buy:

1. Accept an offer to sell that a consumer has made: To do this, look in the column labeled "offers to sell", and highlight the price at which you would like to buy. Then click on the red button labeled "buy".

2. Make an offer to buy, and wait for a potential seller to accept it. To do so, enter a wage in the field labeled "Your offer", and then select "Make a new offer" to submit it to the market. Your offer will then appear in the column labeled "Offers to buy". It may then be accepted by a seller. However, it is also possible that it may not be accepted by any sellers before the current period ends.

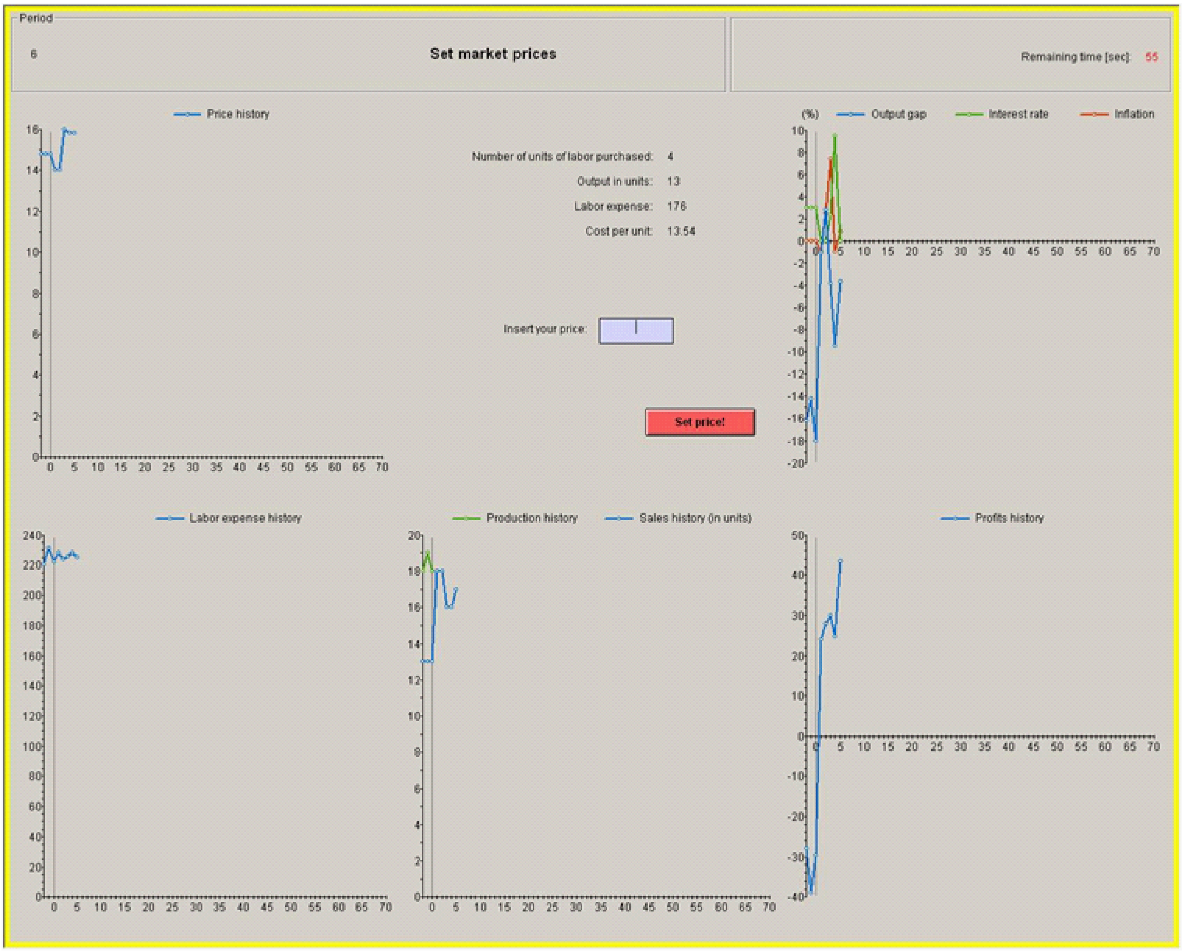
The table in the upper left of the screen, entitled "You require" can help you make your purchase decisions. In the first column is the number of the unit that you are purchasing. 1st corresponds to the first unit you buy in the period, 2nd corresponds to the second unit you are buying in the period, etc... The second column, indicates how many units of product that is produced with each unit of labor. In the example here, each unit of labor produces 3.4 units of product.



