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Abstract

The effectiveness of monetary policy depends, to a large extent, on market expectations of its future actions. In a standard New Keynesian business-cycle model with rational expectations, systematic monetary policy reduces the variance of inflation and the output gap by at least two-thirds. These stabilization benefits can be substantially smaller if expectations are non-rational. We design an economic experiment that identifies the contribution of expectations to macroeconomic stabilization achieved by systematic monetary policy. We find that, despite some non-rational component in expectations formed by experiment participants, monetary policy is quite potent in providing stabilization, reducing macroeconomic variance by roughly half.

JEL classification: C9, D84, E3, E52
Bank classification: Business fluctuations and cycles; Monetary policy implementation; Transmission of monetary policy

Résumé

L'efficacité de la politique monétaire dépend, dans une large mesure, des attentes des marchés à l'égard des décisions futures des autorités monétaires. En recourant à un modèle néo-keynésien standard du cycle économique à anticipations rationnelles, les auteurs établissent que la cohérence des mesures de politique monétaire permet de réduire d'au moins deux tiers la variance de l'inflation et de l'écart de production. Ils mettent en évidence également que les effets stabilisateurs peuvent être nettement moins importants si les anticipations ne sont pas rationnelles. Une expérience est montée dans l'espoir d'évaluer le rôle des anticipations des agents privés dans la stabilisation macroéconomique qu'apporte l'action cohérente des autorités monétaires. Les auteurs découvrent que, même si les anticipations formées par les participants à l'expérience sont en partie non rationnelles, la politique monétaire mise en œuvre parvient à avoir des effets stabilisateurs qui ne sont pas du tout négligeables, en réduisant à peu près de moitié la variance macroéconomique.

Classification JEL : C9, D84, E3, E52
Classification de la Banque : Cycles et fluctuations économiques; Mise en œuvre de la politique monétaire; Transmission de la politique monétaire

1. Introduction

The modern economy is a complex and inherently uncertain environment. To make optimal decisions in such an environment, households and firms in the economy must take into account a possible unravelling of future events. For instance, a household's decision to buy a house will depend on the expectations of its future income, future interest rates and future changes in house value. A retailer's decision to set new prices for its merchandise will be affected by its expectations of future inflation. The importance of expectations for economic decisions underscores their major role for macroeconomic fluctuations.

Monetary policy, mandated to ensure a stable macroeconomic environment, is naturally concerned with how private expectations affect the economy. The key challenge for a central banker is to understand not only how expectations affect the economy and which policy actions they elicit, but also how the stance of monetary policy affects expectations. Managing market expectations is an important tool of monetary policy that central banks often use to stabilize the economy both in normal and extraordinary times.[1] The goal of this paper is to use experimental evidence to measure the degree of macroeconomic stabilization achieved by monetary policy through its effect on expectations.

Despite the central role that expectations play in macroeconomic fluctuations, our understanding of how they are formed and what they imply for policy is far from satisfactory. Since expectations are not directly observed, inference about their formation is mostly based on economic models that assume a particular expectation formation. The vast majority of modern macroeconomic models assume rational expectations, according to which households and firms take into account all information available; have a complete understanding of the workings of the economy, including future consequences of their actions; and make optimal decisions that are consistent with this understanding. Despite its tractability and theoretical appeal, the assumption of rational expectations implies aspects of decision making that are often not consistent with how people think in reality.[2] Moreover, model-based inference of expectations formation faces the difficult task of

[1] Woodford (2003), Galí (2008) and Boivin, Kiley and Mishkin (2010) emphasize the importance of the management of expectations by monetary policy. Boivin (2011) highlights the importance of studying expectations formation for monetary policy design. The importance of forward guidance by central banks during the period of historically low interest rates has been stressed by Carney (2012) and Woodford (2012, 2013).

[2] Boivin (2011) provides an overview of studies of non-rational behaviour.

identifying model restrictions stemming from assumed expectations formation vis-à-vis other model restrictions.

In this paper, we employ an alternative approach that uses economic experiments to obtain direct evidence on how expectations are formed and allows us to quantify their role in macroeconomic stabilization. The key advantage of this approach stems from a more precise control of conditions in which participants in the experiment form their forecasts.[3] Our approach consists of four main parts. First, we introduce a measure of the expectations channel of monetary policy in a standard New Keynesian business-cycle model and demonstrate how stabilization achieved by monetary policy depends on the way expectations are formed. Second, we implement this model in an experimental setting, in which expectations of inflation and the output gap are repeatedly provided by experiment participants. Third, we use experimental data to measure the strength and robustness of the expectations channel, which we then compare to measures obtained in a theoretical setting. Finally, we study individual forecasting behaviour, and how subjects utilize available information to form their expectations.

We begin our analysis by developing a theoretical framework based on a standard New Keynesian business-cycle model à la Woodford (2003) and augmented with a flexible specification for expectations formation. To quantify the strength of the expectations channel, we first derive the responses of inflation and the output gap to the natural-rate-of-interest impulse that occurs in the absence of future responses of nominal interest rates. We then document how much these counterfactual responses are reduced in equilibrium with countercyclical nominal interest rate responses. Our measure of the expectations channel is therefore based on the fraction of conditional variances of inflation and the output gap that are decreased by the systematic monetary policy response over the quarters following the quarter of the shock.

For empirically plausible parameterizations of the model, we find that, under rational expectations, monetary policy reduces the conditional variance of inflation and the output gap by at least *two-thirds*. In contrast, when expectations are non-rational, the decrease in the variance due to monetary policy can be substantially smaller. For example, in versions of the model with

[3] Duffy (2008), Hommes (2011), and Chakravarty et al. (2011) review the literature on experimental macroeconomics. Surveys of households or professional forecasters are another source of direct evidence on expectations formation. See Mankiw, Reis and Wolfers (2004) and Coibion and Gorodnichenko (2012) for recent studies of expectations using survey-of-forecasters data.

adaptive expectations, where expectations rely heavily on past output and inflation realizations, the reduction of macroeconomic volatility by monetary policy is less than one-third and can be as low as zero.

We then design an experiment that implements this model in a learning-to-forecast setting, in which expectations of inflation and the output gap are repeatedly provided by experiment participants. There are two novel features in our experimental design. First, we provide full information about the only exogenous shock process (for the natural-rate-of-interest disturbance), as well as complete information about the underlying model. This set-up allows us to estimate aggregate and individual forecasts as functions of observed shock history, which we then use to quantify the contribution of expectations to macroeconomic stabilization. Second, we provide, at a small time cost, information about the histories of past outcomes and shocks, and a detailed model description. This allows us to monitor how information is used, and whether it improves forecast accuracy.

In the experiment, inflation and the output gap predominantly exhibit stable cyclical behaviour, with the peak-to-trough time ranging between 3.9 and 7.5 quarters in the benchmark treatment, which is within the range of 3 to 20 quarters predicted by our baseline model under various expectations formations. Subjects quickly converge to their stationary behaviour, and experimental outcomes do not seem to be driven by factors outside the data-generating process, such as sunspots or strategic behaviour.

Our main finding is that, in the experiment, monetary policy provides a substantial degree of macroeconomic stabilization via its effect on subjects' expectations. In the benchmark treatment, the fraction of conditional variance of inflation and the output gap, reduced by the anticipated response of nominal interest rates, is 0.51 and 0.45, respectively. Our theoretical model predicts that the reduction in the variance should range between 0.73 for inflation (0.65 for the output gap) under rational expectations and virtually zero under strong forms of adaptive expectations. Therefore, despite falling somewhat short of the stabilization that could be achieved if agents behaved rationally, monetary policy is quite potent, reducing roughly half of the variance of inflation and the output gap.

We show that a version of the theoretical model with a weak form of adaptive expectations, which puts significant weight on the last-period output and inflation realizations, fits best both the magnitude and the timing of aggregate fluctuations in the experiment. For example, in the model with this form of adaptive expectations, the standard deviations of inflation, the output gap and their forecasts are between 0.70 and 1.24 times those documented for the sessions in the benchmark treatment (versus 0.36 to 0.74 for the model with rational expectations). Correlations between the experimental and model time series range between 0.76 and 0.89 (versus 0.55 to 0.71 for the model with rational expectations).

We check the robustness of our findings by introducing variation in key features of our experimental design. Our model predicts that two such features are the persistence of macroeconomic fluctuations and the elasticity of the nominal interest rate response to these fluctuations. We therefore conduct two alternative experimental treatments: with more-persistent shocks and with more-aggressive monetary policy. We find that, in accordance with the model's predictions, monetary policy in both treatments provides *more* stabilization than in the benchmark treatment, reducing the variance of inflation (the output gap) by 0.95 (0.96) in the high-persistence treatment and by 0.72 (0.56) in the aggressive monetary policy treatment.

This paper is most closely related to recent experimental studies of expectations formations and their impact on the effectiveness of monetary policy interventions in the context of New Keynesian models.[4] These studies typically find some form of adaptive expectations, which rely heavily on the past history of inflation or the output gap. Adam (2007) finds that sluggish expectations can account for considerable persistence of output and inflation. Assenza et al. (2012) find that monetary policy must be significantly aggressive to changes in inflation from target levels to maintain macroeconomic stability. Pfajfar and Zakelj (2012, 2013) study the stabilizing role of various Taylor rule specifications in a forward-looking New Keynesian model. The consensus of this literature is that expectations play a major role in business-cycle fluctuations, and that they underline the effectiveness of monetary policy in stabilizing those fluctuations.

The main contribution of our paper is in developing the methodology that identifies the degree of stabilization provided by monetary policy via its effect on expectations. Of central importance to

[4] Recent studies include Adam (2007); Assenza et al. (2012); Pfajfar and Zakelj (2012, 2013). Typically, these studies use learning-to-forecast experiments, in which subjects participate as private forecasters. Subjects are paid based on the forecast accuracy alone and are imperfectly informed about the underlying data-generating process. They are provided with all past information on inflation and output, and are asked to provide one- and sometimes two-step-ahead forecasts repeated for at least 40 periods. The average forecast of a group of subjects is used in the calculation of current inflation and output. Expectations formation is inferred from estimating the forecasting rules used by subjects.

this methodology is the experimental design that enables the estimation of expectations as functions of the observed shock history. These functions are used to quantify the counterfactual decrease in the variance of inflation and the output gap due to the systematic response of monetary policy to an exogenous economic disturbance. Our main finding is that, despite a non-rational component in expectations formation, monetary policy is quite potent in providing stabilization, accounting for roughly half of the business-cycle stabilization.

The rest of the paper proceeds as follows. Section 2 develops the theoretical framework that is used to set up artificial macroeconomic simulation in the experimental setting, described in section 3. Section 4 reports the main results of the experiment concerning the behaviour of average expectations as well as the dynamics of the output gap, inflation and the interest rate. Section 5 characterizes differences in how individual expectations are formed as well as how subjects use available information. Finally, section 6 concludes.

