Do Expectations and Decisions Respond to Monetary Policy? *

Luba Petersen
Simon Fraser University

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Abstract

This experiment explores the ability of monetary policy to generate real effects in laboratory general equilibrium production economies. To understand why monetary policy is not consistently effective at stabilizing economic activity, we vary the types of agents interacting in the economy and consider treatments where subjects are playing the role of households (firms) in an economy where automated firms (households) are programmed to behave rationally. While the majority of participants' expectations respond to monetary policy in the direction intended, subjects do form expectations adaptively, relying heavily on past variables and forecasts in forming two-steps-ahead forecasts. Moreover, in the presence of counterparts that are boundedly rational, forecast accuracy worsens significantly. When interacting with automated households, updating firms' prices respond modestly to monetary policy and significantly to anticipated marginal costs and future prices. The greatest deviations in behavior from theoretical predictions arise from human households. Households' persistent oversupply of labor and under-consumption is attributed to precautionary saving and debt aversion. Our results provide evidence that the effects of monetary policy on decision making hinge on the distribution of indebtedness of households.

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1 Introduction

Modern general equilibrium frameworks widely used by policy makers and academics work under the assumption that agents' expectations respond to shocks, and expectations are a driving factor in decision making. This paper explores whether this is, indeed, the case in the context of a laboratory Keynesian-inspired production economy.

We study how agents beliefs and decisions evolve in response to exogenous shocks to nominal interest rates. This experimental study builds on existing production economy experiments conducted by Bosch-Domnech and Silvestre (1997) and Lian and Plot (1998) that explore convergence properties, macroeconomic dynamics, and the effects of expansionary monetary policy. Lian and Plott increase the level of money supply across treatments in a between-subject design and find that larger aggregate money balances lead to higher price levels but no effects on output. Bosch-Domnech and Silvestre gradually increase the availability of credit in a credit-constrained economy. Marginal increases in credit only have significant real effects when the credit-constraint is binding. When the constraint no longer binds, increased liquidity leads to inflation. In both environments, prices are highly flexible - an important impediment for monetary policy to be effective.

More closely related to us are the production economy experiments of Noussair et al. (2014, 2015) and Fenig et al. (2014). These environments involve imperfect competition and nominal rigidities in the form of menu costs and Calvo pricing, respectively. Noussair et al. (2014, 2015) develop a stochastic production economy environment to study how economies respond to exogenous disturbances to productivity and demand shocks. In their environment, they also explore how the endogenously set nominal interest rate influences aggregate outcomes. Fenig et al. (2014), extending the design presented in this paper, construct an environment where subjects play the role of household-investors that make consumption, labour, and asset trading decisions. They explore the effects of asset trading on aggregate outcomes and the ability of monetary policy to dampen asset price bubbles. In both Noussair et al. and Fenig et al., changes in the nominal interest rates do not have a significant effect on production. Feng et al. observe, however, that savers and borrowers respond differently to monetary policy. Borrowers will work significantly more and consume significantly less in response to increases in the nominal interest rate.

In complex interdependent systems it can be challenging to identify causal factors. In the existing experimental work, it is unclear whom to attribute the unresponsiveness of monetary policy. For example, a firm that is under-producing may either be exhibiting risk aversion or may be responding to a lack of consumer demand. To better understand why experimental economies do not respond to monetary policy, we first study agent behaviour in isolation. In one treatment, participants playing the roles of consumer-workers interact with rational automated firms. In a second treatment, participants assume the roles of profit-maximizing firms that interact with rational automated consumers. These treatment variations allow us to identify if either type is prone to under- or over-reaction to monetary policy. Finally, in a third treatment, participants of both types interact together. These results are compared with our theoretical benchmark. Subjects make consumption demand, labour supply, and expectation decisions each period. Our experiment is unique in the production-economy literature in that we elicit subjects' expectations each period to infer if their beliefs respond to changes in the environment and whether their decisions respond to those beliefs.

Our experimental findings suggest that monetary policy does lead to significant real effects in most sessions. The direction and responsiveness of the economy to the shocks are most consistent when subjects playing the role of firms interact with automated consumers. When subjects play the role of consumer, both the size and direction of the economies' reactions become unpredictable. This is due largely to the heterogeneous effects monetary policy has on savers and borrowers. Heavily indebted economies feel less pressure to work when interest rates fall and reduce their labor supply, while high saving environments increase labor supplies to compensate for the lower interest income. Our finding contrasts with the predictions of the representative agent framework that assumes zero net saving in equilibrium. Finally, we observe that the majority of participants' expectations do respond to monetary policy in the direction intended, though forecast accuracy is considerably compromised in the presence of more boundedly rational individuals.

2 Methodological Contributions

Our experimental design deviates from the existing experimental general equilibrium literature in a number of ways. First, we incorporate posted price markets rather than continuous double auctions (CDA) as a mechanism to trade output. The convention has been to employ CDAs to represent highly competitive markets with rapid price adjustment (Smith, 1962). The lack of nominal rigidities in the experimental economies may be a driving factor in the observed neutrality of money. Indeed, the New Keynesian literature has identified price and/or wage rigidities as an essential element in generating real effects from monetary policy. Under a CDA where both firms and consumer-workers are aware of an increase in money supply or credit, price adjustment will be very rapid. Firms may interpret increased money balances as a signal of the households' ability to pay more and consumer' willingness to pay for each unit is non-decreasing in money balances. Moreover, significant price adjustment occurs within a single period as firms can update their prices instantaneously in response to their competitors' asks. Without a sufficient nominal friction, it is natural that prices would increase without any change in output demanded. Posted price markets restrict firms to submit prices once for a single period, impeding competitive pressures. We couple this with Calvo (1983) pricing to generate sufficient nominal rigidity to facilitate a response to monetary policy. Noussair et al. (2014, 2015) also employ a posted price market to generate persistence in output prices but do not study its effects in the context of a monetary policy shock.

Second, we introduce a novel way to calculate nominal wages. Generally, labour markets have been represented by CDAs where firms trade laboratory currency in exchange for labour hours. Instead, we automate the nominal wage based on equilibrium conditions, the current nominal wage, and participant-provided expectations. This design choice allows us to clearly identify factors driving changes in the nominal wage. From a practical standpoint, it reduces the amount of time necessary for markets to converge. GE experiments with multiple markets operated by CDAs lasts 405 hours with instructions and can quickly become very expensive. Elimination of the labour market auction effectively shortens each period by 1.5-2 minutes. This amounts to over 2 hours over a 90 period game.[1] Finally, this approach is closer to the theoretical benchmark that assumes agents take nominal wages as given.

We further modify the monetary instrument. Nearly all laboratory experiments studying the effects of monetary policy shocks do so through the injection of money balances into bank accounts on either one or both sides of a market. This combined with CDA markets only results in rapid inflation. Instead, a monetary shock in the economy presented here occurs through an exogenous decrease in the nominal interest rate on saving and borrowing. All else equal, such an exogenous shock is predicted

[1] A key assumption in the New Keynesian framework is that firms operate in an imperfectly competitive market. This is frequently modelled as monopolistic competition. Consumers' are assumed to have a preference for variety, and purchase a bundle of varieties. To simplify the environment and save time, consumers make decisions on how many units of the bundle they would like to purchase rather than the individual varieties.

to increase the output gap and inflation through an increase in the real wage and consumer demand.

Finally, we ask subjects to form wage and price forecasts at the beginning of each period for the current and following period. These forecasts are used to calculate implied output gap and inflation expectations. There has been a growing literature of learning-to-forecast experiments that study expectation formation in New Keynesian environments. Assenza et al. (2014), Pfajfar and Zakelj (2014a,b), and Kryvtsov and Petersen (2015) study the stabilizing properties of Taylor rules in forward-looking New Keynesian environments. In these experiments, subjects play the role of professional forecasters and are paid based on their accuracy of their forecasts rather than the realized state of the economy. Our experiment is the first to analyze expectation formation within a production economy. This allows us to observe the extent to which forecasts and real decisions are aligned.

3 Theoretical Framework

The theoretical framework follows the benchmark New Keynesian model described in Walsh (2010). The economy consists of households, firms, and a monetary authority. The objective of households is to maximize their expected present discounted value of utility from consumption and leisure. Each period, households decide how many units of consumption bundles to purchase and how many hours to work. The objective of firms is to maximize their real profits by producing and selling a particular variety within the consumption bundle. Firms interact in an imperfectly-competitive market and can only update their prices randomly. Firms face a constant probability of being able to update their price each period, allowing for a dispersion of prices outside of the steady state. Pricing decisions of all firms affect consumer demands for each variety, and, subsequently firms' demand for their sole input, labour. Labour markets are competitive in that all agents take nominal wages as given. Borrowing and saving is conducted through one-period bonds that pay a nominal rate of return. This rate of return is set by the central bank, whose objective is to stabilize inflation to zero. The only economic disturbance that occurs in this economy is an expansionary monetary shock conducted through the nominal interest rate. The shock follows an AR(1) process.

4 Experimental Environment

The laboratory economy consists of two simultaneous markets, labour and output, and two types of participants, firms and households. In each economy there are four households who trade their endowed labour hours for laboratory currency (henceforth "money") to four firms. Using identical technologies, firms transform all labour hours hired into a final output which they sell back to the consumers in exchange for money. Consumers immediately consume the output they have purchased.

Preferences, endowments, and technology are controlled in this environment. The objective of all subjects is to maximize the number of points they individually earn. For consumers, this means consuming as many units of output and working as few hours as possible to maximize their utility. For firms, each sets a price to maximize their real profits.

4.1 Firms

Firms are incentivized to maximize their per-period real profits. For firm i, real profits are calculated as:

$$\Pi_{it} = \frac{P_{it}Y_{it} - W_t N_{it}}{P_t}$$

where $P_{it}Y_{it}$ are the revenues earned by firm i, $W_t N_{it}$is its wage bill, and P_t is the aggregate price of the consumption bundle. Each firm possesses an identical constant-returns-to-scale technology given by

$$Y_{it} = ZN_{it}$$

where Z is a constant productivity parameter.

Firms must decide what price to set for their output. Each period, the probability that a firm can update its price is $1 - \omega$. It must factor in expected nominal wages and demand over its expected lifetime when making its decision.[2]

[2] We employ Calvo pricing to provide a more consistent test of the theoretical framework. One could alternatively design the experiment to incorporate other pricing frictions such as menu costs or quadratic costs associated with price adjustment. Evidence on the nature of pricing frictions is mixed. While Nakamura and Steinsson (2008) find considerable support for benchmark menu cost models with micro data from the Bureau of Labour Statistics, Eichenbaum et al. (2011) argue that even the standard menu cost models fail to match a number of aspects in the micro-data. Prices are more volatile than costs and are generally associated with cost changes. Moreover, neither menu cost or Calvo pricing models are able to capture the simultaneous high-frequency price flexibility and low-frequency price stickiness observed in the data.

The prices set by all firms will determine the level of demand for each variety:

$$Y_{it} = \frac{1}{I} P_{it}^{-\theta} P_t^{\theta} C_t$$

where P_t is the aggregate price level defined as $P_t = I^{\frac{1}{\theta-1}} \left[\sum_{i=1}^{I} \left[(P_{it})^{1-\theta}\right]\right]^{\frac{1}{1-\theta}}$ I is the number of firms in the economy, and $\theta$is a preference parameter describing the household's preference for variety.

4.2 Households

The objective of all households is to maximize their points, U_t. Each period t, households earn points from buying and immediately consuming units of the consumption bundle, C_t, and lose points by working more hours, N_t. The subjects' objective is to maximize their points earned over all periods. Their points in period t are given by:

$$U_t = \frac{C_t^{1-\sigma}}{1-\sigma} - \frac{N_t^{1+\eta}}{1+\eta} \tag{1}$$

where $1/\sigma$ and $1/\eta$ are parameters governing the elasticities of intertemporal substitution and labour supply, respectively. Each period, households are asked to submit their maximum willingness to work (N_t^S) and the maximum amount of output they would like to purchase (C_t^D).[3] Households face the following nominal budget constraint:

$$P_t C_t + B_t = W_t N_t + (1 + i_{t-1}) B_{t-1} + \Pi_t$$

The left hand side of the budget constraint describes the household's nominal expenditures on current consumption and purchase of nominal bonds. The right hand side of the budget constraint describes the household's current flow of income, consisting of wage income, interest on last period's saving, and dividend payments from the firms' profits. That is, participants playing the role of households receive positive but diminishing points for each additional unit of output they purchase and lose an

[3]The composite good is made up of the different varieties:

$$C_t = I^{\frac{1}{1-\theta}} \left[\sum_{i=1}^{I} C_{it}^{\frac{\theta-1}{\theta}}\right]^{\frac{\theta}{\theta-1}}$$

where $C_{it}$is a household's consumption of variety i in period t.

increasing number of points for each hour of labor they supply.