Selling products. After the market for labor closes, you automatically produce one of the three goods using all of the labor you have purchased in the period. You produce good …….. and you will always be the only producer of that good. You can make money by selling the good for ECU. You can do so by using the following screen.

In the upper middle portion of the screen, the number of units of Labor you have purchased in the period is shown in the field labeled 'Number of Units of Labor Purchased'. Just below that field is the amount of the product you produce that the labor you bought has made. The amount of product that you make with a given amount of labor can change from period to period. ´Labor expense ´ indicates how much money you spent on labor in the period.

In the field labeled "Insert your price", you can type in the price per unit, in ECU, that you wish to charge for each unit of the product you have produced. When you have decided which price to charge and typed it in, click on the field called 'set price'. This price will then be displayed to consumers who have an opportunity to purchase from you.



How you make money as a producer. If the amount of ECU you receive from sales is more than the amount that you spent on labor, you will earn a profit.

Your profit in ECU in a period = Total ECU you get from sales of product – total ECU you pay for labor

In period 1, your profit in ECU will be converted to Euro at a rate of . . . . . . ECU = 1 Euro. Therefore:

Your earnings in Euro in period 1 = ...*[ECU you get from sales of product – ECU you pay for labor]

In later periods, the conversion rate of your earnings from ECU to Euro will be adjusted for the inflation rate.

Your ECU balance will be set to zero in each period. However, the profit you have earned in each period, in Euro, will be yours to keep, and the computer will keep track of how much you have earned in previous periods. Your Euro earnings for the experiment are equal to your total earnings in all of the periods.

SPECIFIC INSTRUCTIONS FOR CENTRAL BANKERS.

Setting the interest rate. Three of you are in the role of Central bankers. In each period, the three of you will set the interest rate that consumers will earn on their savings in the current period. You will see the screen shown on the next page at the beginning of each period.

In the field labeled "Interest Rate Decision", you enter the interest rate that you would like to set for the period. Of the three of you who set interest rates, the second highest (that is, the median choice) will be the one in effect in the period.

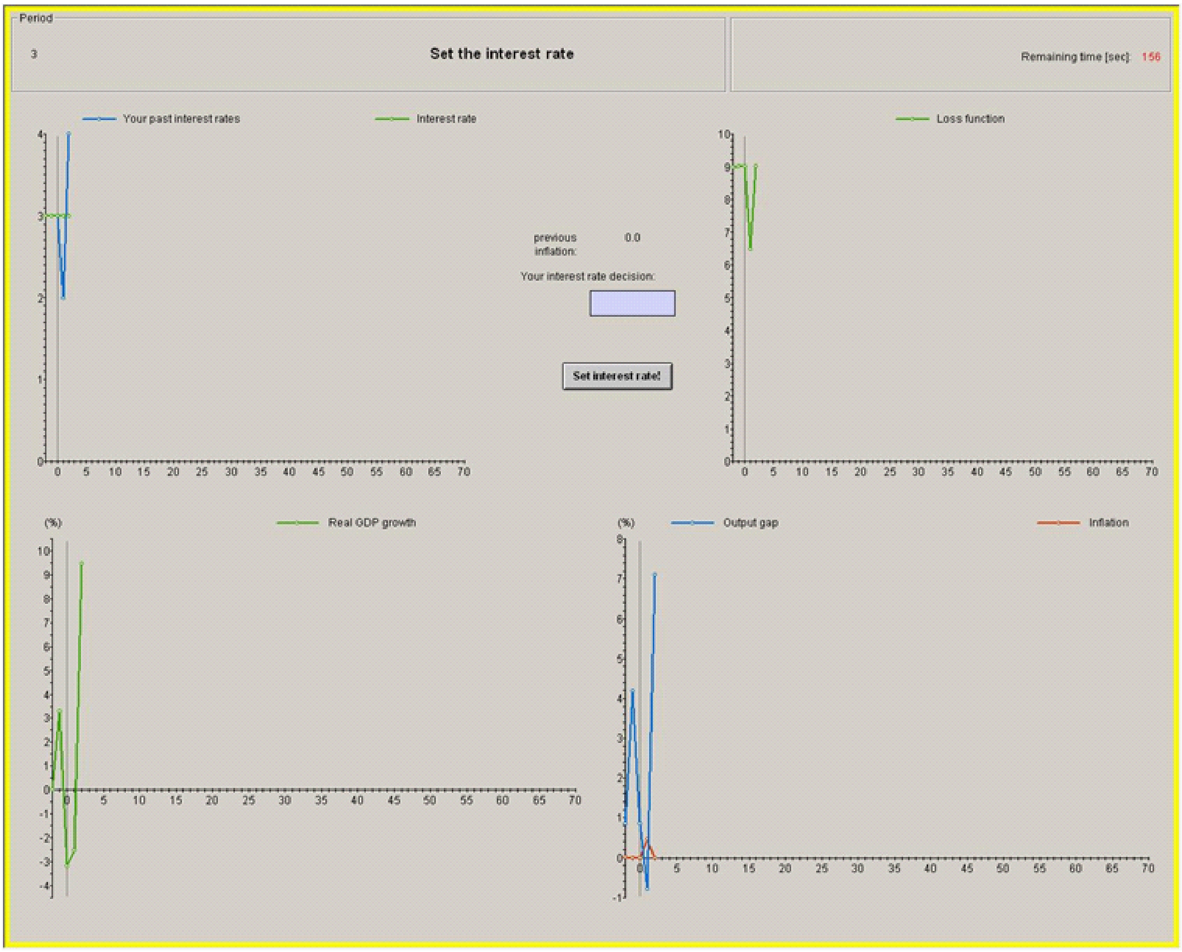
Higher interest rates might encourage consumers to save rather than spend their money and might lead to lower prices, and therefore a lower rate of inflation. On the other hand, lower interest rates might discourage saving, and lead to more spending and higher prices.