2. Theoretical Framework

2.1 Model outline

Our theoretical framework is based on a standard New Keynesian business-cycle model, in which private expectations of future economic outcomes and policy actions play a key role in determining current outcomes.[5] In the model, a unit measure of households consume a basket of differentiated goods, save in one-period nominal bonds and supply working hours to productive firms. Let Y_t^n denote the level of output in this model in the case of fully flexible prices, or the natural rate of output. As Woodford (2003) shows, this concept is convenient for summarizing the effects of shocks on the real marginal cost. Define the output gap, x_t, as the difference between the level of output and the natural rate of output, $x_t = Y_t - Y_t^n$. Households' intertemporal optimization of consumption expenditures implies that, in equilibrium, the level of output (relative to the natural rate of output) must satisfy the Euler equation (written in terms of a log-linear approximation

[5] See Woodford (2003) for detailed assumptions and derivations of equilibrium conditions in the model under rational expectations. Clarida et al. (2000) provide closely related analysis.

around a deterministic steady state):

$$x_t = E_t^* x_{t+1} - \sigma^{-1} \left(i_t - E_t^* \pi_{t+1} - r_t^n \right) \ , \tag{1}$$

where σ is the coefficient of risk aversion; i_t is the risk-free one-period nominal interest rate, controlled by the central bank; π_t is the inflation rate, and r_t^n is the deviation of the natural rate of interest.[6] We will assume that r_t^n follows an AR(1) process:

$$r_t^n = \rho_r r_{t-1}^n + \varepsilon_{rt} \ , \tag{2}$$

where ε_{rt} are i.i.d. draws from $N\left(0, \sigma_r^2\right)$.

Terms $E_t^* x_{t+1}$ and $E_t^* \pi_{t+1}$ denote households' expected values of the next period's output gap and inflation, respectively. Equation (1) says that, in equilibrium, the real aggregate demand (relative to its natural level) depends on the real interest rate (relative to its natural level). For example, if the real interest rate is high (say, if the nominal interest rate is higher than implied by the natural rate of return), households discount future consumption at a higher rate, which means that they need to save more (consume less) in the present in order to ensure their preferred level of consumption in the future.

A continuum of monopolistic firms use labour supplied by households to produce goods of a particular variety. They face constraints on how often they can adjust their prices, but commit to satisfy all demand at the price that they have at any point in time. Under standard assumptions on the demand for goods and on firms' technology, firms' intertemporal optimization leads to an aggregate supply equation that relates the inflation rate to the level of real activity, also known as the New Keynesian Phillips curve, or (in log deviations):

$$\pi_t = \kappa x_t + \beta E_t^* \pi_{t+1} \ . \tag{3}$$

[6] The natural rate of interest may be defined as the equilibrium real rate of return in the case with fully flexible prices. It is the real rate of interest required to keep aggregate demand to be equal to the natural rate of output, Y_t^n, at all times. Its fluctuations may stem from disturbances to government purchases, households' propensity to consume or willingness to work, and to firms' productivity. See Woodford (2003, Chapter 4) for details.

Equation (3) says that a higher level of real activity is associated with a higher marginal cost of production, leading to higher new prices and inflation rates. Since the price set by a given firm may last for many periods in the future, it has to take into account the entire future path of its marginal costs, captured by the term proportional to firms' expected future rate of inflation, $E_t^* \pi_{t+1}$. From the point of view of the policy-maker, equation (3) represents a trade-off between inflation and the output gap. For example, permanently reducing the inflation rate by 1 percentage point is associated with a permanent reduction of the output gap by $\frac{1-\beta}{\kappa}$ per cent. Coefficient κ that governs this trade-off is a function of the parameters that determine the frequency and size of firms' price changes.[7] Note that we assume that households have identical information sets, and that their expectations (of inflation and the output gap) are identical functions of the state history. Under these assumptions, equilibrium equations (1) and (3) have the same form as in Woodford (2003) under rational expectations.[8]

Finally, monetary policy sets the path of short-term nominal interest rates i_t according to a Taylor interest rate rule (in log deviations):

$$i_t = \phi_\pi E_{t-1}^* \pi_t + \phi_x E_{t-1}^* x_t \ , \tag{4}$$

where i_t is an exogenous term reflecting variations in the interest rate target (stemming from nominal demand disturbances or imperfect control of the nominal interest rate by the central bank), and ϕ_π, ϕ_x are the coefficients in front of the expected inflation rate and the output gap, respectively.[9] According to this specification, the monetary authority sets its period-t interest rate in response to deviations of period-t inflation and the output gap expected in period $t-1$.[10] We assume that the

[7] See Chapters 3 and 5 in Woodford (2003) for examples of strategic pricing complementarities.

[8] Preston (2006) studies implications of heterogeneity of information across households in a New Keynesian set-up and finds that targeting private sector expectations can be important if a central bank's inflation forecasts differ from those of the private sector.

[9] It is common in the literature to include in the Taylor rule an exogenous term, ι_t, reflecting variations in the interest rate target (stemming from nominal demand disturbances or imperfect control of the nominal interest rate by the central bank); e.g.,

$$i_t = \iota_t + \phi_\pi E_{t-1}^* \pi_t + \phi_x E_{t-1}^* x_t \ .$$

Since the effects of ι_t on the output gap and inflation in our set-up are identical to those of the r_t^n shock, we will abstract from it here.

[10] A number of papers in the literature argue in favour of a specification of the Taylor rule in which the central bank responds to deviations in the *expected* – as opposed to current – inflation rate. See Clarida et al. (2000); Bernanke and Boivin (2003).

monetary authority has the same information and forecasting functions as the private sector. An important implication of the Taylor rule (4) is that monetary policy responds to fluctuations in the economy with a one-period lag. This assumption captures important timing restrictions commonly made in the monetary policy literature,[11] and will also be useful in the experimental set-up.

The model is closed by specifying how the expected values $E_t^* x_{t+1}$ and $E_t^* \pi_{t+1}$ are determined as functions of the state history. We define these functions by imposing the following general specification for ex ante one-period-ahead forecast errors:

$$E_t \left(E_t^* \begin{bmatrix} \pi_{t+1} \\ x_{t+1} \end{bmatrix} - \begin{bmatrix} \pi_{t+1} \\ x_{t+1} \end{bmatrix} \right) = \sigma^{-1} \rho_r \sum_{s=0}^{\infty} \begin{bmatrix} \kappa L_{s\pi} \\ L_{sx} \end{bmatrix} r_{t-s}^n \ , \tag{5}$$

where E_t denotes the mean conditional on state history through period t, and $L_{s\pi}$, L_{sx} are real numbers representing the elasticity of ex ante forecast errors for inflation and the output gap with respect to shock realizations in periods $t, t-1, \ldots$. Under rational expectations, ex ante forecast errors are always zero, so that $L_{s\pi} = L_{sx} = 0$ for all s. Hence, according to (5), non-rational expectations imply that ex ante forecast errors correlate with current or past shock realizations.[12]

Specification of expectations (5) possesses several features that are important for our study. First, it is sufficiently general to allow us to study alternative expectations formations. Second, non-rational behaviour can be identified by estimating conditional correlations of expectations with past shock realizations (i.e., coefficients $L_{s\pi}$, L_{sx}). We show later in this section that to estimate expectations as functions of the shock history is sufficient to quantify their contribution to the stabilization achieved by monetary policy.[13] Finally, we do not need to know the exact nature of departures from rational expectations in order to quantify their role in the expectations channel of monetary policy.[14]

[11] See Christiano, Eichenbaum and Evans (1999); Nishiyama (2009); Walsh (2009).

[12] Notice that, under non-rational expectations defined by (5), the law of iterated expectations, in general, does not hold; e.g., $E_t^* E_{t+s}^* \pi_{t+1+s} \neq E_t^* \pi_{t+s+1}$ for a given $s = 1, 2, \ldots$.

[13] We assume in the model that non-rational behaviour affects only agents' expectations, and that otherwise they behave optimally, under full information about the underlying model and the fundamental shock. Our experimental design is set up to implement these assumptions as closely as possible. In particular, we will assume that experiment participants observe realizations of the only shock in the model.

[14] Such departures may be due to information rigidities (Woodford, 2001; Mankiw and Reis, 2010; Veldkamp, 2011), adaptive behaviour (Preston, 2006), and cognitive biases (Chakravarty et al. 2011; Boivin, 2011).

The equilibrium in this model is defined as the sequences of the output gap, $\{x_t\}_{t=0}^{\infty}$, inflation, $\{\pi_t\}_{t=0}^{\infty}$ and the nominal interest rate, $\{i_t\}_{t=0}^{\infty}$, that, given expectation functions (5) and sequences of exogenous disturbances, $\{r_t^n\}_{t=0}^{\infty}$, satisfy the system of equilibrium equations (1)–(4).

This model incorporates one of the main channels through which monetary policy affects the real economy. According to the Euler equation (1), the effect of a given change in the nominal interest rate on inflation depends not only on its effect on nominal savings (and hence, nominal consumption expenditures), but also on its effect on *real* consumption expenditures. This effect is dictated by households' preferences to smooth their real consumption over time: real consumption expenditures today depend on the current real rate of interest, given by $i_t - E_t^*\pi_{t+1}$, as well as the expected path of all future real rates of interest, given by the term $E_t^* x_{t+1}$. Quantitatively, the effect on real consumption depends on the trade-off between inflation and the real aggregate supply of goods needed to satisfy consumption demand.

Hence, when prices are sticky, the trade-off between inflation and the output gap, given by the aggregate supply equation (3), implies that the central bank can control inflation not only by setting its short-term nominal interest rate, but also by committing to an entire future path of nominal interest rates. This second way in which the stance of monetary policy affects current economic outcomes is often referred to as the "expectations channel" of monetary policy. The primary goal of our paper is to quantify the strength of this channel by using experimental evidence.

2.2 Model dynamics under rational and non-rational expectations

Under rational expectations, $L_{s\pi} = L_{sx} = 0$ for all s in (5), so that $E_t^* x_{t+1}$ and $E_t^*\pi_{t+1}$ are respective statistical means over distributions of x_{t+1} and π_{t+1} conditional on state history through period t. As is common in the literature, we will denote period-t expected values by an operator E_t. The rational-expectations solution of the equilibrium system implies that period-t expected values of inflation and the output gap are functions of only period-t realization of the real interest rate shock:[15]

$$E_t \begin{bmatrix} \pi_{t+1} \\ x_{t+1} \end{bmatrix} = \begin{bmatrix} \Phi_\pi \\ \Phi_x \end{bmatrix} \rho_r r_t^n \ , \qquad (6)$$

[15] Details of the model solution under various expectations formations are provided in the appendix.

where Φ_π, Φ_x are real numbers that depend on model parameters.

We adopt the model with rational expectations as our baseline, and parameterize it to match the salient features of inflation and the output-gap fluctuations in Canada. We use the Bank of Canada measures of inflation and the output-gap deviations; see the appendix for details. Standard deviation and serial correlation of the r_t^n shock process, σ_r and ρ_r, and the slope of the New Keynesian Phillips curve, κ, are calibrated to match the following three moments in the Canadian data: standard deviation and serial correlation of inflation deviations (0.44 per cent and 0.4, respectively), and the ratio of standard deviations of the output gap and inflation (4.4). This gives us $\sigma_r = 1.13$ per cent, $\rho_r = 0.57$ and $\kappa = 0.13$. The remaining three parameters are assigned values commonly used in the literature. The discount factor, β, is $0.96^{1/4}$; intertemporal elasticity of substitution, σ^{-1}, is one; and the Taylor-rule coefficients in front of the expected inflation and expected output-gap terms are 1.5 and 0.5, respectively, implying that the interest rate responds more than one-for-one to the long-run changes in inflation.