An optimizing agent will trade off current and future consumption according to the following Euler equation:

$$C_t^{-\sigma} = \beta(1 + i_t)E_t C_{t+1}^{-\sigma} \frac{P_t}{P_{t+1}}$$

and will substitute between consumption and leisure in period t according to the equilibrium condition:

$$N_t^{\eta} C_t^{\sigma} = \frac{W_t}{C_t}$$

4.3 Central Bank Policy Rule and Shock Process

An automated central bank operates in the background. It follows a Taylor rule that sets nominal interest rates to target deviations of last period's inflation from its target $\pi^* = 0$:

$$i_t = \rho + \delta(\pi_{t-1} - \pi^*) + v_t$$

where rho is the steady state nominal rate of return, δ denotes the responsiveness of nominal interest rates to deviations of past inflation from the central bank's inflation target, and

$$v_t = \rho_v v_{t-1} + \epsilon_t$$

is a monetary shock that follows an AR(1) process with persistence parameter ρ_v and white-noise process ϵ_t.

The central bank can influence the real interest rate, and subsequently demand and production, through manipulation of its nominal interest rate. The experiment presented here tests whether discretionary monetary policy in the form of an exogenous and unanticipated decrease in the nominal interest rate leads households to increase their consumption and firms to reduce markups on impact of the shock. After subjects have been given time to equilibrate (approximately 12 periods in the first session, and fewer throughout), the policy shock $\epsilon = -0.025$ occurs, lowering the nominal interest from $\rho = 5\%$ to $\rho - \epsilon_t = 2.5\%$.

This approach of stabilization has also been employed by Fehr and Tyran (2001), Davis and Korenok (2010), and Petersen and Winn (2014) to explore the effects of money supply shocks on price adjustment in partial equilibrium frameworks. This feature is absent in the experimental general equilibrium literature, where shocks occur either between treatments (Lian and Plott, 1998) or continuously within a treatment without any opportunity for stabilization (Bosch-Domenech and Silvestre, 1997; Noussair et al., 2011). [4]

Participants were informed that the nominal interest rate would adjust every period, but that in the long run, the experimental central bank would aim to keep the rate at 5% per period. They were encouraged to pay attention to the nominal interest rate as it would affect wages and aggregate prices.

4.4 Wage Determination

At the beginning of each period subjects are presented with the current nominal interest rate and asked to submit forecasts for wages and prices for the current and following period. Median elicited expectations are used to calculate nominal wages:

$$W_t = \overline{W}\left(1 + E_t\hat{W}_{t+1} + \frac{\eta}{\sigma}E_t\left(\hat{P}_{t+1} - \hat{P}_t\right) - \frac{\eta+\sigma}{\sigma}(i_t - \rho)\right) \tag{2}$$

where $\overline{W}$ is the steady state level of nominal wages, i_t is the current nominal interest rate, ρ is the discount rate, and variables with hats refer to log deviations from steady state levels. This wage is taken as given by subjects when they form their pricing, consumption and labour decisions. Derivations of Equation 2 can be found in the Appendix. To avoid manipulation, the human firm that has an opportunity to reset its price is excluded from the calculation

It was important that subjects took the task of forecasting seriously. Each period, participants were paid a small bonus of 0.50 points for relatively accurate forecasts, that is, forecasts that were within 0.01 lab dollars of the correct answer. [5] The bonus was small relative to payments for making labor, consumption, and pricing decisions to ensure that dominance was not compromised. The scoring rule has the virtue of simplicity and, assuming negligible marginal effort costs to improving the forecast, is incentive compatible.

After subjects submit their decisions in the input and output markets, an algorithm is applied to allocate output using a proportional rationing rule. All output is demand determined and subject to a labour supply constraint. In short, no output

[4]We experimented with other stabilization lengths, including as long as 55 periods before shocking the economy. There is not much improved convergence beyond 15 periods. Subjects became very restless during the 55 period stabilization and dominance was potentially compromised.

[5]A firm that was updating its price was ineligible to receive the forecasting bonus.

produced is left unsold. Details of the rationing algorithm are discussed in the next section.

4.5 Markets

Firms and households interact simultaneously in input and output markets. Households submit their labour supply and output demand while firms make pricing decisions. In the case of automated firms, the pricing decision of the updating firm is known a priori. This differs from Noussair et al. (2014, 2015) where the labour market precedes the output markets.

Labor Market

Households trade their labor hours to firms in exchange for money wages, specified at the opening of the market each period. Aggregate demand for labour is determined by households' demand for output, and thus by the prices set by all firms in the economy. Households have a maximum 10 hours in which they may work, and may work fractions of an hour. Households lose an exponentially increasing number of points as they work additional hours.

Output Market

Each firm produces a unique variety of a good (Red, Blue, Green, and Orange). At the beginning of every period one firm is randomly selected to reset its price. An aggregate price index is calculated; this will be the price that households pay for each unit of the composite good. Firms are required to fully supply household demand given its own price and the aggregate price level.

Households must then decide how many units of the composite good they would like to purchase while making their labour decisions. They may borrow up to 150% of their expected wealth in the form of a one-period bond. That bond must be repaid, with interest, in the next period through a deduction in wage income. Alternatively, a household may choose to not consume their entire budget. In that case, their unspent income is automatically saved in form of interest-bearing bonds. The households' desired consumption levels together with the firms' prices determines the demand for each variety.

Procedures

1. Given a wage, one firm has the opportunity to update its price. An aggregate price is then calculated.

2. Households have the opportunity to select how much they would like to work and consume. The demand for each variety is calculated.

3. Total labour demand by firm i given total variety demand by each of the h households is given by:

$$N_{it}^{D} = \frac{\sum_{h=1}^{4} Y_{ht}^{i}}{Z}$$

   Total labour demand is the sum of demands across all four firms:

$$N^{D} = \sum_{i=1}^{4} N_{it}^{D}$$

   while total labour supply is given by the sum of supplies across all four households:

   (a) If $N_t^D = N_t^S$, labor is distributed across firms according to need. Each household works and consumes the amount they submitted.

   (b) If $N_t^D < N_t^S$, there is excess labor supply. Firms will hire up to their desired demand. Each household will consume the amount that they requested, and receive a rationed amount of labor hours. Households that submitted $N_h^S \leq \frac{C_h^D}{Z}$, ie. are not contributing to the relative excess labor supply, will work their desired number of hours. Otherwise, a household is allocated $N^S = \frac{C^D}{Z}$. If there is any remaining labor hours available (due to some households under-working), those hours will be distributed among the over-working households according to relative demand.

   (c) If $N_t^D > N_t^S$, there is excess labor demand. All households will work the maximum amount they desired. Labor will be split across firms according to relative demand. Households that submitted $N_h^S \geq \frac{C_h^D}{Z}$, ie. are not contributing to the relative excess consumption demand, will consume their desired number of units. Otherwise, a household is allocated $C^D = ZN^S$. Remaining units of output are distributed among the over-consuming households according to relative demand.

5 Experimental Implementation

The experiments were conducted at the University of California Santa Cruz. The subject pool consisted of undergraduate student recruited from a wide variety of disciplines using the Online Recruitment System for Economic Experiments (ORSEE) (Greiner (2004)). No subject participated in more than one treatment. Sessions lasted for approximately 2-2.5 hours and consisted of 20 minutes of instructions, a short comprehension quiz, and three rounds of practice with the software. All this was done to familiarize subjects with the experimental environment and their payoff structure.

Six sessions were conducted for each of the three treatments. Each session consisted of five stationary repetitions (or sequences) of varying lengths. Each repetition of the economy lasted for a random number of periods, with the shock occurring near the middle of the repetition. At the start of a new repetition, the economy was reset to the steady state.Table 1 provides details on repetition lengths and periods of shocks. After five repetitions, subjects' points associated with expectations and decision-making (realized output purchases and labor supply for household participants and real profits for firm participants) were converted and paid to subjects in cash. Average earnings were $28.45, including a $5 showup fee.

5.1 Treatments

We implement a number of treatment variations to study the individual and aggregate effects of monetary policy on the decisions of firms and households. Three treatments are studied in a between-subject design:

1. **Benchmark Economy (B):** The experimental economy is populated with computerized rational agents and provides a theoretical reference point for the other treatments

2. **Human Firms (HF):** Four participants play the role of firms and interact with four automated consumers

3. **Human Households (HH):** Four participants play the role of households and interact with four automated firms

4. **Human Firms and Households (HFH):** Four participants play the role of firms while another four participants play the role of consumers

Automated agents form optimal decisions according to the first order conditions described by agents' optimization problems. Decisions that involve expectations of future variables use the median elicited expectations of the human subjects. Details of the automation procedures are provided in the appendix. The treatment variations provide insight into how households and firms respond to policy shocks, holding the other side of the market's decisions constant.

Human Firms Treatment

In the HF treatment, human firms interact with automated households. This environment allows us to detect suboptimal pricing behavior in the presence of optimally behaving households. Firms submit their daily forecasts at the beginning of each period. Only the forecasts made by the non-price setters are used in the median forecast calculations. The nominal wage is computed and firms are informed of the current wage rate and the anticipated demand of households.

The resulting level of aggregate consumption will be given by

$$C_t = \overline{C}\left(1 + \frac{1}{\eta+\sigma}\left(E_t\hat{W}_{t+1} - E_t\hat{P}_{t+1}\right) - \frac{1}{\sigma}(i_t - E_t\pi_{t+1} - \rho)\right) \tag{3}$$

Given this level of consumption, each household's labor supply decision will be given by

$$N_t^S = \left[C_t^{-\sigma}\frac{W_t}{P_t}\right]^{\frac{1}{\eta}} \tag{4}$$

Any income that is unspent on output is saved and earns a nominal rate of return. The updating firm is able to reset its price after learning the nominal wage and aggregate level of consumption. Demand for each variety is determined and profits are calculated.

Human Households Treatment

In the HH treatment, human households interact with automated firms. This environment allows us to observe how subjects playing the role of households trade off current and future consumption, as well as trade off consumption for leisure.

Each period begins with households submitting their daily forecasts and the nominal wage and aggregate price level are then calculated. The automated firm that can update its prices does so optimally given aggregate expectations. All firms prices are initialized at the steady state level in the first period. Conveniently, we do not need to obtain the optimal price of the updating firm to calculate the price index. Rather, we can make use of the New Keynesian Phillips Curve, substitute in the New Keynesian IS curve and simplify to obtain an equation for the inflation rate:

$$\pi_t = \beta E_t \pi_{t+1} + \kappa \left\{ \frac{1}{\eta + \sigma} \left(E_t \hat{W}_{t+1} - E_t \hat{P}_{t+1} \right) - \frac{1}{\sigma} \left(i_t - E_t \left(\hat{P}_{t+1} - \hat{P}_t \right) - \rho \right) \right\}$$

The price of the composite good is then given by

$$P_t = P_{t-1}(1 + \pi_t) \tag{5}$$

Human Firms and Households Treatment

In the HFH treatment both types of participants interact together. They begin each period by submitting forecasts for wages and prices. The median forecasts are used to calculate the nominal wage. The updating firm can adjust its price while consumers are making their consumption and labour decisions. After all decisions are submitted, the aggregate price is calculated and labour hours and consumption units are allocated.

5.2 Parameterization

Table 1 outlines the parameter set used throughout the experiment. Calibrations are constant across treatments and are selected to ensure a sufficiently large predicted behavioral effect of the shock. In most cases, we are able to use empirically consistent parameters. To implement exponential discounting of future payoffs and the stationarity associated with an infinite horizon, we follow the advice of Duffy (2012) and have a constant probability β of continuation onto a next period. If a sequence does not continue onto a next period, a new sequence is begun. As we cannot feasibly keep subjects for very long stretches of time, we do not use the standard $\beta = 0.99$, but reduce it slightly to $\beta = 0.9523$, implying an expected duration of 21 rounds from the start of each pre-drawn sequence.