How you make money as a central banker. You earnings in each period will depend on the inflation rate in the current period. The inflation rate for a period is calculated in the following way. The average price for the three products is calculated for this period and last period. The percentage that the prices went up or down is determined. This percentage is the inflation rate.

For example if the prices of the three products are 60, 65 and 70 in period 9, the average price in period 9 is 65. If the average prices in period 8 were 55, 55, and 70, the average price in period 8 was 60. Prices increased by (65 – 60)/60 =.0833 = 8.33% in period 9. Notice that prices could either increase or decrease in each period.

You make more money the closer the inflation rate is to .....% in each period.

Specifically you earnings in Euro will be equal to ...... - (Actual Inflation Rate - .....%)^2 in each period.



ADDITIONAL INFORMATION DISPLAYED ON YOUR SCREENS. There are graphs on each of the screens described above that give you some additional information about market conditions. You are free to use this information if you choose, to help you make your decisions. In all of the graphs, the horizontal axis is the period number.

Consumers. If you are a consumer, the graphs show for each period, histories of:

- the interest rate (that you earn on the ECU you save),
- the inflation rate (the percentage that average prices for the three goods have gone up or down between one period and the next),
- the output gap (a measure of the difference between the most products that could be made and how much are actually made; the smaller the gap, the lower is production),
- the wage you received (for the labor you sold),
- the average wage in the economy (the average amount consumers received for selling labor),
- the number of units of labor you sold,

- your consumption (how much money that you spent on products)
- your savings (how much of your money that you didn't spend on products),
- the price of each of the three products
- the quantity you bought of each of the three products

Producers. If you are a producer, the graphs show histories of:

- the interest rate,
- the inflation rate,
- the output gap,
- the wage you paid (for the labor you bought),
- the average wage in the economy,
- the number of units of labor you bought,
- your labor expense (how much you spent on labor),
- your production (how much you have produced),
- your sales (how much you have sold),
- your profits

Central Bankers. If you are a central banker, the graphs show histories of:

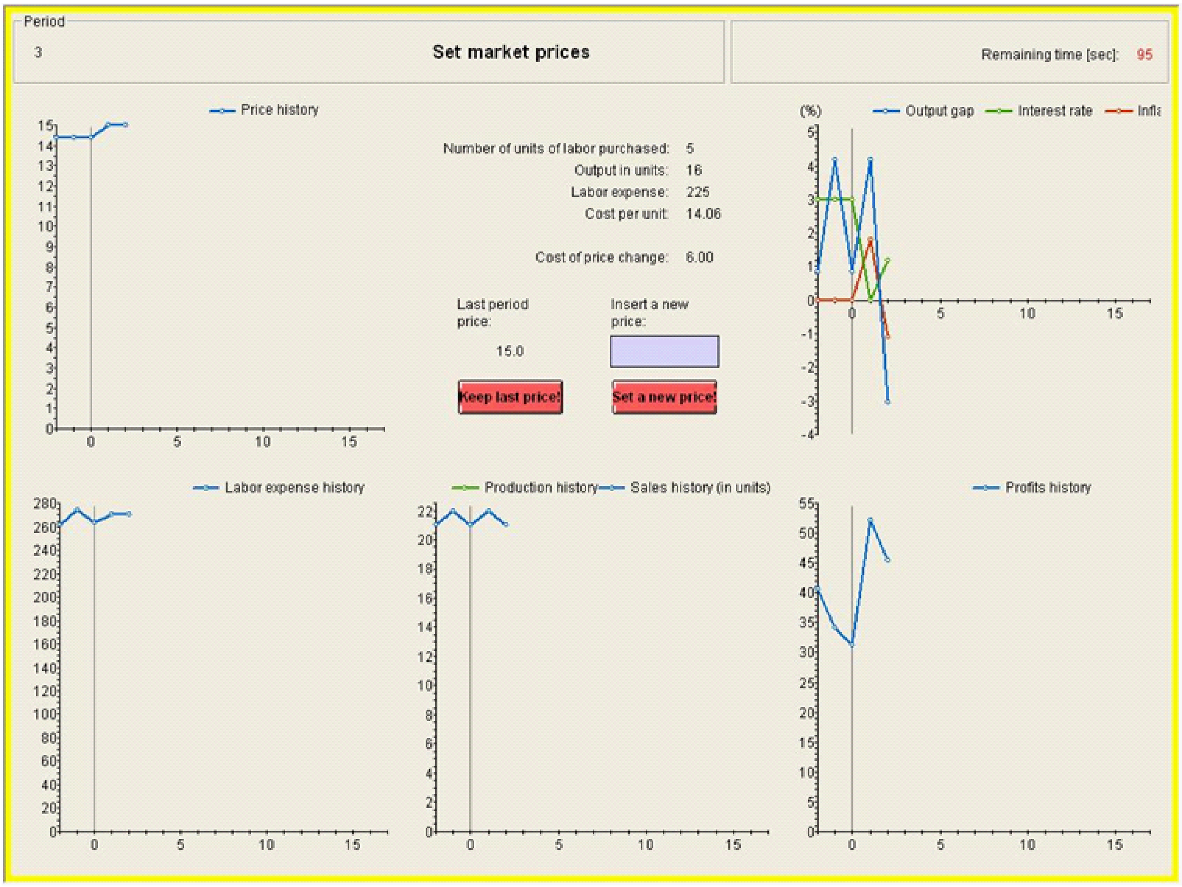
- Interest rates,
- Your earnings,
- The GDP, a measure of how much the economy is producing
- The output gap.

ENDING THE EXPERIMENT. The experiment will continue for at least 50 periods. You will not know in advance in which period the experiment will end. At the end of the experiment, any consumer who has ECU will have it converted automatically to Euro and paid to him/her.

If you are a consumer, we will convert your ECU to Euro in the following manner. We will imagine that the experiment would continue forever, with your valuations and costs following the downward trend they had during the experiment. We will then calculate how much you would earn if you made the best possible savings, labor selling, and product buying decisions that are possible, given the savings you currently have. We will use the average prices for labor and products during the experiment to make the calculation. We will then take the resulting amount of Euro and credit them to you.

STARTING THE EXPERIMENT. In the first two periods of the experiment, we will place limits on the range of wages and prices that can be offered. You will be informed of these limits when the experiment begins. These restrictions will be lifted in period three.

A.5. Differences with the instructions in other treatments. In the Baseline and Low Friction treatments, subject received the same instructions as those in Appendix A4, except for Section 4 entitled *Specific Instructions for Central Bankers.* That part was not included in Baseline and Low Friction, because the interest rate was set automatically by the computer.



In the Menu Cost treatment, section 4 was absent, similarly to the Baseline and Menu Cost treatments. In Menu Cost only, the screen-shot in the figure above was displayed in Section 3.b, entitled *Selling products*, instead of the one shown in Appendix A4. The screen shown in the Menu Cost treatment was accompanied by the following text:

After the market for labor closes, you automatically produce one of the three goods using all of the labor you have purchased in the period. You produce good .... and you will always be the only producer of that good. You can make money by selling the good for ECU. You can do so by using the following screen.

In the upper middle portion of the screen, the number of units of Labor you have purchased in the period is shown in the field labeled Number of Units of Labor Purchased'. Just below that field is the amount of the product you produce that the labor you bought has made. The amount of product that you make with a given amount of labor can change from period to period. ‘Labor expense’ indicates how much money you spent on labor in the period.

In the field labeled “Insert your price”, you can type in the price per unit, in ECU, that you wish to charge for each unit of the product you have produced. When you have decided which price to charge and typed it in, click on the field called ‘set price’. This price will then be displayed to consumers who have an opportunity to purchase from you. You can change your price from one period to the next or you can keep it the same as in the last period. However, if you change the price you are charging for your product, you have to pay a cost that is calculated in the following way.

Cost to change price = (price you charged last period)*(how many units you have produced this period)*0.025.