For non-rational expectations, we first consider specification (5), in which ex ante forecast errors are positively correlated with recent state history. For concreteness, we consider the case with $L_{0\pi} > 0, L_{0x} > 0$ and $L_{s\pi} = L_{sx} = 0,\ s = 1, 2, ...$. This case implies that period-$(t+1)$ forecast errors are negatively correlated with period-t shocks. For example, if in period t there is a positive shock to the real interest rate, $r_t^n > 0$, then agents' forecasts tend to be more elastic with respect to rational forecasts. For this reason, we term such expectations formation *sensitive expectations.*

If, instead, the deviation from the rational expectations goes in the opposite direction (i.e., if $L_{0\pi} < 0$ and $L_{0x} < 0$), then period-$(t+1)$ forecast errors are *positively* correlated with period-t shocks. For example, if in period t there is a positive shock to the real interest rate, $r_t^n > 0$, then agents' forecasts tend to be *less* elastic than rational forecasts. We therefore term these expectations *static expectations.*[16] For example, if $L_{0\pi} = L_{0x} = -1$, expectations do not move at all; i.e., $E_t^* x_{t+1} = E_t^* \pi_{t+1} = 0$.[17]

So far, we have considered deviations from rational expectations that imply that agents' forecast errors do no persist for a long period of time. In particular, we considered the case of

[16] We show in the appendix that, under sensitive (static) expectations, agents' forecasts are identical to rational forecasts under a more- (less-) persistent shock. Hence, despite the full knowledge of the underlying shock, agents form sensitive (static) expectations as if they perceive the fundamental shock to be more (less) persistent than it is.

[17] We do not find significant effects from adding one or two lags to the formation of sensitive and static expectations.

(5), in which forecast errors systematically differ from zero only over the first two periods after the shock. To study the implications of forecast errors that persist for a long time, we examine another specification of non-rational expectations. For convenience, we substitute specification (5) with an equivalent specification, in which the expected values of inflation and the output gap are functions of past realizations of inflation and the output gap.[18] Specifically, we assume that ex ante forecast errors are

$$E_t\left(E_t^*\begin{bmatrix}\pi_{t+1}\\ x_{t+1}\end{bmatrix}-\begin{bmatrix}\pi_{t+1}\\ x_{t+1}\end{bmatrix}\right)=-\omega\left(E_t\begin{bmatrix}\pi_{t+1}\\ x_{t+1}\end{bmatrix}-\begin{bmatrix}\pi_{t-l}\\ x_{t-l}\end{bmatrix}\right). \tag{7}$$

Therefore, in period t, agents use a period $t-l$ realization of inflation (the output gap) to form expectations of period-$(t+1)$ inflation (the output gap). For example, if realized inflation in period $t-l$ is high (low), then agents' forecasts of inflation tend to be higher (lower) than would be implied under rational expectations. We therefore term such expectations *adaptive(l) expectations*, where the value in parentheses provides the lag in (7). One important implication of adaptive expectations is that, unlike in the case of static or sensitive expectations, agents' forecast errors persist forever; see the appendix.[19]

How does the model economy respond to a one-standard-deviation innovation to the r_t^n shock? According to the IS equation (1), the increase in the real interest rate increases the rate at which households discount consumption over time, hence increasing the demand for current consumption, leading to a higher output gap. The response of the output gap, however, is 1.6 times higher than implied by the direct effect of the real interest rate increase. This endogenous component of the output-gap response is the result of two effects. First, the persistence of the shock implies positive effects on future consumption, which, due to consumption smoothing, has a positive effect on the current consumption and the output gap. Second, future positive output gaps imply higher future inflation. Since the response of the nominal interest rate is zero at the time of the shock, the real interest rate is below the shock on impact. Furthermore, if future responses of the nominal interest rate are not large enough (i.e., if ϕ_π and ϕ_x are not too large), future real interest rates are also not

[18] Such specification is commonly used in the literature on adaptive expectations. See, for example, Arifovic et al. (2013) and references therein. Hommes and Lux (2013) demonstrate that AR(1) forecasting rules can have a simple behavioural interpretation.

[19] Throughout the paper we assume that $\omega = 0.5$.

large enough to offset the future levels of r_t^n.

To illustrate the role that expectations play in the ability of monetary policy to stabilize such fluctuations, Figure 1 compares impulse responses of inflation for different expectations formations. Sensitive expectations imply more volatile expected values of inflation and the output gap, leading to more volatile inflation. In contrast, static expectations lead to muted responses of expected values and, hence, smaller responses of inflation. Under adaptive(1) expectations, the impulse response is hump-shaped and takes about three years to fully dissipate. Such strong endogenous persistence under adaptive expectations implies that the stabilization of such expectations by monetary policy responses following the shock is smaller.

2.3 Measuring the importance of expectations

Since the goal of this paper is to understand how macroeconomic stabilization by monetary policy depends on the formation of expectations, the key to our analysis is to find a statistic that quantifies such stabilization. When inflation or the output gap are destabilized after a shock or a series of shocks, the countercyclical response of the entire path of future nominal interest rates implies that those deviations will be reduced. The expectation of reduced future deviations of inflation and the output gap, in turn, limits their deviations at the time of the shock.

Identifying such a mechanism is confounded by the dynamic nature of inflation and the output gap, as well as by the endogeneity of monetary policy and expectations. Namely: (i) since the fundamental shock process is persistent, innovation to that shock at any period will have effects in future periods; (ii) since monetary policy has an endogenous component, its response depends on the history of inflation and the output gap, as well as their future expected paths; (iii) expectations of inflation and the output gap may be correlated with shock realizations; and finally, (iv) concurrent countercyclical responses of the nominal interest rate provide stabilization that should be distinguished from that via the expectations channel.

To properly identify and measure the effect of the expectations channel, we propose a statistic that is based on counterfactual responses of inflation and the output gap to an innovation to r_t^n, conditional on zero future responses of nominal interest rates. Such counterfactual responses can be constructed using the following steps. Denote by $s = 0, 1, 2, ...$ the number of periods after the impulse ε_{r0} to the natural-rate-of-interest deviation, so that its impulse response is $r_s^n = \rho_r^s \varepsilon_{r0}$. Let

x_s, π_s and i_s denote the equilibrium impulse responses of the output gap, inflation and interest rate, respectively.

To construct counterfactual responses of the output gap $\tilde{x}_s$ and inflation $\tilde{\pi}_s$, we assume that expectations of inflation and the output gap converge sufficiently close to the steady state after T periods after the impulse, so that we can assume $E_T^* \tilde{x}_{T+1} = E_T^* \tilde{\pi}_{T+1} = 0$. We then use equations (1) and (3) to solve recursively for the output gap and inflation for $s = T, T-1, ..., 0$ under the assumption that nominal interest rate responses are zero in all periods. Denote those paths by $\tilde{x}_s^*$ and inflation $\tilde{\pi}_s^*$:

$$
\begin{aligned}
\tilde{x}_T^* &= \sigma^{-1} r_T^n, \quad \tilde{\pi}_T^* = \kappa \sigma^{-1} r_T^n \ , \\
& ... \\
\tilde{x}_s^* &= \sigma^{-1} r_s^n + E_s^* \tilde{x}_{s+1}^* + \sigma^{-1} E_s^* \tilde{\pi}_{s+1}^*, \qquad s = 1, ..., T-1 \ , \\
\tilde{\pi}_s^* &= \kappa \sigma^{-1} r_s^n + \kappa E_s^* \tilde{x}_{s+1}^* + \left(\beta + \kappa \sigma^{-1}\right) E_s^* \tilde{\pi}_{s+1}^*, \qquad s = 1, ..., T-1 \ , \\
& ... \\
\tilde{x}_0^* &= \sigma^{-1} r_0^n + E_0^* \tilde{x}_1^* + \sigma^{-1} E_0^* \tilde{\pi}_1^* \ , \\
\tilde{\pi}_0^* &= \kappa \sigma^{-1} r_0^n + \kappa E_0^* \tilde{x}_1^* + \left(\beta + \kappa \sigma^{-1}\right) E_0^* \tilde{\pi}_1^* \ .
\end{aligned}
$$

Note that the differences between $\tilde{x}_s^*, \tilde{\pi}_s^*$ and equilibrium responses x_s, π_s are due to shutting down the countercyclical response of the nominal interest rate to the shock. Since we want to focus only on the effect of *future* responses of the nominal interest rate, we also need to account for the concurrent effects of the nominal interest rate by adding $-\sigma^{-1} i_s$ to $\tilde{x}_s^*$, and $-\kappa\sigma^{-1} i_s$ to $\tilde{\pi}_s^*$, obtaining the following counterfactual responses of inflation and the output gap:

$$
\begin{aligned}
\tilde{x}_s &= \tilde{x}_s^* - \sigma^{-1} i_s, \qquad s = 0, ..., T \ , \\
\tilde{\pi}_s &= \tilde{\pi}_s^* - \kappa \sigma^{-1} i_s, \qquad s = 0, ..., T \ .
\end{aligned}
$$

In computing $\tilde{\pi}_s$ and $\tilde{x}_s$, we assume that agents perfectly observe fundamental shock realizations and are able to forecast the next-period shock rationally, which implies that $E_s^* \tilde{x}_{s+1}^* = \tilde{x}_{s+1}^*$ and $E_s^* \tilde{\pi}_{s+1}^* = \tilde{\pi}_{s+1}^*$. Therefore, by construction, counterfactual responses $\tilde{\pi}_s$ and $\tilde{x}_s$ do not depend on the form of expectations. We incorporate this convenient feature in our experimental design by allowing the subjects to observe both shock realizations and their rational forecasts.

Figure 2 compares impulse responses of inflation in the model with rational and adaptive(1) expectations. Since the response of the nominal interest rate is countercyclical, the counterfactual response is larger than both of the equilibrium responses. The degree of the stabilizing effect of the anticipated monetary policy response is indicated by the decrease in the total response of inflation. The greater the decrease, the stronger is the expectations channel of monetary policy. Specifically, we summarize the strength of the expectations channel by computing the decrease in the cumulative absolute response due to future responses in nominal interest rates; i.e., we compute

$$\Xi_\pi = \frac{\sum_{s=0}^{T} |\tilde{\pi}_s| \ - \sum_{s=0}^{T} |\pi_s|}{\sum_{s=0}^{T} |\tilde{\pi}_s|} \ , \quad \text{and} \quad \Xi_x = \frac{\sum_{s=0}^{T} |\tilde{x}_s| \ - \sum_{s=0}^{T} |x_s|}{\sum_{s=0}^{T} |\tilde{x}_s|} \ .$$

2.4 Model predictions for the expectations channel

How much does monetary policy stabilize the economy after a shock via its effect on expectations? Table 1 shows that, in the baseline model, expectations play a substantial role in the ability of monetary policy to stabilize fluctuations in the output gap and inflation. The shares of the conditional variance of inflation and the output gap that decreased due to the expectations channel, Ξ_π and Ξ_x, are 0.73 and 0.65, respectively.

To gain further intuition regarding the workings of the expectations channel, we compute Ξ_π and Ξ_x for different parameter values in the model with rational expectations.[20] We show that Ξ_π and Ξ_x are monotonically increasing in ρ_r, κ, σ^{-1} and ϕ_π, and can even take on negative values. Higher shock persistence, ρ_r, extends the horizon over which future nominal interest rates stay high, therefore increasing the stabilizing effect of the expectations channel. Table 1 shows that increasing ρ_r from 0.57 to 0.80 raises stabilization from 0.73 to 0.97 for inflation, and from 0.65 to 0.98 for the output gap.