5.3 Computer Interface

The software was programmed in z-Tree (Fischbacher (2007)). Screen shots of the computer interface can be found in the Appendix.[6] Participants were not informed that their forecasts are used in the calculation of nominal wages and in the decisions of automated agents. Each consumer received tables and a computerized calculator to determine the points he would earn from different combinations of consumption and hours worked. Similarly, each firm had access to a computerized calculator that would inform her of how real profits would be calculated for different combination of her price and the aggregate market price.

5.4 Experimental Predictions

Under the experimental calibrations, optimal levels of labour and consumption can be determined from the consumer's first order conditions. In the steady state, each subject i should work $L_i = 3.38$ hours and consume $C_i = 33.8$ units of output, resulting in an aggregate $L = 13.52$ hours worked and $C = 135.2$ units consumed.

There are two mechanisms by which expansionary monetary policy may affect aggregate demand and production. Changes in the nominal interest rate that affect the real interest rate should induce households to adjust their intertemporal tradeoff of consumption and labour. Decreases in the nominal interest rate should lead to a positive increase in current consumption and labor supply. Monetary policy will also influence the economy through an expectations channel. Expectations of future low interest rates lead to higher real wage expectations, which in turn will lead to immediately higher real wages and an opportunity for consumers to purchase more output.

Assuming households form rational expectations about future variables, a 2.5% decrease in the nominal interest rate induces consumers to increase their labor supply and consumption by 7.74% to $N_i = 3.63$ and $C_i = 36.3$. That is, an increase in aggregate labour hours and consumption to $L = 14.52$ hours and $C = 145.2$ units.

Monopolistically competitive firms are expected to maintain a markup of 15% in the steady state. When the shock occurs, the theoretical predictions of the model suggest that the markup should fall. Inflation should equal 1.1% resulting in a small change in the nominal price from 1.15 to 1.1626.

[6] The online Appendix can be found at http://www.sfu.ca/ lubap

6 Results

We analyze our data by first studying whether subjects' expectations respond to changes in their environment as well as to the shocks that occur. We then estimate the extent to which agents' condition on their forecasts when making decisions. Finally, we highlight some intriguing behaviour worth exploring in future experiments.

6.1 Expectations

In every period t, subjects submit forecasts for wages and prices in both the current period and one period ahead. Let $E_t^i W_t$ and $E_t^i P_t$ denote the forecasts subject i submits in period t regarding period t wages and prices and let $E_t^i RW_t$ be its implied real wage forecast. Similarly, let $E_t^i W_{t+1}$, $E_t^i P_{t+1}$, and $E_t^i RW_{t+1}$ denote subject i's period t forecasts for nominal wages, prices, and the real wage for period $t+1$. Real wage forecasts are simply computed for each individual as their expected wage divided by their expected price.

We plot the kernel density functions for absolute real wage forecast errors in Figure 1. The solid blue line denotes the densities associated with forecasts for the current real wage while the dashed red lines denote densities for the following period's real wages. For each type of participant we observe that there is considerably greater mass around zero forecast errors when participants form their period t expectations. Period t+1 forecast errors are considerably larger. Median absolute forecast errors are consistently larger when participants are forecasting $t+1$ real wages. For household participants, the $t+1$ forecast errors are 0.03 units higher in HH and 0.07 units higher in HFH. Similarly, firm participants' $t+1$ forecast errors are larger by 0.07 units in HF and 6.02 units in the HFH treatments. These results suggest that forming forecasts further into the future is considerably more difficult for participants, especially in the presence of boundedly rational firms.

Forecast errors also increase considerably when participants face human households or firms on the other side of the market. For households participants, the inclusion of human firms increases median RW_t forecast errors by 0.05 units and RW_{t+1} forecast errors by 0.09 units. For firms, the introduction of human households does not alter median current period forecast accuracy (the error decreases by 0.001 units), median RW_{t+1} forecast errors increase by 5.94 units.

What drives expectations? Under the canonical model, changes in the nominal interest rate should immediately influence participants' wage and price expectations.

Extensive experimental evidence by Pfajfar and Zakelj (2014), Kryvtsov and Petersen (2013), and Assenza et al. (2014), however, suggests that forecasters rely heavily and persistently on past realized wages and prices to inform their predictions. To understand how individuals' expectations respond to monetary policy, we conduct the following fixed effects regression: $E_{i,t}W_t = \alpha_i + \beta_0 i_t + \beta_1 i_t \times HF + i_t \times HFH^H + i_t \times HFH^F + \gamma W_{t-1} + \epsilon_{it}$, where α_i refers to a time-invariant individual effect, i_t refers to the period t interest rate, HF, HFH^H and HFH^F are dummy variables that take the value of 1 when the participant is a firm in the HF, household in the HFH treatment and a firm in the HFH treatment, respectively, and e_{it} is the error term. Household participants in the HH treatment are taken as the baseline response. We also consider a specification that takes the one-step ahead forecast $E_{i,t}W_{t+1}$ as the dependent variable. Similar regressions are conducted for price and real wage expectations. The results from the pooled regressions are presented in Table 2 and discussed below. We also estimate, for each individual, the above regressions and plot the estimated coefficients associated with nominal interest rates as cumulative density functions in Figure 2. The CDFs indicate that the majority of participants anticipate wages, prices, and real wages will respond positively to decreases in the nominal interest rate, suggesting they had a decent understanding of the data-generating process. At the same time, we observe that nearly 45% of HH participants and 25% of participants in other treatments whose expectations respond negatively to decreases in the nominal interest rate.

The first two columns refer to nominal wage expectations. In the HH treatment, expectations of the current wage decrease modestly in response to changes in the nominal interest rate. A 1% increase in the nominal interest rate leads to a 0.014 unit decrease in the expected nominal wage. Behaviour is not significantly different across treatments due to considerable heterogeneity. HF participant increase their wage expectations by 0.01 units in response to a 1% increase in the interest rate. Participants in the HFH treatment reduce their expectations even further than HH participants, but again this is not significantly different from behavior in the HH treatment. We compare HF to HFH^F participants (not reported here) and find that while HFH^F participants respond more negatively to increases in the nominal interest rate, the differences are not statistically significant (p-value = 0.177). We observe similar outcomes when we take $E_{i,t}W_{t+1}$ as the dependent variable. The only key difference is that firms' expectations in the HFH treatment are significantly more responsive to expansionary monetary policy than in the HH treatment. Moreover, firms' reactions to changes in nominal interest rates are significantly more pronounced when they interact with boundedly rational households in the HFH treatment.

Monetary policy also has quantitatively small and statistically insignificant effects on participants' price and real wage expectations. In the third and fourth columns, we present results from current price and the following period price expectations with the HH participants as the baseline. HH participants' price forecasts barely respond to increases in the nominal interest rate. While HFH^H household participants exhibit considerably more contractionary reactions compared to HH participants, the differences across treatments are not statistically significant. If we change the baseline treatment to HF, we observe that HFH^F participants form relatively more contractionary price expectations, $E_{i,t}P_t$, and this difference is statistically significant at the 5% level. Real wage forecasts do have a sizeable reaction to monetary policy but there is a high degree of heterogeneity in participants forecasts and we cannot reject at the 10% level that their reactions are different from zero. We also do not observe any significant differences between HH participants and the other types.

By contrast, participants respond considerably and significantly to lagged information. Nominal wage, price, and real wage expectations respond strongly to the their corresponding previous period's values. Controlling for changes in the nominal interest rate, a 1 unit increase in the nominal wage last period results in average E_tW_t rising by 0.736 and E_tW_{t+1} by 0.681. The response to lagged wages is significant at the 1% level. Similarly, expected prices significantly respond to changes in past prices: a 1 unit increase in lagged prices results in a 0.623 unit increase in E_tP_t and 0.626 unit increase in E_tP_{t+1}. Real wage expectations - as a result - are highly dependent on lagged real wages.

6.2 Individual Decision Making

Having shown that monetary policy has a highly heterogeneous impact on participants' expectations - regardless of type - we now turn to their market decisions. Of interest is how expectations and monetary policy influence decision making.

We begin with firm price-setting behavior. When randomly given the opportunity to reset their price, firms must consider the expected future wages, prices, and interest rates that influence consumer demand. Over the course of the entire horizon, mean prices (updated prices) are 1.163 (1.166) in the HF treatment and 1.169 (1.172) in the HFH treatment. At the session-level, a two-sided Wilcoxon rank sum test fails to reject the null hypothesis that the mean aggregate price index and the mean updated prices are different across treatments (p-value > 0.63 in both cases).

We conduct a series of fixed effects panel regression on pricing decisions formed by the price setter in each round, where we consider the impacts of interest rates, expectations, and lagged realized values. The results are presented in Table 3.

The first specification considers the effect of interest rates and expectations on pricing decisions. Expected current wages and expected future prices have sizeable and significant effects on pricing decisions. Higher expected wages in the current period motivate firms to increase their prices in the current round. For a 1 dollar increase in E_tW_t, the average firm will raise its price by 0.012. This reaction is significant at the 10% level. Expected increases in wages in the next period do not have a large of significant effect. Longer run expected prices have a quantitatively large and highly significant effect on firms' pricing decisions. A 1 dollar increase in E_tP_{t+1} is associated with a 0.655 increase in prices. Given that a price setting participant should not expect to update his or her price for some number of periods, the positive reaction to future higher prices indicates that participants are behaving consistently with the strategic complementarity assumption of the environment. Higher interest rates lead to minimal changes in prices. A 1% increase in the nominal interest rate leads price-setters to reduce their prices by 0.2 cents. While this is consistent with the predictions of the model, the response is highly heterogeneous and not statistically significant.

The second specification explores whether lagged wages and prices can explain pricing behavior. Higher nominal wages and prices both result in firms raising their prices. This is consistent with the previous specification, as expectations have been shown to be highly and significantly dependent on lagged information. Firms are an order of magnitude more responsive to lagged prices than lagged wages.

Pooling all the aforementioned variables together in the third specification, we observe that most of our previous findings hold. Expected wages and prices, driven largely by past realized values, remain an important driver of prices. Holding expectations and lagged information constant, interest rates continue to have a modest and now significantly contractionary effect on prices. Finally, in our fourth specification, we consider whether HF and HFH^F firms respond differently to monetary policy by including the interaction term $i \times HFH^F$. In this case, we find that the average reaction to monetary policy is considerably muted in the HFH^F treatment. Holding expectations and lagged information constant, HF firms decrease their prices by 0.6 cents in response to a 1% increase in the nominal interest rate. By contrast, HFH firms decrease by 0.1 cents less, or by approximately 0.5 cents. This difference is statistically significant at the 10% level. While monetary policy does not have a consistent effect on expectations, it does lead price-setting firms to consistently respond in the direction of our model's predictions. To get a better sense of the heterogeneity in reactions to policy, we estimate Specification (4) at the individual level and plot the distributions of estimated coefficients associated with monetary policy for each treatment in Figure 3. Across the entire distribution, HF firms respond more negatively to increases in nominal interest rates than their HFH counterparts. There are more firms in the HF treatment behaving consistently with the price-setting predictions of the model than in the HFH treatment. Moreover, among the firms that increase prices in respond to higher interest rates, we observe that HFH firms increase their prices by more than HF firms. The mean price-setter in the HF treatment lowers its price by an average 0.01 dollars for every 1% increase in the nominal interest rate. By contrast, the mean HFH firm increases its marginally price by 0.002.

Households face a more complex task of deciding how much labor to supply and output to consume while managing their bank account balances. This involves considering expected future wages, prices, and nominal interest rates. Experimental findings by Meissner (2014), Fenig et al. (2014) and Fenig and Petersen (2014) consistently finds heterogeneous consumption and labor smoothing behavior along wealth levels. Indebted individuals to significantly overwork and under-consume in an effort to get out of debt. As such, we divide our household participants into savers and indebted. Participants that have positive bank account in more (less) than 50% of the periods are considered savers (indebted). Chronically indebted participants account for approximately 36% of HH and 41% of HFH households.

Figure 4 presents cumulative distribution functions of mean individual labor supplies and output demands by treatment and phase of each repetition (pre- or post-shock). The mean supplies are computed for each individual over pre- and post-shock phases of all five repetitions. Solid CDFs indicate savers while dashed CDFs refer to Indebted types. Vertical solid and tight-dotted lines indicate the steady state and on-impact-of-shock equilibrium levels of individual labor supply and output demand, respectively. Savers supply less labor and demand less output than their indebted counterparts in both phases of the HH and HFH experiments and the majority of participants of both types tend to supply more labor than predicted. The exception is the preshock HFH saving households whose median labor supply is very close to the equilibrium prediction (though there are many participants supplying above and below this value). The median saver in the HH treatment has demands very close to the equilibrium prediction in the preshock phase, but their demands minimally change in the postshock phase. By contrast, the median indebted household tends to demand more than predicted in the preshock phase but less than predicted in the postshock phase. We observe a similar pattern in the HFH treatment with the exception that savers in the preshock phase considerably under-demand output. Both savers and indebted participants increase their labor supplies and output demands in the postshock phase. In the preshock phase of the HH treatment, median labor supply (output demand) is 3.65 (33.89) for savers and 3.61 (36.12) for indebted participants, while postshock, median labor supplies (output demands) increase to 3.74 (33.70) and 3.91 (35.66), respectively. Similarly, in the HFH treatment, preshock labor supply (output demand) for savers is 3.38 (31.67) and 3.92 (34.28) for indebted participants and increases in the postshock phase to 3.67 (34.35) and 4.17 (34.60).

We next consider the determinants of labor supply decisions in Specification (1) of Table 4. Labor supply is considerably impacted by the participants' output demand. Increasing demand by an additional 1 unit leads households to also raise their labor supply by approximately 0.038 hours. A 1% increase in the nominal interest rate leads household participants to supply an additional 0.6 hours. This effect is significant at the 10% level. Labor decisions also respond positively to rising real wages, with a 1 dollar increase in the real wage increasing labor supply by an average of 0.13 hours. The response is highly heterogeneous across participants and not statistically significant. In Specification (2), we observe that participants' labor supply decisions are, on average, minimally and insignificantly responsive to their expected future real wage inflation. However, the response to expected real wage inflation is highly heterogeneous, as noted by the relatively large standard errors. In Specification (3), nominal interest rates are interacted with a summary variable $Indebted$ which takes a value of 1 when a participant's last period bank account balances were negative and 0 otherwise. This interaction term identifies a differentiated responsiveness to monetary policy among indebted and savers. Indebted participants increase their labor supplies dramatically and significantly more than savers, as interest rates increase. For a 1% increase in the nominal interest rate, indebted households raise their labour supply by 0.12 hours. By contrast, those with saving modestly decrease their labor supply by 0.1 hours. In Specifications (4) and (5), we alternatively consider the effect of entering bank account balances, $Bank_{t-1}$ on labor supply decisions. For every additional dollar of saving, households decrease their labour supply by 0.04

hours. By interacting participants' bank balances with the *Indebted* dummy, we see that as a participant becomes increasingly more indebted, their labor supply grows larger. Indebted participants are significantly more responsive to their bank account balances than savers. Combining all the variables together in Specification (6) yields similar results.

In Figures 5 and 6, we plot the cumulative distribution functions of estimated coefficients associated with regressions conducted on each individual i, where we conduct the following regression $L_{i,t} = \alpha_i + \beta C^D_{i,t} + i_t + \gamma RW_t + \phi E_{i,t}\pi^{RW}_{t+1} + \eta Bank_{i,t-1} + \epsilon_{i,t}$, and a similar specification for output demand. The distributions are broken down by treatment and by IndebtedType. As nominal interest rates increase, approximately 80% of savers in the HH treatment respond by cutting their labor supply. Their indebted counterparts, by contrast, modestly increase their labor supply. In the HFH treatment, saving households respond positively to changes in the interest rate across the entire distribution. The median saver increases its labor supply by 0.16 hours in response to a 1% change in the nominal interest rate. This is significantly higher than in the HH treatment. 48% of indebted household participants in the HFH treatment respond to higher rates by decreasing their labor supply, but this reaction is relatively small. However, many indebted participants exhibit very strong positive reactions to rising rates, and a quarter of participants increase their hours by more than 0.5 hours per 1% increase in interest rates. Thus, indebted participants are prone to supplying considerably more labor than savers in order to pay off debt.

When real wages are expected to increase in the future, households should reduce their labor supply in the current period and work more later. We observe that labor supply decreases for nearly 70% of HH savers as expected real wage inflation increases. Indebted HH participants, on the other hand, increase their labor hours by more in response to the same changes across the entire distribution, suggesting a muted ability to respond to their expectations. In the HFH treatment, the opposite occurs. Savers respond relatively more positively to increases in expected real wages than those in debt.

In response to an extra dollar gained in their bank accounts, nearly all participants decrease their costly labor supply. Median HH and HFH savers are generally the least responsive, with estimated coefficients of η of -0.028 and -0.026, respectively. Indebted participants, by contrast, decrease their labor supplies by 0.038 hours in the HH treatment and 0.578 hours when their bank accounts rise by an additional dollar. Another way to interpret this result is that as households will supply significantly labor when they are chronically in debt as their bank accounts become increasingly negative.

The outcomes of the output demand regressions are presented in Table 5. Across all specifications, higher labor supply is associated with greater output demand. Higher nominal interest rates have, on average, a small positive effect on consumer demand by the response is extremely heterogeneous. Similarly, a 1 dollar increase in the real wage increases average output demand by 2.8-3.1 units, but again this reaction is highly variable across participants and for many participants higher real wages are associated with a reduction in consumer demand. The anticipation of real wage inflation in the future leads to a modest reduction in current consumption, presumably in favor of future consumption. In Specification (3) we introduce nominal interest rates interacted with the *Indebted* dummy variable and observe that indebted participants respond significantly more to increases in the nominal interest rate. While savers increase their consumption by approximately 0.47 units for each 1% increase in nominal interest rates, indebted individuals decrease their consumption by 0.34 units. The differentiated response to monetary policy between borrowers and savers is significant at the 1% level. A similar outcome exists when we instead consider the effects of bank account balances on consumption patterns. As bank accounts rise, participants with saving increase their consumption by significantly more than those with debt. For a $1 increase in bank account balances, savers demand an additional 0.065 units of output.

We again observe a highly heterogeneous reaction to higher nominal interest rates. Median (mean) HH savers profit from higher interest rates and so increase their consumption by an additional 0.817 (0.54) units for a 1% rise in the rate. Median (mean) indebted HH households decrease their consumption by 0.594 (0.973) units, and behavior among the indebted HH stochastically dominates their saving counterparts. Intriguingly, we observe the opposite reaction by savers and borrowers in the HFH treatment. There, for the same 1% increase in interest rates, the median (mean) saving HH household decrease their consumption by 0.601 (0.916) while the median (mean) indebted HFH household decreases (increases) their consumption by an additional 0.143 (0.744) units. In terms of consumption responses to own expectations, there exists little difference across the treatments and types.

Most participants who gain an extra dollar will increase their consumption, irrespective of treatment or wealth level. However, we do find that additional consumption is more prevalent among those with saving. Two-sample Kolmogorov Smirnov tests fail to reject the null hypotheses that any of the distributions are identical, with combined K-S p-values equal to 1.00 in all cases. However, it is quite clear from the cumulative distribution functions that the majority of savers from both treatments demand more output than their indebted counterparts.

6.3 Aggregate Outcomes

In this subsection, we explore whether a nominal interest rate-induced wage increase leads to a change in the labor supply.

A vector autoregression (VAR) analysis on each treatment is conducted to detect whether changes in the nominal interest rate have an effect on the level of output. None of the variables require detrending. A Dickey-Fuller unit root test is applied, rejecting the presence of a unit root in all cases at $p < 0.001$. The number of lags to be chosen in the HF, HH, and HFH treatments is 1 based on the optimal information criteria test. For a thorough treatment of vector autoregression methods, see Stock and Watson (2001).

More specifically, we are interested in studying the impulse responses of the nominal interest rate, inflation, and the output gap to a 2.5% exogeneous decrease in the nominal interest rate while holding the errors associated with inflation and the output gap constant. This can be achieved by imposing that the errors of all three variables are uncorrelated across equations. We estimate a recursive VAR ordered as (i) nominal interest rates, (ii) output, (iii) inflation. The interest rate is the dependent variable and is regressed on lagged values of all three variables. In the second equation, output is the dependent variable and the regressors are lagged values of all three variables plus the value of the current interest rate. Finally, the third equation describes inflation as a function of the lagged values of all three variables plus the current values of the nominal interest rate and the level of output. The recursive VAR essentially constructs the error terms. Thus, the exactly identified system appears as follows:

$$i_t = \alpha_{10} + \alpha_{11} i_{t-1} + \alpha_{12} x_{t-1} + \alpha_{13} \pi_{t-1} + \epsilon_t^i \tag{6}$$

$$x_t = \alpha_{20} + \alpha_{21} i_{t-1} + \alpha_{22} x_{t-1} + \alpha_{23} \pi_{t-1} + \alpha_{24} i_t + \epsilon_t^x \tag{7}$$

$$\pi_t = \alpha_{30} + \alpha_{31} i_{t-1} + \alpha_{32} x_{t-1} + \alpha_{33} \pi_{t-1} + \alpha_{34} i_t + \alpha_{35} x_t + \epsilon_t^\pi \tag{8}$$

The recursive VAR structure imposes that the error terms in each regression are uncorrelated with the error term in the preceding equation. The ordering is easily justified in this experimental environment. The interest-rate rule has been set to be completely backward looking. Output depends on workers' labor supply decisions. When making their decision, they know the current nominal interest rate, wage rate and past prices. Contemporaneous values of inflation do not play a direct role in their labor decisions. Finally, firms update their price with an estimate of current household demand and knowledge of the current nominal interest rate. We assume the covariances between the variables are unrelated and estimate only their own variance.

The VARs are estimated in all instances with the full sample of repetition-5 data using two methods. First we consider a data set of 84 periods, consisting of each of the 21-period repetition-5 data from the six sessions of each treatment. We also estimate VARs for individual sessions to highlight any heterogeneity and outliers that may be present. The policy shock and the resulting responses are normalized to be expansionary. Impulse response functions are presented in Figure 7. The top panel presents average orthogonalized impulse responses (solid line) from the aggregate data, upper and lower bounds (ub and lb) associated with a 95% confidence interval (dashed lines), and the theoretical benchmark predictions. The bottom panel presents impulse responses from individual sessions. On impact, a 2.5% decrease in the nominal interest rate generates predicted inflation of 1.1% and a predicted output gap of 7.74%. The effects of the shock last for four to five periods.

The realized nominal interest rate has a tendency to overshoot its predicted value after the first or second post shock period. This is due to the fact that inflation tends to adjust slower than predicted. In many instances it peaks a period after the shock occurs rather than on impact (eg. S1 and S3 in HF, S1 and S2 in HH, and S3 in HFH). By that point though, the shock to the nominal interest rate has begun to dissipate. The backward looking nominal interest rate increases when previous period inflation increases. With large inflation and a significantly lower residual shock, the nominal interest rate rises above its steady state value.

Human Firms

In response to an expansionary monetary shock, human firms raise their prices on average by 0.5%, less than half of the predicted adjustment. This increase in average prices is largely driven by behavior in S5, where inflation increased by 2.2%. Most sessions under price, and in S3, firms appear to respond to decreases in the nominal interest rate by decreasing prices on impact. This was followed by significant inflation. Interestingly, S2 appears to maintain steady positive inflation.

The output gap is positive and on average 2.5%, indicating that automated households increased their desired consumption and labor supply in response to an increase in the real wage. The impact on output is significantly dampened for most of the sessions because subjects did not form sufficiently large output gap expectations.

Human Households

In the human household treatment inflation rises on impact in response to the nominal interest rate shock. At the individual session level, the automated firms respond by increasing prices to generate inflation but the degree of inflation varies significantly from just below 0.1% to 1.6% and is dependent on the inflationary and output gap expectations formed by human households in the economy. The output gap increases an average 10.5% on impact while inflation increases by 0.7%. The shock leads to a significant adjustment in the output gap for all sessions, but in one-third of the cases the shock results in an initial contraction followed by an expansion of smaller magnitude.