For a shock of given magnitude, κ and σ^{-1} increase the elasticities of inflation and the output gap with respect to the current increase in the nominal interest rate. This would allow

[20] Ξ_π and Ξ_x are computed for the range of each of these parameters, keeping other parameters fixed at the benchmark levels. Figures A.2 and A.3 in the appendix provide Ξ_π for a range of parameter values and for alternative expectations formations.

future increases in the nominal interest rate to be more efficient in offsetting deviations in inflation and the output gap, increasing the importance of the expectations channel. Doubling each of these parameters increases the effect of policy on conditional variance to over 0.8 for both inflation and the output gap (see Table 1).

An increase in the elasticity of the nominal interest rate to expected inflation and the output-gap fluctuations increases the aggressiveness of future nominal rate increases with respect to inflation and the output-gap deviations, thus increasing the effect of expectations on current outcomes. Doubling the elasticity of the policy response increases the fraction of variance explained by the expectations channel from 0.73 to 0.82 for inflation and from 0.65 to 0.75 for the output gap.[21]

We also consider alternative specifications of the policy rule (4). First, we compute Ξ_π and Ξ_x for the model in which the terms on the right-hand side of the Taylor rule are $\phi_\pi \pi_t + \phi_x x_t$, instead of $\phi_\pi E^*_{t-1}\pi_t + \phi_x E^*_{t-1} x_t$ in our baseline model. Without a policy lag, the contribution of expectations to stabilization is marginally larger, increasing from 0.73 to 0.76 for inflation.

Second, we allow for interest rate smoothing in the Taylor rule:

$$i_t = \phi_i i_{t-1} + \phi_\pi E^*_{t-1}\pi_t + \phi_x E^*_{t-1} x_t \ .$$

This specification implies that the nominal interest rate depends, in addition to expected inflation and the output gap, on its previous value, with parameter ϕ_i denoting the weight attached to the past value. Adding interest rate smoothing extends the horizon during which the nominal interest rate responds after the shock, thus allowing it to stabilize the economy more than without smoothing.[22] For example, for simulation with $\phi_i = 0.8$, conditional variance is decreased by 0.87 for inflation (relative to 0.73 with no smoothing) and by 0.75 for output (0.65 with no smoothing); see Table 1, row 6.[23]

Turning to the degree of stabilization under non-rational expectations, rows 1 and 2 of Table

[21] In this exercise, we change ϕ_π, ϕ_x proportionally, so that $\phi_\pi/\phi_x = 3$.

[22] This implies a well-known result that, under price-level targeting (corresponding to $\phi_i = 1$), the expectations channel is stronger than under monetary policy characterized by the standard Taylor rule.

[23] Pfajfar and Žakelj (2013) study the stabilizing role of various Taylor rule specifications in a forward-looking New Keynesian model. They find that economic stability is enhanced when the policy rule is conditioned on current inflation, rather than expected future inflation. In their work on expectations and uncertainty, Pfajfar and Žakelj (2012) find that inflation targeting produces lower uncertainty and higher forecast accuracy than inflation-forecast targeting, where larger deviations of expectations from the target result in larger interest rate adjustments.

2 show that, when expectations are sensitive (static), monetary policy is able to stabilize respective outcomes less (more). For sensitive expectations, the decrease in conditional variance due to the expectations channel of monetary policy is lower than under rational expectations, 0.55 and 0.54 for inflation and the output gap, respectively. For static expectations, the decrease is larger, 0.89 and 0.74, respectively.

Rows 3, 4 and 5 of Table 2 show moments for equilibrium dynamics for adaptive(0), adaptive(1) and adaptive(2) expectations, respectively. In all cases, the contribution of future nominal interest rate responses to the stabilization of inflation and the output-gap deviations is lower than under rational expectations, 0.55, 0.20 and -0.14, respectively, for inflation, and 0.51, 0.32 and 0.35 for the output gap. The intuition is similar to the case of sensitive expectations: the positive realization of the period-t real interest rate shock implies higher expected future values of the output gap and inflation. Unlike sensitive expectations, for which such effects last a finite number of periods, period-t shock realization has long-lasting effects on agents' forecast errors. These results demonstrate that, under non-rational expectations, the stabilization benefits of monetary policy can be substantially smaller, or even none.

We show in the appendix (Figure A.3) that the relative rankings of the contribution of future terms implied by alternative expectations are invariant across all combinations of model parameters. Namely, under static expectations, monetary policy is the most effective in reducing the variance of inflation and the output gap, even more effective than under rational expectations. Sensitive expectations imply a less important role for expectations than rational expectations. Finally, adaptive expectations imply the lowest contribution of future terms to inflation variance. Differences in implications under alternative expectations are larger for smaller values of ρ_r, κ, σ^{-1} and ϕ_π, and the differences dissipate as those values increase.

As an additional robustness check, we also compare those rankings under recalibrated values of σ_r, ρ_r and κ that allow each version of the model to match the same calibrated targets as in the baseline model under rational expectations. The relative rankings remain the same, with differences in the degree of stabilization even larger than without recalibration.

The above exercises demonstrate that the relative rankings of the importance of expectations for inflation variance under alternative expectations formations are not sensitive to a particular parameterization of the model. We conclude that our metric, in theory, provides a reliable measure of the importance of expectations for inflation and the output-gap stabilization by monetary policy.

3. Experimental Design

The experiment was conducted at CIRANO's Experimental Economics Laboratory in Montréal, Quebec. This lab has access to a large subject pool with a large number of non-student participants. Subjects were invited to participate in sessions that involved 30 minutes of instructions and 90 minutes of game participation. Each session involved nine subjects interacting together in a single group. Earnings, including a $10 fee for showing up, ranged from $18 to $45, and averaged $36 for 2 hours.

3.1 Procedures

Participants were provided with detailed instructions before the experiment began. Using clear, non-technical language, we explained, both verbally and via their computer screens, how the output gap, inflation and interest rate would evolve given their expectations, monetary policy and shocks.[24] The participants' task was to submit forecasts for the next period's inflation and output gap. We explained that their period score depended only on the accuracy of their two forecasts submitted for that period. In particular, subject i's score in period t was determined by the following function of absolute forecast errors:

$$S_{i,t} = R_0 \left(e^{-\alpha \left| E^*_{i,t-1}\pi_t - \pi_t \right|} + e^{-\alpha \left| E^*_{i,t-1}x_t - x_t \right|} \right) ,$$

where $R_0 = 0.3$, $\alpha = 0.01$ and $E^*_{i,t-1}\pi_t$, $E^*_{i,t-1}x_t$ are subject i's forecasts submitted in period $t-1$. This scoring rule implied that subjects could earn over $70 for the entire experiment if they made accurate forecasts. Another key feature of the scoring rule is that it provided an incentive to make accurate forecasts: for every additional error of 100 basis points for both inflation and the output-gap forecasts, the subjects' score in that period would decrease by half.

While the written and verbal instructions, provided prior to the experiment, included a qualitative description of the IS and Phillips curve as well as the central bank's policy function, they did not explain functional forms or calibrations of the model economy. Subjects were informed that

[24] In the experiment, we used the term "output" to denote the output gap, for simplicity.

a shock to the output gap would occur each period, that it would gradually dissipate with persistence parameter ρ, and that its size would be randomly drawn from a normal distribution, with mean zero and variance σ_r^2. In each period, the average forecasts, $E^*_{t-1}\pi_t$ and $E^*_{t-1}x_t$, appearing in the IS curve, the Phillips curve, and the Taylor rule, were computed as medians across subjects' individual forecasts, $E^*_{i,t-1}\pi_t$ and $E^*_{i,t-1}x_t$.[25] Subjects never directly observed other subjects' forecasts or the average forecasts.

In each experimental session, subjects participated in four practice rounds before commencing two multi-round sequences, or "repetitions." Each repetition was initiated at the long-run steady state of zero inflation, the output gap and interest rate. The historical graphs and tables available to subjects showed the time horizon beginning at period −5 with all values at their long-run values through to period 0. The purpose of this design feature was to emphasize to subjects that the economy had been fully reset. Subjects were informed that each sequence would end randomly between 45 and 55 periods. Periods lasted up to 1 minute in the first 10 periods of each sequence, and for 45 seconds thereafter. This sequential design of the experimental sessions allowed us to control for subjects learning the experimental and economic environment: results of practice rounds are not included in the analysis, and the results of the first and second repetitions across sessions will be compared.

3.2 Interface

The experiment was programmed in Redwood, an open-source software (Pettit et al., 2013). Throughout the experiment, participants had access to three interchangeable screens: the main (default) screen, the history screen and the screen with technical instructions.[26] In addition, the header, containing subject identification, period, time remaining and total score, was seen throughout the experiment. We designed the experimental interface to separate different types of information across the three screens. This allowed us to track the information that subjects focused on when forming their forecasts, and how much time they spent on each screen.

The main screen, as a default, appeared in front of the other screens. All subjects observed the current period's interest rate and shock realization, as well as the expected value of the next

[25] Median forecasts were not sensitive to extreme individual entries, making it more difficult for subjects to manipulate the average forecasts.

[26] Screen designs, instructions and other details of the experimental interface are included in the appendix.

period's shock. If all subjects behaved rationally, this information would be sufficient for making rational forecasts. At the beginning of each period t, subjects were able to enter and submit their forecasts for the next period's output gap and inflation. If a subject did not submit the forecasts within the time limit, those forecasts were not included in the median calculation, and the subject received a score of zero.

The history screen was located on a second tab. To access it, subjects could click on the tab located at the left of the main screen. Subjects could freely switch between the screens, although only one screen could be open at a time. Within the history screen, subjects could see graphs of time series for the realized output gap and inflation, their forecasts, the nominal interest rate and shock values. Our interactive software allowed subjects to see exact values for each series at any point on a graph by placing their cursor at that point.

Technical instructions were located on the third and final screen. These supplementary instructions provided a detailed description of how inflation, output, the interest rate, and shock evolved and included calibrated parameter values. The technical instructions were meant to imitate open-access technical material that is available on the central bank's website. Our software enabled us to monitor the time that each subject allocated to reviewing the information in each period. Subjects were allowed to use the Windows calculator as well as to write down their calculations.

This interface implements two key features of our experimental design. First, shock realizations are directly observed by the subjects. This allows us to directly estimate forecasts as functions of the shock history. Second, making the auxiliary information available at a small time cost gives subjects a choice between information about the shock and information about the history of inflation and the output gap, or about model details. We can use observations on how often subjects switch across these screens to understand how they use available information to form their expectations.

3.3 Treatments

The experiment included three treatments that explored the robustness of outcomes in our experimental economy. In the benchmark treatment, experimental outcomes were determined by the baseline model described in section 2, in which expectations $E_t^* \pi_{t+1}$ and $E_t^* x_{t+1}$ were given by the median forecasts for inflation and the output gap provided by subjects in each period.

In the high-persistence treatment, the persistence of the shock was increased from $\rho_r = 0.57$

to $\rho_r = 0.8$. The model predicts that although inflation and the output-gap volatilities increase, the degree of stabilization provided by monetary policy should also increase.

In the aggressive monetary policy treatment, the elasticity of interest rates to inflation and the output gap was doubled to $\phi_\pi = 3$ and $\phi_x = 1$, respectively. The model predicts that a more aggressive monetary policy will provide more stabilization via its effect on expectations, leading to more-stable output-gap and inflation fluctuations.