Human Firms and Households

In the combined human firm and household treatment, the impact of the shock generates an average increase in inflation of 0.4%, with a treatment minimum of -0.2% and maximum of 1.5%. The reaction of consumers is mixed. On average, the output gap decreases by 5.6%. As in the HH treatment, there is significant variance in this estimate. Output falls by 36% in S1 but increases by 8.5% in S4. These impulse responses are all significantly different from zero on impact of the shock.

7 Discussion

The goal of this study was to understand whether changes in nominal interest rates influence expectations and decision making in line with the predictions of a representative agent New Keynesian framework. We construct a simple experimental economy with price-setting, monopolistically competitive firms, consumer-worker households, and an inflation-targeting central bank that face exogenous expansionary monetary policy shocks. Many aspects of the New Keynesian model are supported by our experimental data. In terms of price setting ability, firms that interact with automated optimizing households do learn to respond to expansionary monetary policy and the subsequent expected rise in real wages by increasing their prices. The majority of participants, in all treatments, form optimistic expectations in response to lower interest rates, indicating an understanding of the stabilizing effects of monetary policy. Mean expectations in the HH and HF treatments are also largely accurate. Expectations are, however, highly naive in that they expect previous real wages to persist into the future.

In the theoretical framework we explore, the representative household is assumed not to carry any bank account balances across period and as a result does not condition on its bank balance when forming optimal decisions. In our environment, we allow households to carry any possible balances from one period to the next. As a result participants become either savers or borrowers, and their wealth factors into their decision making considerably. Savers can afford to demand more output and work less, while indebted individuals, exhibiting homegrown debt aversion preferences, work considerably harder and spend considerably less in an effort to escape debt. This heterogeneity in wealth leads to highly differentiated responses to monetary policy. While lowering interest rates in the debtless representative agent framework is predicted to increase labor supply and output demand, in our environment, we observe many cases where expansionary monetary policy motivates indebted participants to cut their labor supply in response to the reduced interest burden. Many savers choose to work more and consume less to supplement their lower interest income.

When some market agents are automated and highly predictable, it is relatively easier to form accurate forecasts. The interaction of human firms and households, however, reduces the forecasting accuracy of both types of participants. Given this lack of predictability, we observe firms in the HFH treatment setting relatively higher prices and considerably less sensitive to changes in the nominal interest rate. We interpret such behavior as an effort on the part of firms to buffer themselves from uncertain household behavior. Either in response to this or because of the comparable uncertainty of firm pricing decisions, households demand significantly less output. This, coupled with the effects of indebtedness on labor supply and output demand, reduces the consistency of monetary policy to influence aggregate activity in the anticipated direction.

Our findings provide a richer understanding of how monetary policy influences individual decision making and aggregate activity. We have shown explicitly the spillover effects of counterpart bounded rationality onto potentially rational optimizing individuals, both in terms of expectation formation and pricing decisions. Household indebtedness with accompanying debt aversion are shown to impede the success of monetary policy. Further work on how household debt and monetary policy interact is an important avenue of future research where further experimentation may prove fruitful.

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Table 1: Parameterization of Experimental Environment

Z	Productivity level	10
$1-\omega$	Fraction of firms updating	0.25
ρ_v	Persistence of shock	0.5
δ	CB reaction to lagged inflation	1.005
ϵ	Shock	-0.025
κ	Slope of NKPC	0.07904
θ	Measure of substituability	7.666
β	Rate of discounting	0.9523
χ	Disutility coefficient	1
$1/\sigma$	Elasticity of intertemporal substitution	2
$1/\eta$	Frisch labor supply elasticity	3.03
ρ	Steady state nominal rate of return	0.05
μ^*	Steady state markup $(\theta/(1-\theta))$	1.15
C^*	Steady state consumption	33.8
N^*	Steady state labor supply	3.38
W^*	Steady state nominal wage	10
P^*	Steady state price	1.15
FirmsN	Number of firms	4
HouseholdN	Number of households	4
Sessions	Number of sessions per treatment	6
Repetition	No. Periods	Period of Shock
1	22	12
2	13	8
3	15	11
4	10	5
5	21	12
Treatment	No. Firms	No. Households
HF	4 human	4 computerized
HH	4 computerized	4 human
HF	4 human	4 human
Phase	L_i^*	C_i^*
Steady State	3.38	33.8
Period of Shock	3.63	36.3

Table 2: Fixed Effects Specifications of Expectation Formation [I]

	$E_{i,t}W_t$	$E_{i,t}W_{t+1}$	$E_{i,t}P_t$	$E_{i,t}P_{t+1}$	$E_{i,t}RW_t$	$E_{i,t}RW_{t+1}$
i_t	-1.402*	-0.819	0.049	0.066	-1.312	-0.970
	(0.80)	(0.72)	(0.14)	(0.17)	(0.99)	(1.31)
$i_t \times HF$	2.433	1.800	0.267	0.225	0.105	-0.323
	(2.61)	(1.99)	(0.17)	(0.24)	(1.65)	(1.78)
$i_t \times HFH^H$	-0.425	-0.101	-0.165	-0.127	0.753	0.496
	(2.59)	(2.21)	(0.22)	(0.23)	(1.83)	(2.13)
$i_t \times HFH^F$	-1.789	-3.340*	-0.134	-0.012	0.266	-2.249
	(1.99)	(1.84)	(0.18)	(0.20)	(2.45)	(2.53)
W_{t-1}	0.736***	0.681***				
	(0.06)	(0.06)				
P_{t-1}			0.623***	0.626***		
			(0.05)	(0.06)		
RW_{t-1}					0.654***	0.599***
					(0.08)	(0.08)
α	2.775***	3.336***	0.437***	0.435***	3.170***	3.652***
	(0.54)	(0.61)	(0.06)	(0.07)	(0.67)	(0.65)
N	7053	7054	7054	7054	6626	6627
A.I.C	13129.9	14433.9	-18614.6	-17276.6	23134.1	23362.0
B.I.C	13164.2	14468.2	-18580.3	-17242.3	23168.1	23396.0

(I) Significance levels: $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$. Standard errors are presented in parentheses and clustered at the session-level.

Table 3: Firm Pricing Decisions [I]

$P_{i,t}$	(1)	(2)	(3)	(4)
i_t	-0.289	-0.437	-0.547*	-0.611**
	(0.30)	(0.33)	(0.31)	(0.31)
$E_{i,t}W_t$	0.012*		0.005**	0.005**
	(0.01)		(0.00)	(0.00)
$E_{i,t}P_t$	0.046		0.116	0.116
	(0.04)		(0.26)	(0.26)
$E_{i,t}W_{t+1}$	0.003		0.000	0.000
	(0.00)		(0.00)	(0.00)
$E_{i,t}P_{t+1}$	0.655***		0.712***	0.714***
	(0.09)		(0.26)	(0.27)
W_{t-1}		0.034***	0.020***	0.020***
		(0.01)	(0.00)	(0.00)
P_{t-1}		0.413***	-0.108	-0.115
		(0.14)	(0.10)	(0.10)
$i_t \times HFH^F$				0.132*
				(0.07)
α	0.220**	0.371**	0.097	0.106
	(0.10)	(0.16)	(0.11)	(0.11)
N	880	822	822	822
χ^2	105.9	61.87	6387.0	8705.8

(I) Significance levels: $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$. Standard errors are presented in parentheses and clustered at the session-level.

Table 4: Household Labor Supply Decisions [I]

Desired Labor Supply	(1)	(2)	(3)	(4)	(5)	(6)
$C^D_{i,t}$	0.038***	0.038***	0.041***	0.038***	0.026***	0.026***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
i_t	5.890*	5.872*	-1.536	3.858	4.771	5.550*
	(3.32)	(3.30)	(2.96)	(2.74)	(3.12)	(2.97)
RW_t	0.130	0.129	0.151	0.232	0.153	0.150
	(0.27)	(0.26)	(0.26)	(0.31)	(0.20)	(0.21)
$E_t\pi^{RW}_{t+1}$		0.070	0.060	0.050	0.062	0.063
		(0.07)	(0.05)	(0.06)	(0.07)	(0.07)
$i_t \times Indebted$			13.242***			-1.387
			(4.33)			(3.29)
$Bank_{i,t-1}$				-0.040***	-0.001	-0.001
				(0.00)	(0.00)	(0.00)
$Bank_{i,t-1} \times Indebted$					-0.069***	-0.069***
					(0.00)	(0.00)
α	1.428	1.435	1.230	0.686	1.333	1.361
	(2.35)	(2.34)	(2.19)	(2.48)	(1.69)	(1.72)
N	3582	3582	3582	3340	3340	3340
χ^2	52.69	54.00	67.38	1563.4	33829.6	105026.3

(I) Significance levels: $^*p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$. Standard errors are presented in parentheses and clustered at the session-level.

Table 5: Household Output Demand Decisions [I]

Desired Output Demand	(1)	(2)	(3)	(4)	(5)	(6)
$L^S_{i,t}$	1.754***	1.755***	1.876***	2.208***	2.012***	1.965***
	(0.52)	(0.52)	(0.56)	(0.60)	(0.72)	(0.73)
i_t	2.969	2.929	47.479	-1.214	0.332	37.258
	(30.44)	(30.46)	(29.20)	(32.77)	(33.12)	(35.73)
RW_t	3.104	3.103	2.887	2.962	2.940	2.769
	(2.55)	(2.55)	(2.62)	(2.32)	(2.22)	(2.26)
$E_t\pi^{RW}_{t+1}$		-0.108	-0.049	-0.115	-0.095	-0.061
		(0.29)	(0.28)	(0.29)	(0.30)	(0.31)
$i_t \times Indebted$			-81.175***			-65.366***
			(30.76)			(23.30)
$Bank_{i,t-1}$				0.096*	0.119**	0.105***
				(0.05)	(0.05)	(0.04)
$Bank_{i,t-1} \times Indebted$					-0.054**	-0.062***
					(0.02)	(0.02)
α	0.582	0.590	1.547	-0.012	0.608	1.902
	(20.63)	(20.65)	(21.41)	(18.75)	(17.79)	(18.21)
N	3582	3582	3582	3340	3340	3340
χ^2	79.78	95.81	171.0	234.0	277.3	281.6

(I) Significance levels: $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$. Standard errors are presented in parentheses and clustered at the session-level.