We also conducted an auxiliary communication treatment based on the benchmark treatment, in which, in every period, subjects observed on their main screens a forecast of future interest rates for the following nine periods.[27] This stylized treatment provided information about the value of the central bank's communication of its likely future actions. If subjects made their decisions based on a complete understanding of the model (and monetary policy), such communication regarding future expected monetary policy actions *should not* have had significant effects on the outcomes in this treatment.

In all, we conducted five sessions for each of the benchmark, high-persistence, and aggressive monetary policy treatments, and six sessions for the communication treatment.[28]

4. Experimental Results: Aggregated Outcomes

4.1 Summary of experimental outcomes

In all of our experimental sessions (second repetitions), inflation and the output gap exhibit stable cyclical behaviour, with the peak-to-trough time ranging between 3.9 and 7.5 quarters in the benchmark treatment, which is within the range of 3 to 20 quarters predicted by our baseline model under various expectations formations. The experimental outcomes, therefore, do not seem to be driven by factors outside the data-generating process, such as sunspots or strategic behaviour.[29] Furthermore, throughout our experiment the results do not differ significantly between the first and second repetitions, suggesting that subjects quickly converge to their stationary behaviour. The

[27] The central bank's forecast is constructed using a model solution under rational expectations. See the appendix for details.

[28] Prior to conducting our experiment, we ran seven pilot sessions, which allowed us to refine our instructions and design. See the appendix (section 2.A) for details.

[29] Marimon and Sunder (1993) and Marimon, Spear and Sunder (1993) study non-stable behaviour in macroeconomic and monetary experimental settings.

stability of the experimental outcomes provides support for the sound experimental implementation of our theoretical model.

Table 3 provides summary statistics for the dynamics in the experiments for each of the three treatments: benchmark, high-persistence and aggressive monetary policy. We first calculate the statistics for each repetition, and then provide in the table the median, min and max values of those statistics over repetitions.[30] To control for learning by subjects, we provide statistics only for repetition 2, noting, however, that results including repetition 1 are very similar.

For the benchmark treatment, monetary policy (acting via the future expected path of nominal interest rates) removes about half of the conditional variance: 0.51 for inflation and 0.45 for output. Such a degree of stabilization falls in the midpoint between values predicted by the theoretical model under rational expectations, 0.73 and 0.65, and under adaptive(1) expectations, 0.20 and 0.32. So although the degree of stabilization is somewhat smaller than predicted by the baseline model with rational expectations, monetary policy is quite potent in providing stabilization, accounting for roughly half of the business-cycle stabilization.

What type of expectations formation leads to the outcomes observed in the benchmark treatment? Further examination of Table 3 reveals that both inflation and the output gap are more volatile in the experiment (0.79 per cent and 3.0 per cent, respectively), relative to those in the baseline model with rational expectations (0.44 per cent and 1.9 per cent), although the ratio of the standard deviation of the output gap and inflation is not as high as in the baseline, 3.8 vs. 4.4. Fluctuations in the experiment also are more persistent than in the baseline model, with serial correlations of 0.56 and 0.40, respectively.

A comparison of the experimental results with the model predictions in Table 2 suggests that the closest fit to the experimental results is given by models with sensitive and adaptive(1) expectations. For example, in the model with sensitive expectations, the reduction of the conditional variance for inflation and the output gap is 0.55 and 0.54 (0.51 and 0.45 in the experiment), the unconditional standard deviations are 0.70 and 2.6 per cent (0.79 and 3.0 per cent in the experiment), and the serial correlation of inflation is 0.40 (0.56 in the experiment). The model with adaptive(1) expectations, in turn, slightly overpredicts the size and persistence of inflation fluctuations and

[30] Results in Table 3 are not sensitive to whether means, instead of medians, are reported.

underpredicts stabilization by monetary policy.

The bottom two panels in Table 3 compare outcomes in two alternative treatments – high-persistence and aggressive monetary policy – to the benchmark treatment. In both cases, experimental outcomes are consistent with those predicted by the theoretical model (see Table 2).[31] Namely, increasing shock persistence leads to more-volatile and more-persistent output-gap and inflation fluctuations, a smaller ratio of output-gap volatility to inflation volatility, and finally, a larger decrease in the fraction of conditional variance explained by the expectations channel of monetary policy. In turn, more-aggressive monetary policy leads to less-volatile and less-persistent output-gap and inflation fluctuations, a larger ratio of output-gap volatility to inflation volatility, and a larger decrease in the fraction of conditional variance explained by future nominal interest rates.[32]

Such consistency between the experimental results and the predictions of the theoretical model supports our assumption that subjects understand the workings of the data-generating model. This understanding, however, is not complete. This can be seen from the results of the auxiliary communication treatment. We show in the appendix (Table A.2) that public announcements of the forecast of future interest rates lead to more-volatile fluctuations, and, therefore, less-effective monetary policy. For example, the standard deviation and the persistence of inflation in the communication treatment are 1.18 per cent and 0.75, respectively, both higher than 0.79 and 0.56 in the benchmark treatment. The fractions of conditional variance of inflation and output decreased via the expectations channel of monetary policy are 0.19 and 0.10, respectively, both lower than 0.51 and 0.45 in the benchmark treatment. These results point to the potentially detrimental consequences of interest rate forecast announcements.[33]

4.2 Comparisons of experimental and theoretical outcomes

Since, by design, the shock is observed, we can gain further insight into the implications of

[31] Mann-Whitney tests significantly reject the null hypotheses that the statistics are identical across treatments ($p<0.02$ in all cases).

[32] Assenza et al. (2012) find that monetary policy must be significantly aggressive to changes in inflation from target levels to maintain macroeconomic stability. Our analysis allows us to map the aggressiveness of monetary policy to the reduction in the size of macroeconomic fluctuations. For example, in our experiments, the doubling of the countercyclical interest rate response implies an additional 21 and 11 percentage-point reduction of the conditional variance of inflation and output.

[33] Galí (2011) questions the usefulness of central banks announcing nominal interest rate projections, using a standard New Keynesian model as a reference framework. Baeriswyl and Cornand (2012) study the effectiveness of central bank communication in reducing the overreaction of financial markets to public information.

expectations formation for aggregate fluctuations by comparing experimental time series to those predicted by our theoretical model for the *same* history of shock realizations that occurred during the experiment. We compare the time series for inflation, the output gap, their average forecasts and the interest rate observed in our experiment to their theoretical counterparts constructed using decision functions for model equilibria under alternative forecast functions characterized by (5). For example, under rational expectations, the decision functions are

$$\begin{aligned}
E_t^*\pi_{t+1} &= 0.080r_{t-1}^n + 0.141\varepsilon_{rt} \ , \\
E_t^*x_{t+1} &= 0.269r_{t-1}^n + 0.472\varepsilon_{rt} \ , \\
\pi_t &= -0.195E_{t-1}^*\pi_t - 0.065E_{t-1}^*x_t + 0.199r_{t-1}^n + 0.349\varepsilon_{rt} \ , \\
x_t &= -1.5E_{t-1}^*\pi_t - 0.5E_{t-1}^*x_t + 0.919r_{t-1}^n + 1.613\varepsilon_{rt} \ , \\
i_t &= 1.5E_{t-1}^*\pi_t + 0.5E_{t-1}^*x_t \ .
\end{aligned}$$

For each history of shock realizations observed over repetitions, we construct counterfactual sequences of model outcomes corresponding to equilibria under a given formation of expectations (in the above case, rational).

Table 4 compares counterfactual time series for four alternative expectations formations to those obtained in the experiment. The time series for the experiment correspond to the benchmark treatment (repetition 2). The time series for the model correspond to equilibrium outcomes given the same shock history. We compare moments for five time series: $E_t^*(\pi_{t+1})$, $E_t^*(x_{t+1})$, π_t, x_t and i_t. The top panel provides the ratio of standard deviations for the counterfactual and empirical time series, and the bottom panel provides the correlation of the counterfactual and empirical time series. The entries in the table are medians across five sessions.

Among the four alternative expectations, in keeping with our findings in Table 3, sensitive and adaptive(1) expectations are the most consistent with the magnitude of fluctuations observed in the experiment. For example, under rational expectations, standard deviations of inflation and the output-gap fluctuations are 0.58 and 0.74, respectively, relative to those in the experiment. Under sensitive and adaptive(1) expectations, they are closer in magnitude to those in the experiment, at 0.93 and 1.01, respectively, under sensitive expectations, and 1.24 and 0.91, respectively, under adaptive(1) expectations. A similar story concerns fluctuations in the forecasts of inflation and the output gap. For instance, their standard deviations are 0.36 and 0.38 under rational expectations, while under sensitive (adaptive 1) expectations they are 0.72 and 0.76 (1.24 and 0.70), respectively.

In terms of the timing of fluctuations between the counterfactual and empirical time series, adaptive(1) expectations provide the best fit. For example, while, under rational expectations, correlations between the time series range from 0.55 to 0.71, under adaptive(1) expectations the range is 0.76 to 0.89. Sensitive expectations do not provide better correlations between the counterfactual and experimental time series.

So far, we have examined evidence for outcomes observed in the experiment and compared those outcomes to those implied by model equilibria under alternative expectations formations. We find that sensitive and adaptive expectations imply outcomes that fit best (among the alternatives) those observed in the experiment. To better understand these results, we next link them to inflation and output-gap forecasts characterized as functions of the observed shock history. We first estimate these functions for model simulations and then compare them to those estimated for the experiment.

4.3 Estimated forecast functions

In accordance with the theoretical model in section 2.1, equation (5), we estimate ex ante forecast errors as functions of the history of innovations to r_t^n shocks.[34] For example, for inflation ex ante forecast errors, we estimate the following specification:

$$E_t\left(\pi_{t+1} - E_t^{*}\pi_{t+1}\right) = G_0^{\pi}\varepsilon_{rt} + G_1^{\pi}\varepsilon_{rt-1} + ... + G_T^{\pi}\varepsilon_{rt-T}\ , \tag{8}$$

where T is a finite integer that is big enough to approximate (5) well, and coefficients G_i^{π} fully characterize inflation ex ante forecast errors.[35]

Panel A in Figure 3 plots ex ante forecast errors for inflation in a theoretical model for alternative expectations. For the baseline model with rational expectations, ex ante forecast errors are uncorrelated with shock innovations at any lags. For static expectations, forecast errors correlate

[34] For simple cases in the model, these functions can be derived analytically.

[35] We estimate an OLS regression, $\pi_{t+1} - E_t^{*}\pi_{t+1} = G_0^{\pi}\varepsilon_{rt} + G_1^{\pi}\varepsilon_{rt-1} + ... + G_T^{\pi}\varepsilon_{rt-T}\ + \epsilon_{t+1}$, where $E_t^{*}\pi_{t+1}$ is the expected value of π_{t+1} in period t given by (5) or the median forecast in the experiment, and ϵ_{t+1} are i.i.d. zero mean draws. Note that G_i^{π} also approximates the responses of ex ante forecast errors in quarter i after an impulse to r_t^n.

positively with shocks, since forecasts are not sensitive to shocks. In contrast, for sensitive expectations, forecast errors are negatively correlated with shock innovations, since forecasts overshoot rational forecasts. For adaptive(1) expectations, ex ante forecast errors display a distinct pattern: they are positive at the time of the shock, since the inflation forecast is expected to undershoot relative to inflation next period, and they are negative thereafter, since inflation forecasts are expected to persist while inflation slowly returns back to its pre-shock level.

To provide better intuition for the implications of alternative forecast functions, we also estimate forecast decision functions by estimating specification (8) for median forecasts as a dependent variable. Panel B in Figure 3 plots forecast functions for inflation in the theoretical model for alternative expectations. For the baseline model with rational expectations, the inflation forecast is positive and highest at the time of the impulse (which equals 113 basis points), 14 basis points. For (our parameterization of) static expectations, forecasts are identically zero. For sensitive expectations, forecasts are twice as volatile as those for rational expectations. For adaptive(1) expectations, forecasts are not only more volatile, but they peak one period after the original impulse. In other words, adaptive(1) expectations take time to respond to shock innovations, in this case, one period.

Panels C and D in Figure 3 plot the ex ante forecast errors and forecast functions estimated from the experimental data, respectively (blue lines).[36] There are clear over- and undershooting patterns for the ex ante forecast errors, inherent to those for the adaptive(1) expectations, as discussed in the previous paragraph. It is evident from Figure 3 that the adaptive(1) expectations provide the best fit to forecasts in our experiment. Not only are the overall shape and size of forecast functions and ex ante errors similar to those from the experiment, but the timing of over- and undershooting (of forecast errors) and peaks (of forecasts) coincide as well. We therefore conclude that, in forming their expectations, the subjects rely mostly on information drawn from very recent history (up to four lags or so) of shock realizations, and that this behaviour can be well-captured by a forecast rule that puts around half of the weight on lagged model outcomes (i.e., inflation and the output gap). An important implication of this behaviour is that, in response to a shock, expectations take time to align with changes in the economy: e.g., in response to a positive r_t^n shock, inflation and output-gap expectations take one quarter to catch up with the growing inflation and

[36] We estimate equation (8) for each of the five second repetitions in the benchmark treatment. We plot median-point estimates, together with two-standard-deviation bands.

the output gap, and then they are persistently higher when inflation and the output gap start to return to the pre-shock level.[37]

Adaptive(1) is a relatively weak form of adaptive expectations, since half of the weight falls on very recent outcomes (as opposed to outcomes farther in the past) and since the rest of the weight is on rational expectations. We show in the appendix (Figure A.4) that stronger forms of sensitive and adaptive expectations are worse at matching the data, missing on both the timing and magnitude of responses of forecasts and forecast errors. We conclude that the model with adaptive(1) expectations most accurately predicts the fluctuations that we observe in the experimental setting.

5. Experimental Results: Individual Behaviour

5.1 Individual forecast errors

Our theoretical model assumes no heterogeneity in how expectations are formed. In accordance with the model, our experimental design provides full information about the driving shock and complete details about the model itself, both of which should minimize differences in subjects' information sets during the experiment. Therefore, we assume that aggregate expectations are well approximated by the average (median) forecast and argue that implications of heterogeneity in expectations are not very important in our approach.

There is, expectedly, some degree of heterogeneity in forecasting behaviour across subjects.[38] For example, in the benchmark treatment (repetition 2), the standard deviation of forecast errors for inflation (the output gap) is 94 (401) basis points. Such dispersion in forecasts is of the same order of magnitude as the size of the fluctuations: for example, the standard deviation of the median inflation (output-gap) forecast is 56 (176) basis points. Although the dispersion may seem large,

[37] Adam (2007) considers a two-equation New Keynesian model that is similar to the one in this paper, and asks whether sluggish expectations can account for the considerable persistence of output and inflation. Similar to our results, he finds that subjects exhibit adaptive behaviour: inflation expectations rely strongly on past inflation, although not on past output. Such behaviour leads to considerable persistence of output and inflation in response to nominal shocks, possibly due to the fact that subjects neither knew the underlying model nor directly observed the fundamental shock driving the fluctuations. Amano et al. (2011) show that, under price-level targeting, experiment participants did not fully incorporate the mean-reverting nature of the price level in their forecasts.

[38] Dispersion in forecasts may stem from differences in the subjects' cognitive abilities, information sets or strategic behaviour. See section 2. Assenza et al. (2012) fit a heterogeneous expectations switching model to the experimental data in a New Keynesian macroeconomic set-up. They show that individual learning takes the form of switching from one heuristic learning rule to another.

it does not necessarily have a large effect on the aggregate outcomes that are computed using the median forecast.

To assess the importance of the forecast dispersion, we compare the accuracy of the best and the worst forecasters to each other, as well as to the accuracy of a hypothetical rational forecaster. As in the previous section, our experimental design allows us to estimate those behaviours directly. We ask which of the forecasts the median forecast is the closest to: the best or the worst, and whether those forecasts are close to rational.

For every session, we identify the highest and second-lowest ranking forecasters as the subjects who accumulate the most and second-least forecasting scores in the second repetition.[39] To estimate the behaviour of a hypothetical rational forecaster, we estimate equilibrium outcomes for x_t and π_t in our experiment as the following functions of the state history:

$$\begin{aligned}\pi_t &= D_0^{\pi}\varepsilon_{rt} + D_1^{\pi}\varepsilon_{rt-1} + ... + D_T^{\pi}\varepsilon_{rt-T} \ , \\ x_t &= D_0^{x}\varepsilon_{rt} + D_1^{x}\varepsilon_{rt-1} + ... + D_T^{x}\varepsilon_{rt-T} \ ,\end{aligned}$$

where T is a large enough integer. The specifications above imply that rational one-period-ahead forecasts for inflation and output are given by

$$\begin{aligned}E_t\pi_{t+1} &= D_1^{\pi}\varepsilon_{rt} + ... + D_T^{\pi}\varepsilon_{rt-T+1} \ , \\ E_t x_{t+1} &= D_1^{x}\varepsilon_{rt} + ... + D_T^{x}\varepsilon_{rt-T+1} \ .\end{aligned}$$

By construction, rational forecasts provide an upper bound on the accuracy of individual forecasts in the experiment.

We find that inflation and output forecasts, submitted by the top performers in a given session, are not significantly different from the median forecasts. For example, Mann-Whitney tests yield p-values of $p > 0.34$ in all cases. Both the median and top performer's forecasts are significantly different from the rational forecasts, with $p < 0.01$. These results are robust to the treatment variations we considered.

[39] We discard the lowest-ranking subjects, who may be outliers.

Figure 4 shows plots for inflation and output forecasts for the top and bottom forecasters, and the rational forecast for session 5 in the benchmark treatment. Bottom performers' forecasts are significantly less accurate than those by the top performers, or the median or rational forecasts. For example, for inflation forecasts in the benchmark treatment, the average root mean squared error (RMSE) for the bottom performer is 110 basis points, which is up to one and a half times larger than RMSEs for the top performer, 83 basis points, and for the median forecast, 71 basis points. This also suggests that the dispersion of forecast errors is mainly driven by bottom performers.

In sum, we document that (i) the forecasts of best performers are not significantly different from the median forecasts, and (ii) subjects' forecasts are significantly less accurate than rational forecasts, and (iii) the dispersion of forecast errors is mainly driven by bottom performers. This leads us to conclude that, in accordance with our theoretical and experimental framework, taking into account heterogeneity in expectations formation is unlikely to affect results that are based on median forecasts.

5.2 Tab times

Our software allowed us to track how much time a subject spent on the forecast, history and technical instructions screens. Subjects made virtually no use of the technical instructions, visiting the screen only 2.2 times over a 50-period repetition, each time spending, on average, 2.4 seconds, which amounts to only 0.3 per cent of the available decision time. In contrast, subjects used the history screen extensively, visiting it, on average, 2.4 times per period and spending around 45 per cent of their decision time there (see Table 5). The fact that most subjects visited the history screen at least twice per period can be related to their need to form two forecasts per period (for inflation and for the output gap). We therefore conclude that subjects valued information about the history of aggregate outcomes much more than details about the underlying data-generating model.

There was little variation in screen usage among subjects. Across all four treatments and repetitions, the median time spent on the history screen ranged from 40 to 46 per cent of subjects' time. The top forecasters reviewed historical information significantly more often than the lowest-ranking subjects, and there was no significant difference between the top and median forecasters. This provides further evidence that the top-performing subjects did not follow significantly different strategies than most subjects.[40]

Finally, we investigate whether screen usage can tell us anything about subjects' forecasting behaviour. We find a statistically significant relationship between the amount of time a subject spent reviewing historical information and the weight they assigned to recent shocks when forming their forecasts. Using repetition 2 data, we estimate individual forecast functions and compare the results with the subjects' screen usage. Pooling data from the benchmark, high-persistence, and aggressive monetary policy treatments, we find that the average proportion of time spent reviewing the history screen is positively correlated with the weight of ε_{t-2} on $E^*_{i,t}\pi_{t+1}$ and $E^*_{i,t}x_{t+1}$: the Spearman correlation coefficient for inflation forecasts is 0.17 ($p = 0.04$) and for output-gap forecasts it is 0.19 ($p = 0.02$). The subjects' tab usage was not significantly correlated with current shocks, ε_t, or one-period-lagged shocks, ε_{t-1}. Subjects in the communication treatment exhibited similar behaviour.

Hence, in our experiment, subjects relied mostly on recent data and a qualitative understanding of the working of the economy to form their forecasts, rather than study the technical instructions to learn quantitative details of economic mechanisms. Our findings suggest that subjects avoided costly effort associated with information overload by using simplifying heuristics.[41] Our analysis therefore indicates that such behaviour, at the aggregate level, does not preclude monetary policy from being effective in stabilizing macroeconomic fluctuations.

5.3 Questionnaires

Subjects were asked to complete follow-up questionnaires after each session. More than 70 per cent (95/135) of the subjects in our benchmark, high-persistence, and aggressive monetary policy treatments did take nominal interest rates into consideration while forming their forecast. We asked subjects to describe the strategies and information they used to form their forecasts: 81 per cent of subjects (109/135) reported that they used some form of historical information to construct their forecast (e.g., past inflation and output levels, forecasts, and forecast errors), while 23 per

[40] Note that for all treatments, except communication, there is a non-monotonic relationship between the number of visits to the history screen and forecasting performance. Both top and bottom forecasters visited the screen less frequently than the median forecaster. This may suggest a non-monotonic relationship between the value of the history screen information and forecasters' ability to use that information.

[41] The decision-science literature studies behaviour aimed at reducing the amount of effort exerted to make a decision or complete a task (see Payne, Bettman and Luce 1996; Payne, Bettman and Johnson 1998).

cent (31/135) discussed extrapolating trends from the data. This supports our earlier findings that subjects rely significantly on historical information when forecasting. Finally, we find very little evidence of strategic considerations in subjects' responses. Only 5 out of 135 subjects made any reference to other subjects' behaviour when forming their forecasts. None of these five subjects were among the top performers in their session.

Subjects in the communication treatment more frequently stated that they conditioned their forecasts on the interest rate. Over 83 per cent (45/54) of subjects considered the nominal interest rate, suggesting that the additional information had some success at emphasizing that nominal interest rates were important. Many subjects noted that they initially used the interest rate forecasts to aid in their decision making, but later ignored the information, since it did not appear to be helpful for their forecasting accuracy. Otherwise, information usage was not considerably different from other treatments.