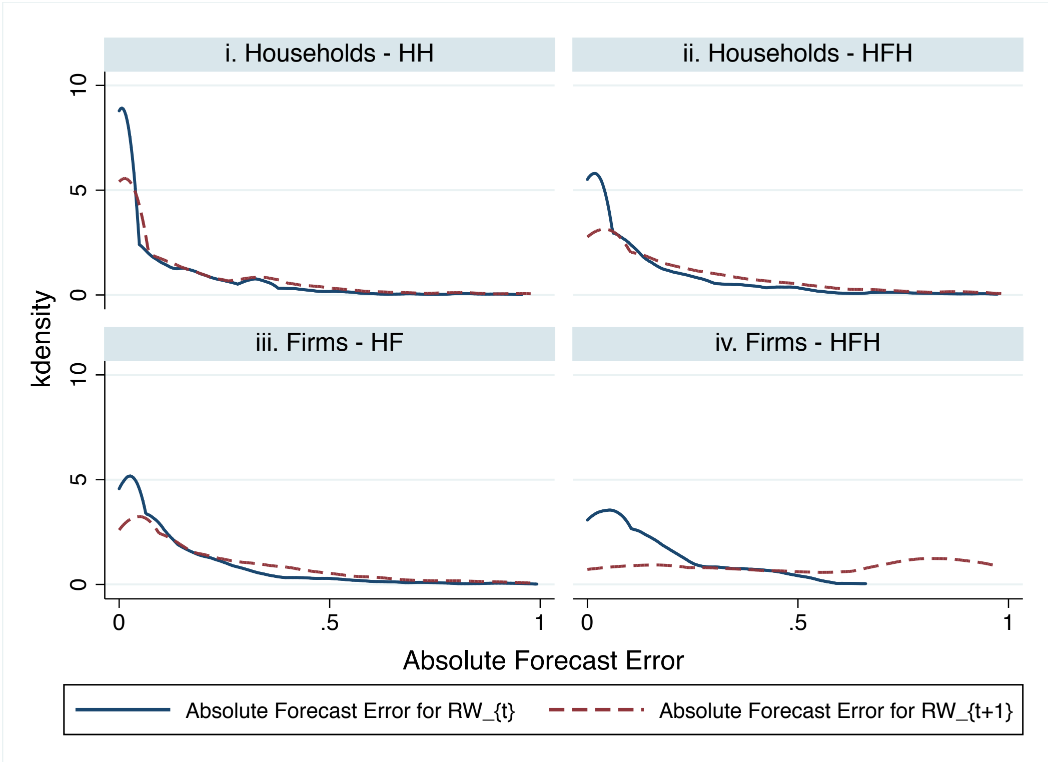
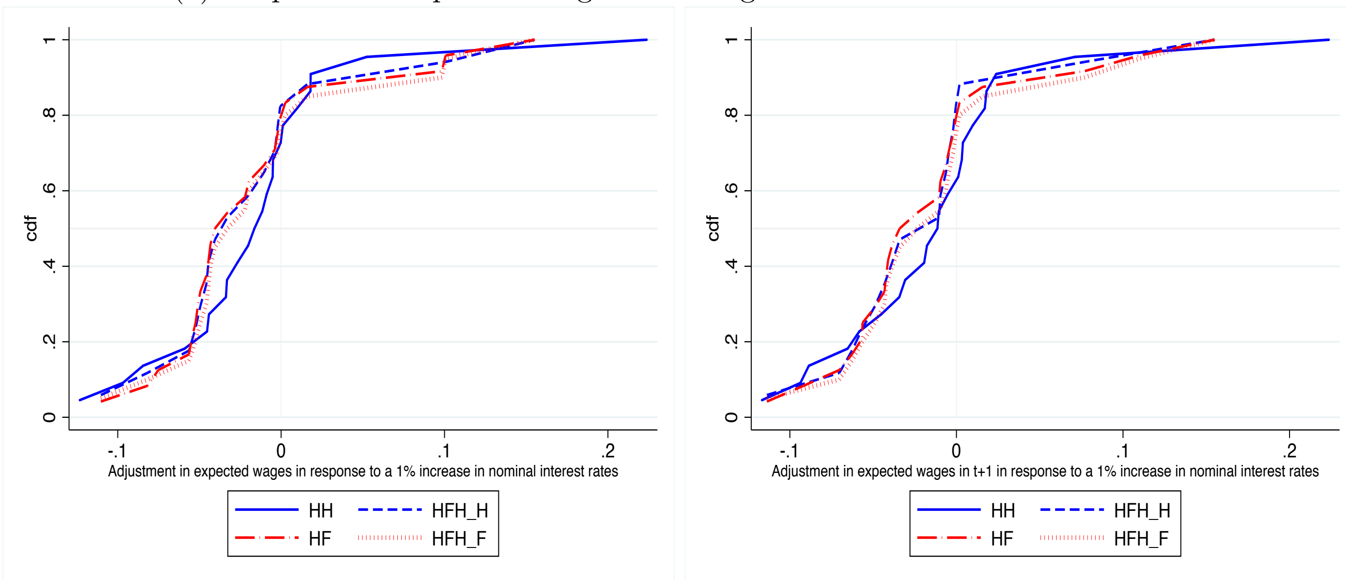
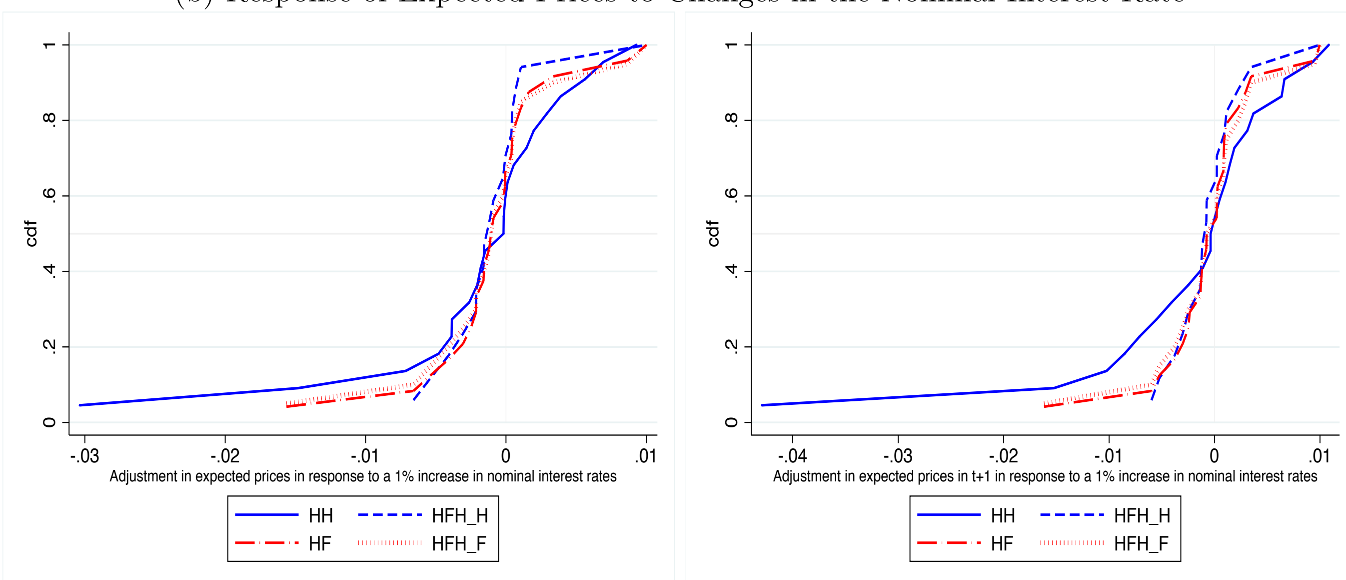


Figure 1: Distribution of Absolute Real Wage Forecast Errors for Periods t and t+1, by type and treatment

(a) Response of Expected Wages to Changes in the Nominal Interest Rate



(b) Response of Expected Prices to Changes in the Nominal Interest Rate



(c) Response of Expected Real Wages to Changes in the Nominal Interest Rate

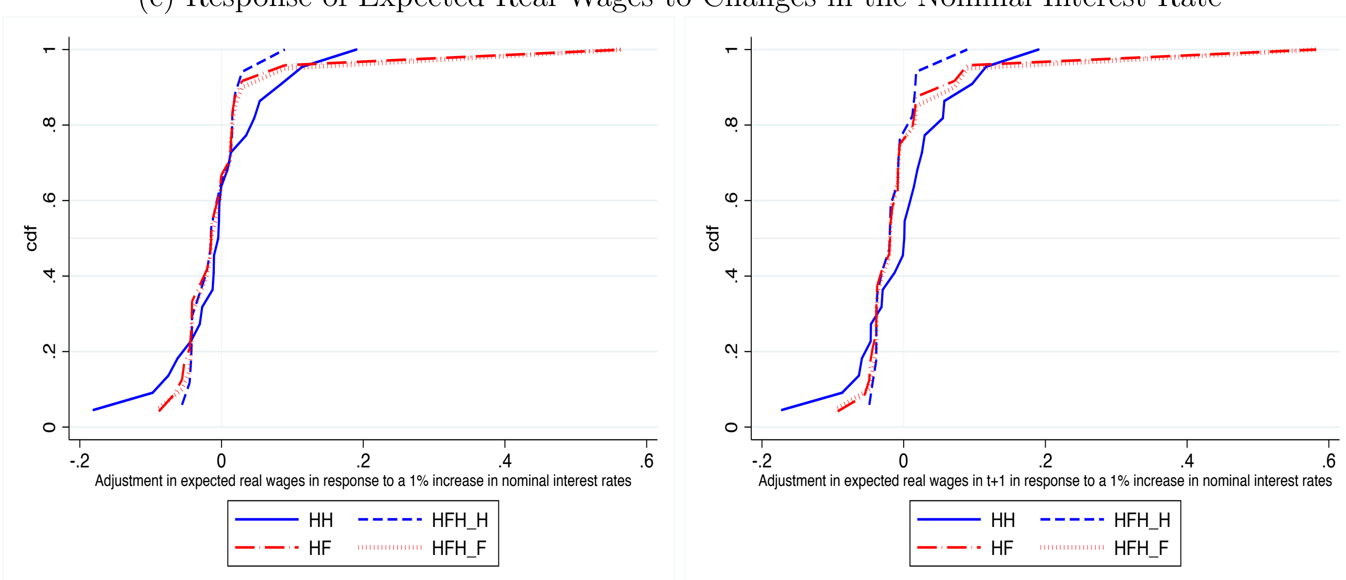


Figure 2: Distribution of Individual Expectation Responses to Changes in the Nominal Interest Rate

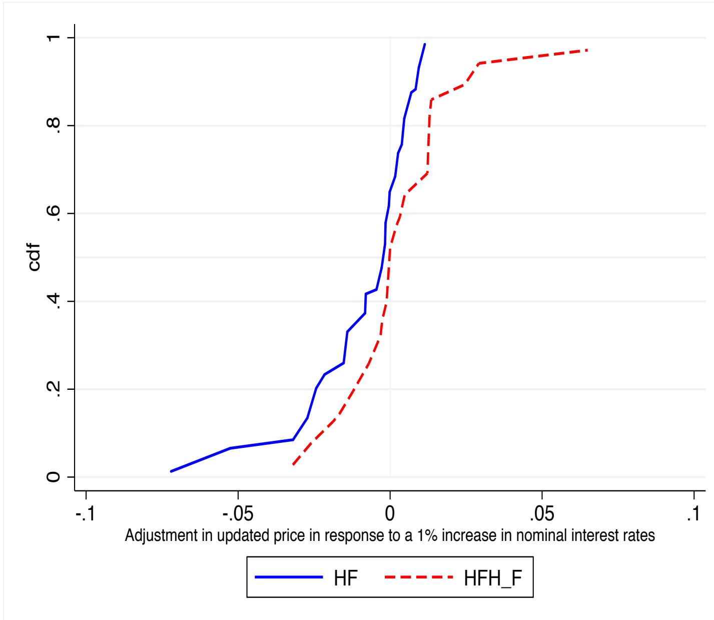


Figure 3: Distributions of Mean Price Responses to Changes in Nominal Interest Rates, by treatment

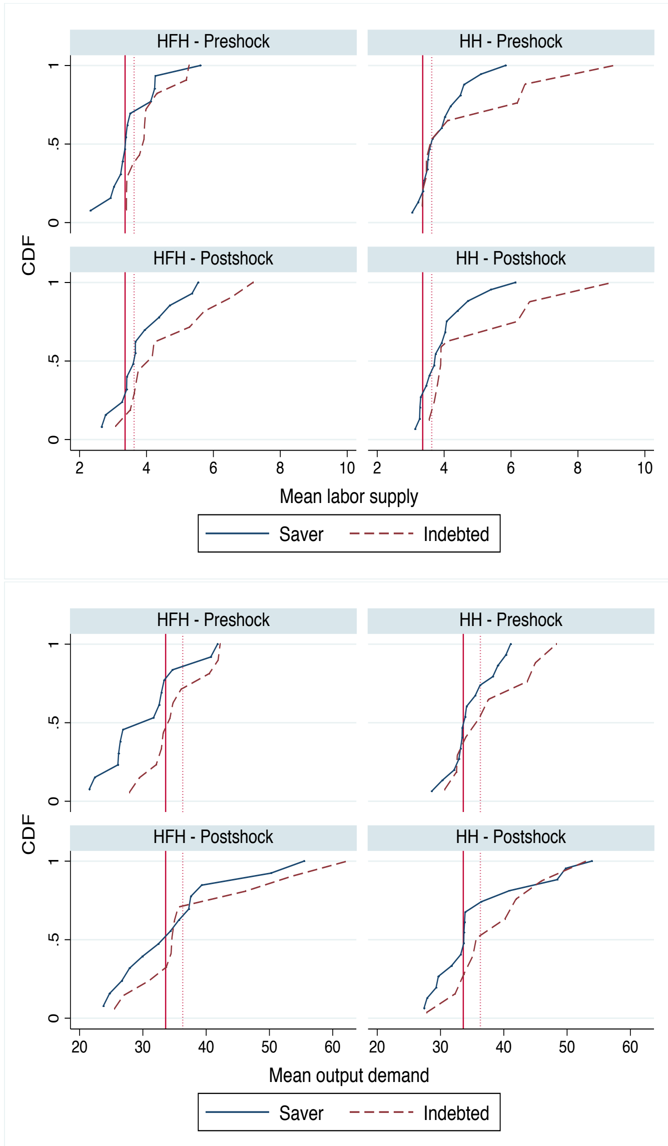


Figure 4: Distributions of Mean Labor Supply and Output Demand for Savers and Indebted Participants, by treatment and phase

Solid vertical lines indicate the steady state prediction while tight-dotted vertical lines indicate the equilibrium prediction on impact of the nominal interest rate shock.