6. Conclusions

Monetary policy plays an important role in guiding public expectations of future inflation and output, and thus in influencing economic activity. Indeed, if a central bank is successful in anchoring public expectations, monetary policy is more likely to have its intended effects. In this paper we utilize experimental laboratory evidence to quantify the expectations channel of monetary policy. We design a laboratory experiment that allows us to identify the contribution of expectations to macroeconomic stabilization achieved by systematic monetary policy.

We find that individuals rely mostly on recent data and a qualitative understanding of the working of the economy to form their expectations, importantly paying attention to the behaviour of the nominal interest rate. Despite some non-rational component in individual expectations, we find that monetary policy is quite potent in providing stabilization, accounting for roughly half of the business-cycle stabilization. This finding underlines the important role of communication as a tool that central banks use to manage agents' expectations in both normal periods and more extreme circumstances. Our communication treatment suggests, however, that public announcements of the future course of monetary policy may be detrimental to macroeconomic stability. The caveat, therefore, is that the implications of central bank communication should be studied more extensively, and that experimental approaches can be useful.

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Table 1: Model Predictions under Rational Expectations

		Fraction of conditional variance decreased via expectations channel π_t	Fraction of conditional variance decreased via expectations channel x_t	std(π_t)	ser.cor.(π_t)	$\frac{\text{std}(x_t)}{\text{std}(\pi_t)}$
	Baseline	**0.73**	**0.65**	**0.44**	**0.40**	**4.4**
1	High-persistence	0.97	0.98	1.16	0.71	2.4
2	Steep NKPC	0.89	0.86	0.80	0.39	2.4
3	Lower risk aversion	0.81	0.88	0.66	0.35	5.1
4	Aggressive policy	0.82	0.75	0.31	0.35	5.1
5	No policy lag	0.76	0.73	0.34	0.57	3.4
6	Interest rate smoothing	0.87	0.75	0.27	0.19	6.3

Table 2: Model Predictions under Alternative Expectations

		Fraction of conditional variance decreased via expectations channel π_t	Fraction of conditional variance decreased via expectations channel x_t	std(π_t)	ser.cor.(π_t)	$\frac{\text{std}(x_t)}{\text{std}(\pi_t)}$
	Baseline	**0.73**	**0.65**	**0.44**	**0.40**	**4.4**
1	Sensitive	0.55	0.54	0.70	0.40	3.7
2	Static	0.89	0.74	0.18	0.57	7.7
3	Adaptive(0)	0.55	0.51	0.81	0.14	3.5
4	Adaptive(1)	0.20	0.32	1.00	0.74	2.6
5	Adaptive(2)	-0.14	0.35	0.96	0.87	2.4

Table 3: Experimental evidence, summary statistics

Treatment	Fraction of conditional variance decreased via expectations channel		std(π_t)	ser.cor.(π_t)	std(x_t)/std(π_t)
	π_t	x_t			
<u>**Benchmark**</u>					
Model (Rational)	**0.73**	**0.65**	**0.44**	**0.40**	**4.4**
Model (Adaptive 1)	**0.20**	**0.32**	**1.00**	**0.74**	**2.6**
Experiments					
median	0.51	0.45	0.79	0.56	3.8
min	0.25	0.03	0.54	0.49	3.0
max	0.56	0.56	0.92	0.69	4.1
<u>**High-persistence**</u>					
Model (Rational)	**0.97**	**0.98**	**1.16**	**0.71**	**2.4**
Model (Adaptive 1)	**0.95**	**0.98**	**2.07**	**0.87**	**1.6**
Experiments					
median	0.95	0.96	3.96	0.81	2.5
min	0.86	0.92	1.80	0.76	2.1
max	0.97	0.98	11.18	0.87	2.6
<u>**Aggressive policy**</u>					
Model (Rational)	**0.82**	**0.75**	**0.31**	**0.35**	**5.1**
Model (Adaptive 1)	**0.68**	**0.51**	**0.46**	**0.56**	**4.1**
Experiments					
median	0.72	0.56	0.48	0.28	5.5
min	0.71	0.48	0.40	0.11	4.7
max	0.79	0.59	0.56	0.44	6.0

<u>Note:</u> Statistics for each treatment in the experiments are computed for five sessions of repetition 2.

Table 4: Time-series comparisons, Experiment vs. Model

Statistic	Rational	Sensitive	Static	Adaptive(1)	Adaptive(2)
$\text{std}(X_t^{\text{Model}})/\text{std}(X_t^{\text{Experiment}})$					
$E_t^*(\pi_{t+1})$	0.36	0.72	0.15	1.24	1.03
$E_t^*(x_{t+1})$	0.38	0.76	0.23	0.70	0.72
π_t	0.58	0.93	0.27	1.24	0.87
x_t	0.74	1.01	0.53	0.91	0.81
i_t	0.43	0.86	0.23	1.07	0.88
$\text{corr}(X_t^{\text{Model}}, X_t^{\text{Experiment}})$					
$E_t^*(\pi_{t+1})$	0.55	0.55	-0.46	0.76	0.48
$E_t^*(x_{t+1})$	0.56	0.56	-0.52	0.78	0.52
π_t	0.71	0.69	0.83	0.86	0.63
x_t	0.68	0.66	0.83	0.89	0.75
i_t	0.61	0.61	-0.51	0.83	0.59

Notes: Time series for the experiment correspond to benchmark treatment (repetition 2). Time series for the model correspond to equilibrium outcomes given the same shock history. The entries are medians across five sessions.

Table 5: Individual usage of history screen

Treatment	Clicks per period			Fraction of time per period		
	Median forecaster	Top forecaster	Bottom forecaster	Median forecaster	Top forecaster	Bottom forecaster
Benchmark	2.4	1.9	1.0	0.45	0.45	0.34
High-persistence	2.2	1.9	2.2	0.46	0.56	0.33
Aggressive policy	2.0	1.9	1.4	0.41	0.35	0.25
Communication	1.7	2.4	1.3	0.40	0.46	0.26

Note: Entries are means across periods for sessions in the benchmark treatment (repetition 2).