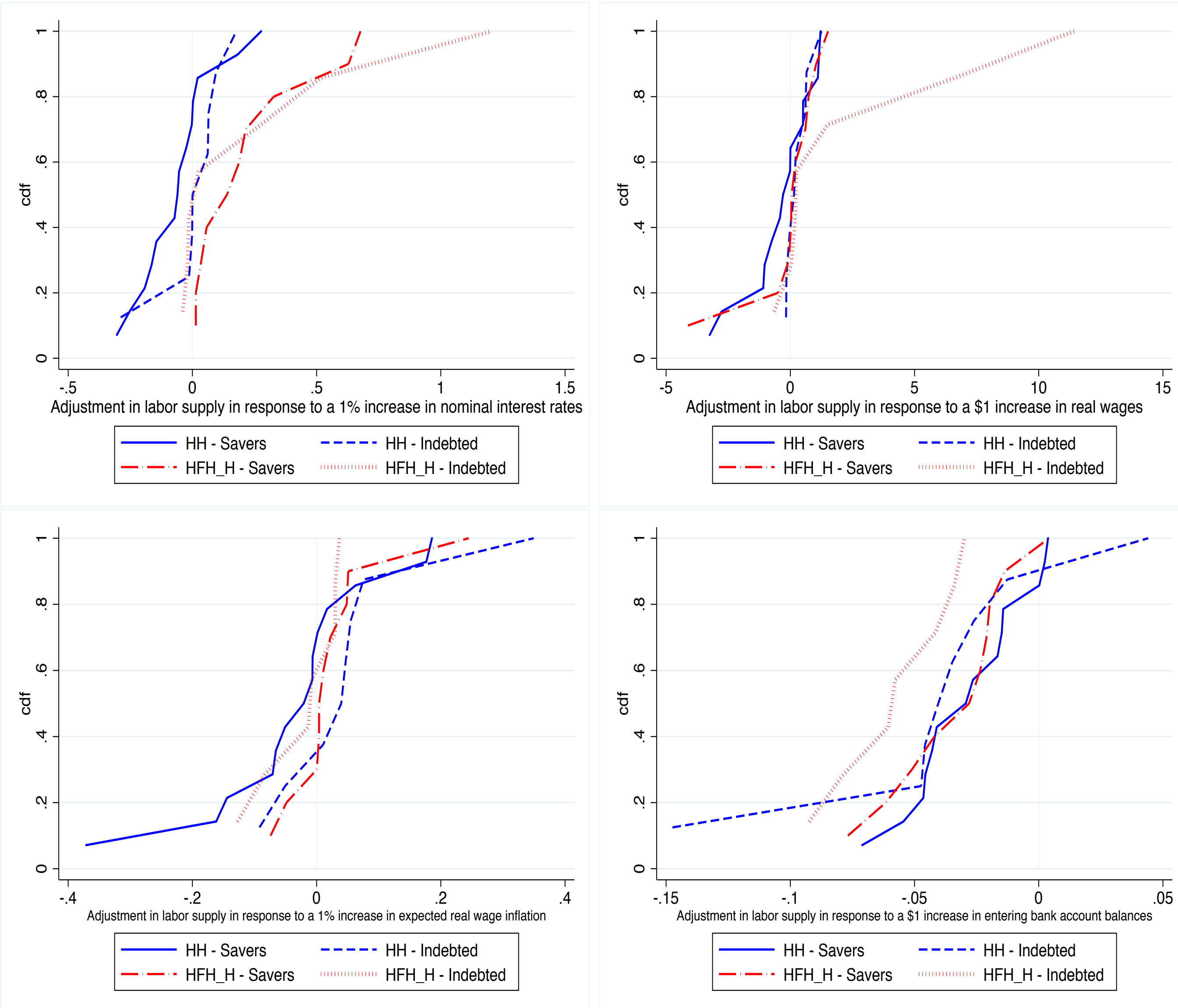


Figure 5: Distributions of Individual Labor Supply Responses, by treatment and wealth status

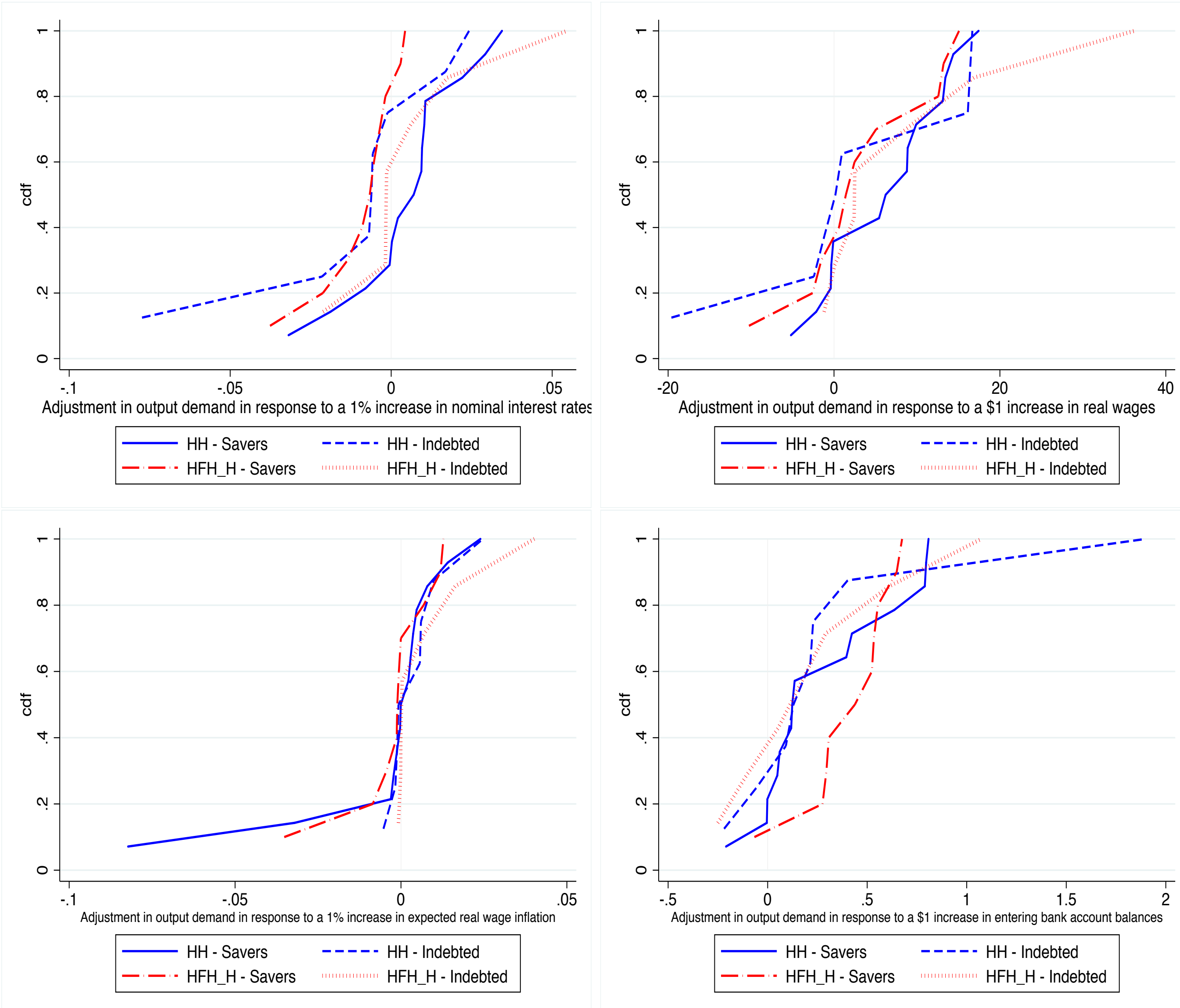
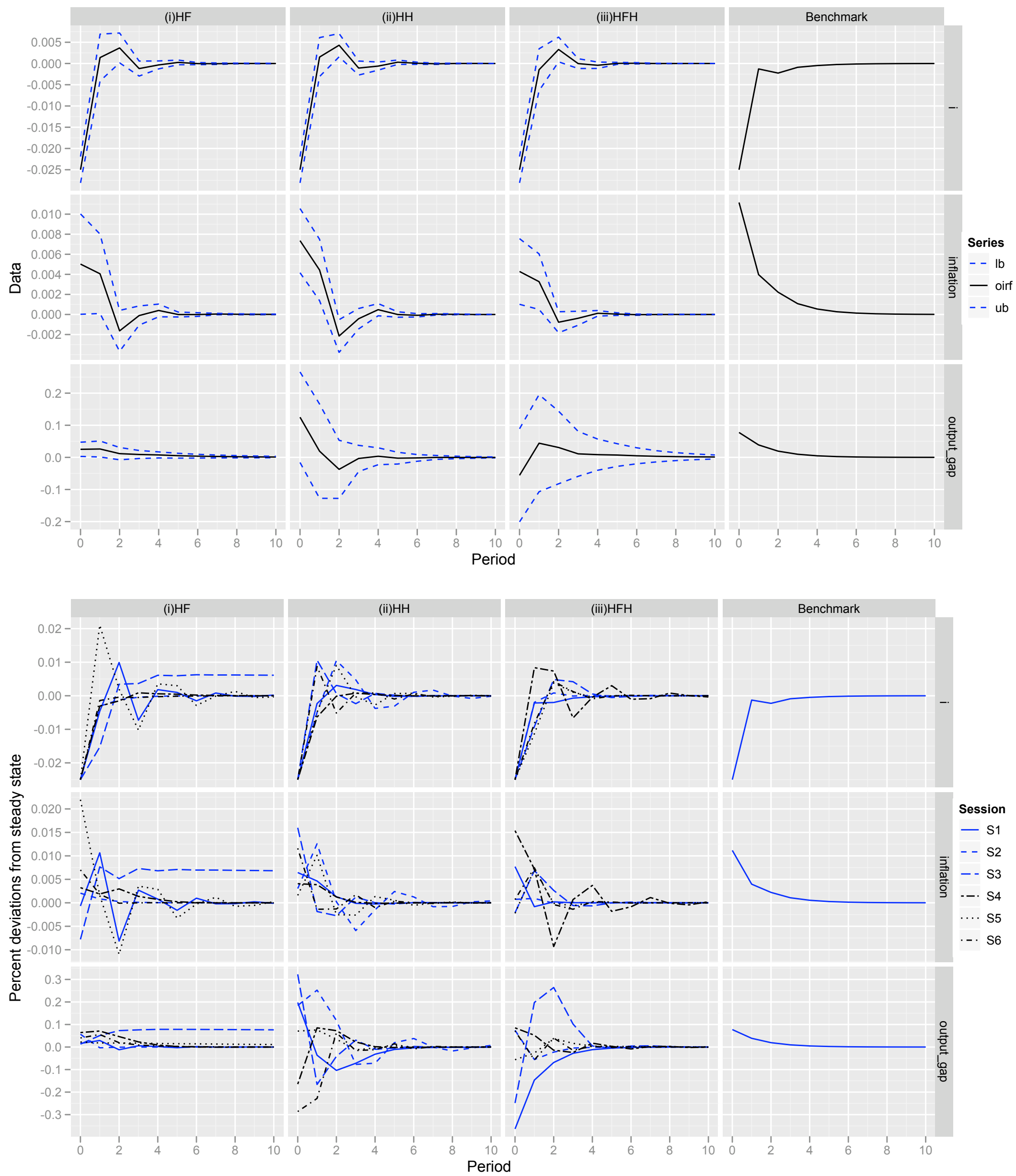


Figure 6: Distributions of Individual Output Demand Responses, by treatment and wealth status

Figure 7: Orthogonalized impulse responses to a nominal interest rate shock



The top panel presents average orthogonalized impulse responses (solid line) from the aggregate data, upper and lower bounds (ub and lb) associated with a 95% confidence interval (dashed lines). The bottom panel presents estimated impulse responses for each session.

9 Appendix

9.1 Nominal Wages and Expectations

A key feature of this experiment is that nominal wages are not determined through negotiations or market interactions. Rather, subjects are presented with the nominal wage and asked to make labor supply or pricing decisions. This is consistent with the notion that agents take the nominal wage as given. This has the desirable feature that inventories and the risks of advance production are absent. Output is "made-to-order", and consistent with the New Keynesian framework all output produced is consumed. It also allows us to reduce the amount of time required to complete a period. Eliminating the 1.5 minutes needed for the labor market to clear saves us over 2 hours. Given that the nominal wage is not our focus of interest, it is reasonable to let it be automated.

Our approach is to use a reformulated expectational IS equation to generate a nominal wage. In short, we note that the output gap can be rewritten as a function of deviations of the real marginal cost, $\hat{\phi}_t$, from its flexible price level[7]:

$$\begin{aligned} x_t &= \frac{1}{\eta + \sigma} \hat{\phi}_t \\ &= \frac{1}{\eta + \sigma} \left(\hat{W}_t - \hat{P}_t \right) \end{aligned}$$

The expectational IS curve is given by

$$x_t = E_t x_{t+1} - \frac{1}{\sigma} \left(i_t - E_t \pi_{t+1} - \rho \right)$$

Substituting in for x_t, $E_t x_{t+1}$ and noting that $\pi_t = \hat{P}_t - \hat{P}_{t-1}$, we can express the log wage deviations from the steady state as a function of known variables

$$\hat{W}_t = E_t \hat{W}_{t+1} + \frac{\eta}{\sigma} E_t \left(\hat{P}_{t+1} - \hat{P}_t \right) - \frac{\eta + \sigma}{\sigma} (i_t - \rho)$$

The nominal wage, in levels, is given by

$$W_t = \overline{W} \left(1 + \hat{W}_t \right)$$

[7] $\hat{Z}_t$ is dropped from the real marginal cost formulation as productivity measures are fixed at their steady state level for the duration of the experiment. The symbol ˆ denotes log deviations from the steady state flexible price level.

where $\overline{W}$ is the steady state nominal wage.

The nominal wage can be determined through agents expectations about nominal wages and prices. This is obtained by asking all subjects to make forecasts about period t and $t+1$ nominal wages and prices at the beginning of period t. The median forecasts, which are less easily manipulated by subjects than the mean, and the current nominal interest rate are used in the calculation of the nominal wage. To further avoid manipulation, the human firm that has an opportunity to reset its price is excluded from the calculation.[8]

9.2 The Linearized Aggregate Economy

The equilibrium of the economy can be described by a system of four equations linearized around a zero-inflation, zero-output gap steady state:

$$x_t = E_t x_{t+1} - \frac{1}{\sigma}\left(i_t - E_t \pi_{t+1} - \rho\right) \tag{9}$$

$$\pi_t = \beta E_t \pi_{t+1} + \kappa x_t \tag{10}$$

$$i_t = \rho + \delta \pi_{t-1} + v_t \tag{11}$$

$$v_t = \rho_v v_{t-1} + \epsilon_t \tag{12}$$

The derivations of this system are discussed in the Appendix. The output gap, x_t, is defined as deviations of output from its flexible price level. The inflation rate is given by π_t. The nominal interest rate, i_t, depends on the long run nominal interest rate, ρ, and on past inflation. Finally, v_t is an AR(1) process with persistence ρ_v that governs the nominal interest rate and is initially displaced from its steady state value of zero by the shock ϵ_t.

Equation (9) is the expectational investment-saving (IS) equation and describes the demand side of the economy. It says that production and demand will expand if agents expect the output gap to expand, or if the real interest rate were to decrease. Equation (10) is the New Keynesian Phillips equation that describes the evolution of the aggregate price level. Inflation will increase due to expectations of future inflation or due to current expansions of the output gap. Equation (11) is the central bank's nominal interest rate setting equation. The central bank reacts to increases in past inflation by raising nominal interest rates. The nominal interest rate is also subject to exogenous shocks that follow an autoregressive process, described by Equation (12).

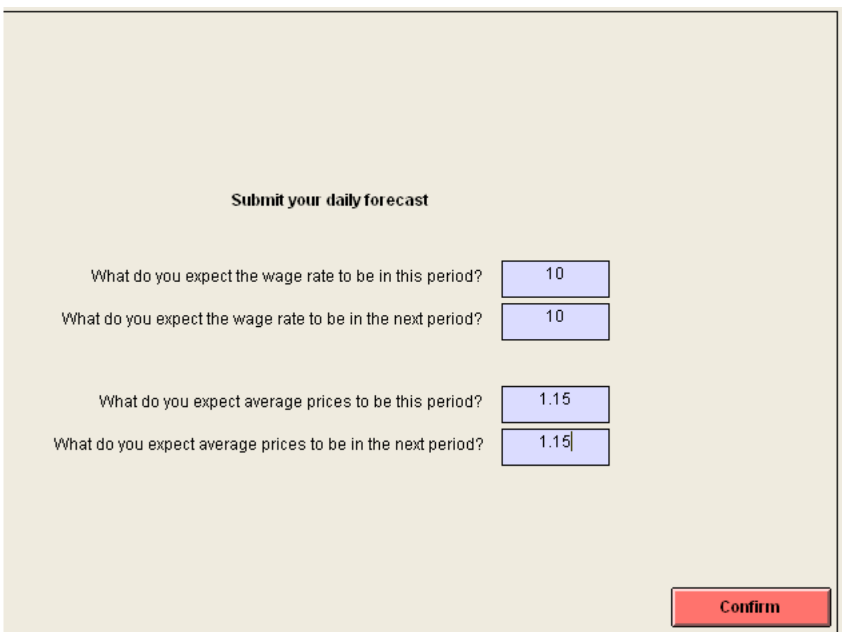
An unanticipated exogenous and persistent decrease in the nominal interest rate in period t will affect the household immediately. On impact, households will prefer

[8] Agents in the New Keynesian world are assumed to form rational expectations about the output gap and inflation. These are in percentage terms, a concept that can be cognitively challenging for many people. Forecasting nominal wages and prices provides an equivalent expectation in percent deviation forms and is a simpler task for the subject.

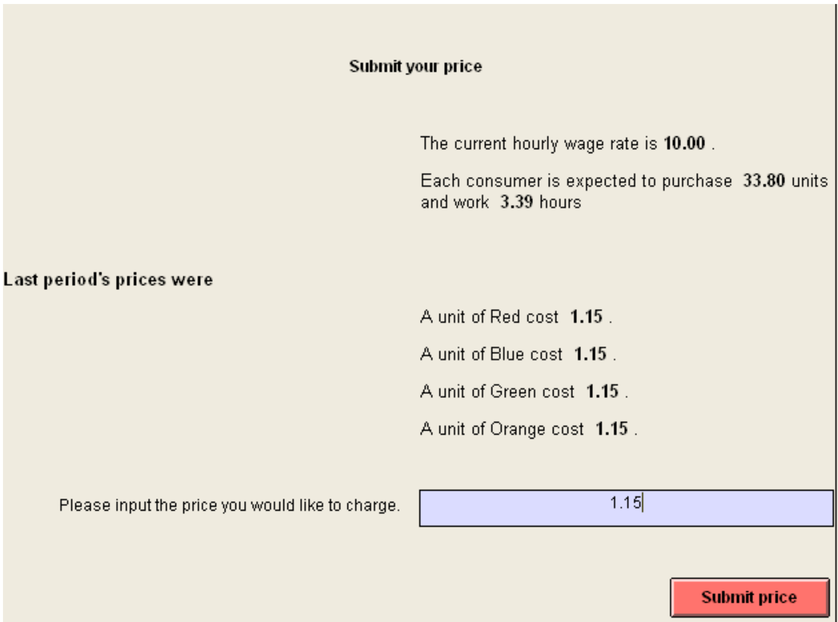
to increase their consumption in period t to take advantage of the lower real interest rates. Moreover, because the shock is persistent, a rational household should anticipate future demands to be relatively high as well. This will result in upward pressure of prices. To avoid higher future prices, the household should increase its consumption even more on impact of the shock. An increase in overall consumption requires more output production (ie. more labour participation). Real wages must adjust upward to entice workers to supply more labour. In an environment with price rigidities, this requires that firms' markups decrease.

9.3 Screen Shots

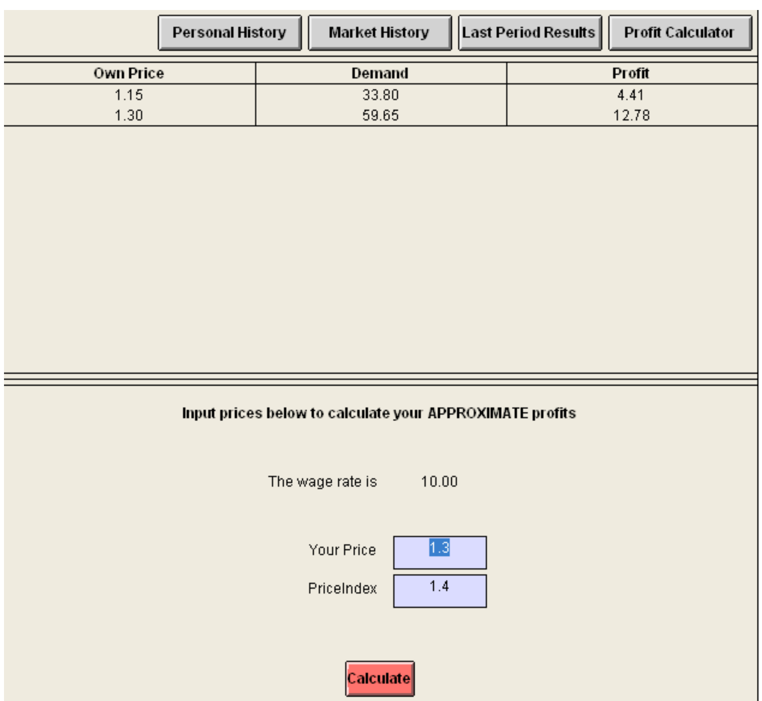
Forecast Input Screen



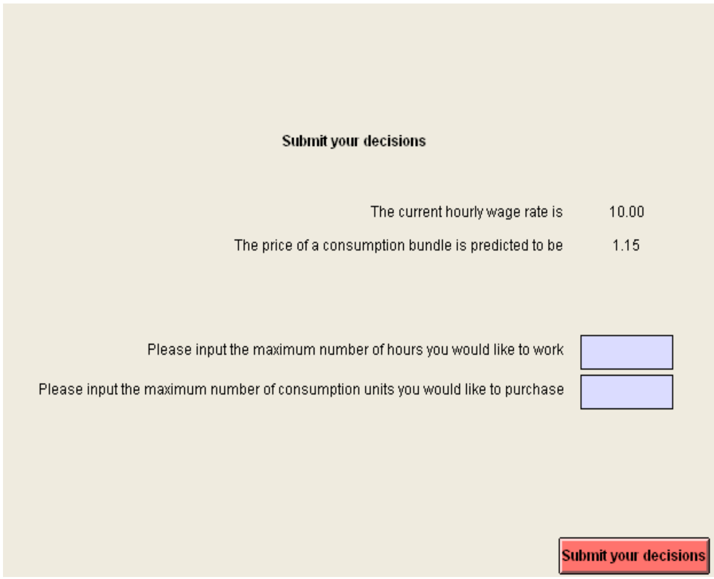
Firm Price Input Screen



Firm Profit Calculator



Household Labor and Consumption Input Screen



Household Calculator