Figure 1: Inflation responses to 113 bps r_t^n impulse

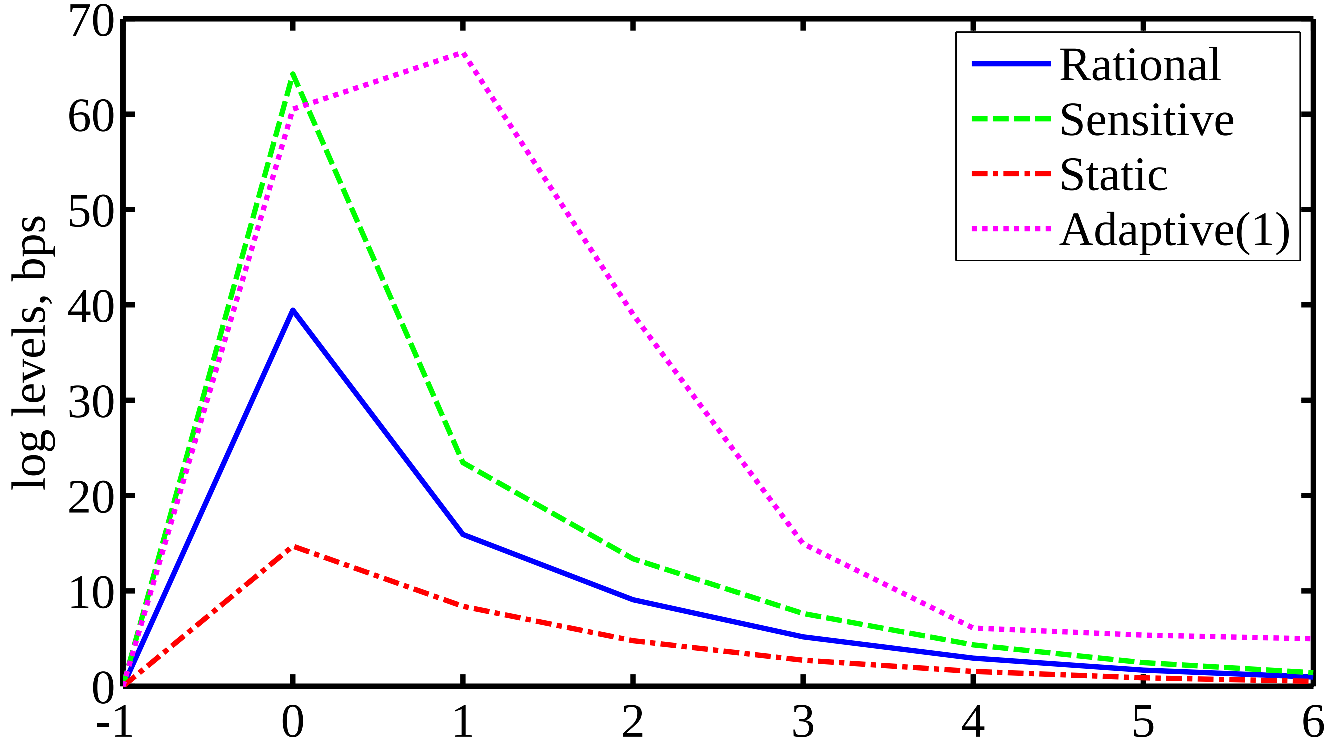


Figure 2: Stabilization of inflation via expectations

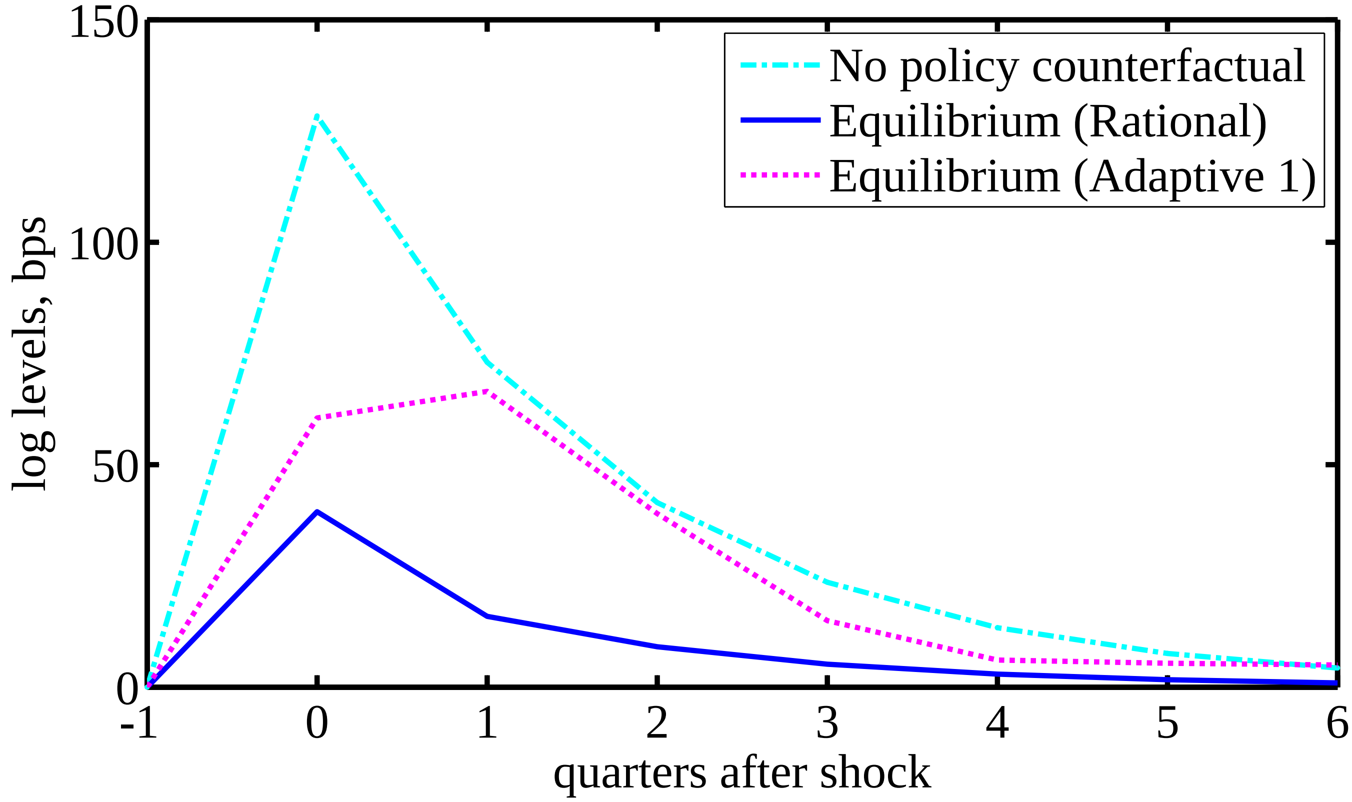


Figure 3: Responses of inflation forecasts and errors, Model vs. Experiment

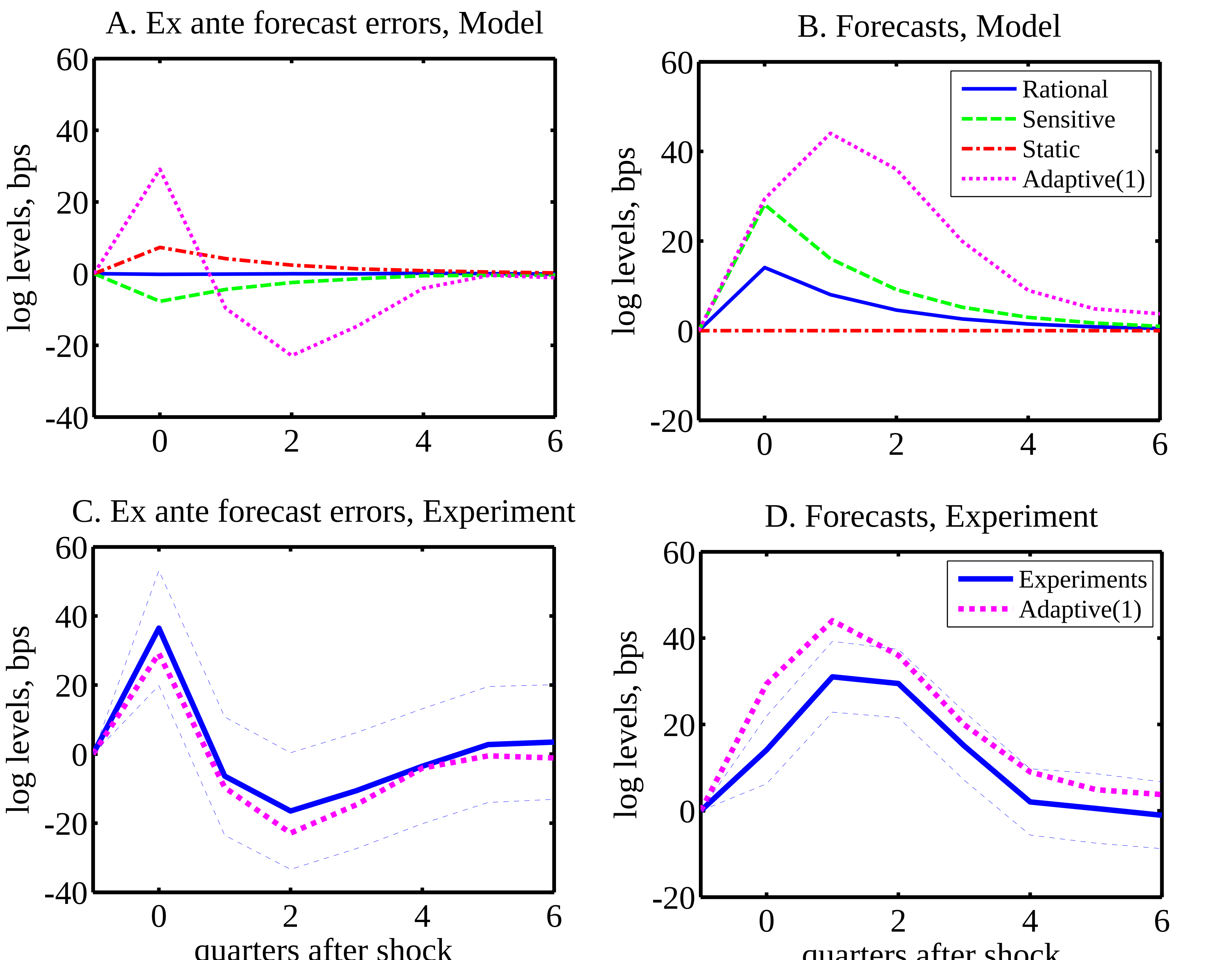
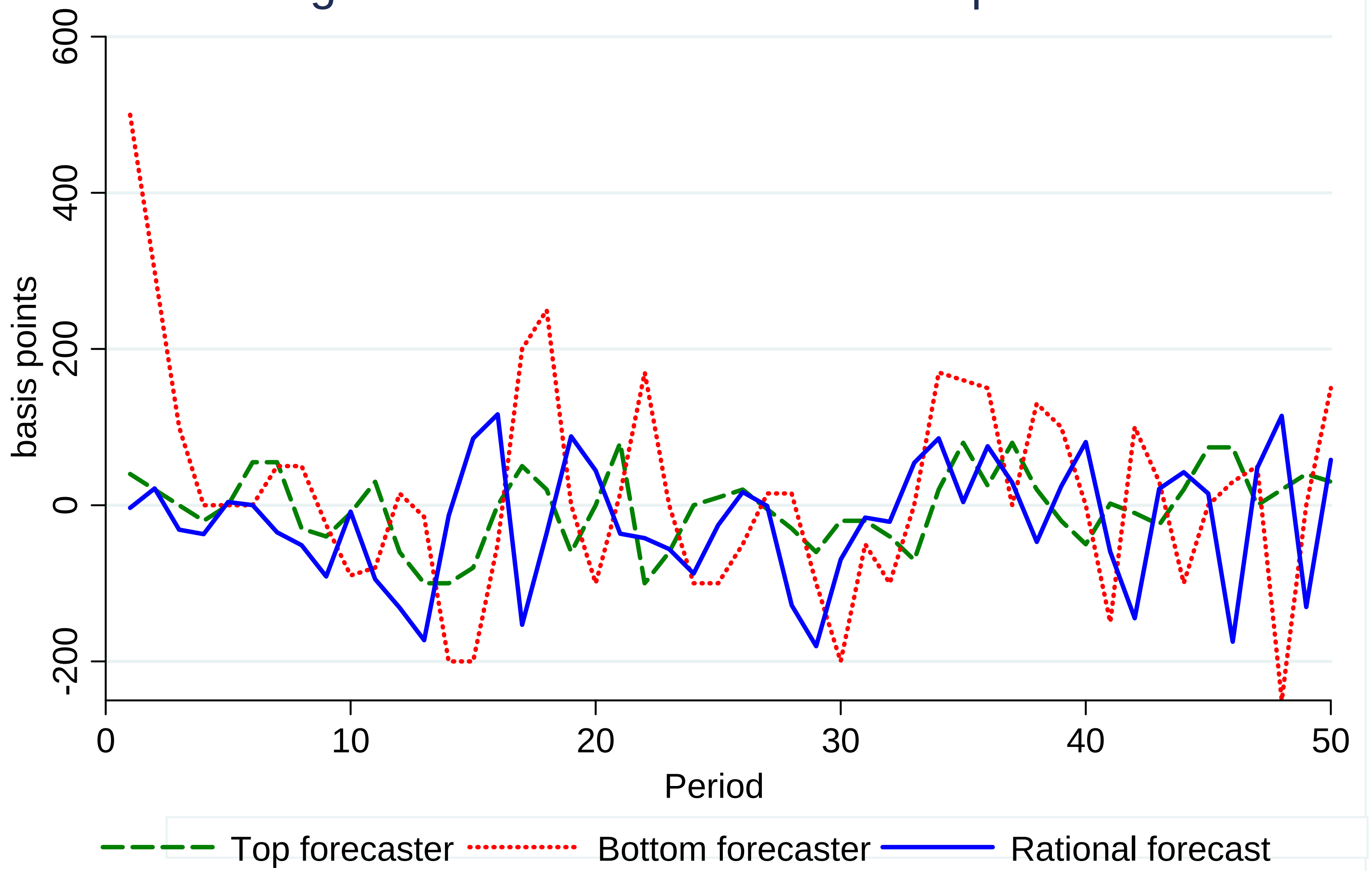


Figure 4: Inflation forecasts in experiment



Benchmark treatment, session 5, repetition 2

Appendix: Model and Experiments

1. Model

A. Model solution under rational expectations

Denoting $\pi_t^e = E_t\pi_{t+1}$, $x_t^e = E_t x_{t+1}$, we can write the rational expectations solution of the equilibrium system (1)–(3) as

$$\begin{bmatrix} \pi_t \\ x_t \end{bmatrix} = \begin{bmatrix} A_{\pi\pi} & A_{\pi x} \\ A_{x\pi} & A_{xx} \end{bmatrix} \begin{bmatrix} \pi_{t-1}^e \\ x_{t-1}^e \end{bmatrix} + \begin{bmatrix} B_\pi \\ B_x \end{bmatrix} r_t^n$$

The equilibrium system of equations can be written as

$$E_t \left[A_1 \begin{bmatrix} \pi_t^e \\ x_t^e \\ \pi_{t+1} \\ x_{t+1} \end{bmatrix} + A_2 \begin{bmatrix} \pi_{t-1}^e \\ x_{t-1}^e \\ \pi_t \\ x_t \end{bmatrix} + shock\ terms \right] = 0$$

where

$$A_1 = \begin{bmatrix} 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & \beta & 0 \\ 0 & 0 & \sigma^{-1} & 1 \end{bmatrix}, \quad A_2 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & \kappa \\ -\sigma^{-1}\phi_\pi & -\sigma^{-1}\phi_x & 0 & -1 \end{bmatrix}$$

Following the method in Blanchard and Khan (1980), we can construct generalized eigenvalues of $-A_1^{-1}A_2$, which will give us $A_1^{-1}A_2 = -V\Lambda V^{-1}$, where V and Λ are matrixes of eigenvectors and eigenvalues, respectively. Eigenvalues are found by solving the generalized eigenvalue problem:

$$\det\left(A_1^{-1}A_2 + \lambda I\right) = 0$$

This gives

$$\frac{\lambda^2}{\beta}\left(\beta\lambda^2-\left(1+\beta+\kappa\sigma^{-1}+\beta\sigma^{-1}\phi_x\right)\lambda+1+\kappa\sigma^{-1}\phi_\pi+\sigma^{-1}\phi_x\right)=0$$

So there are four generalized eigenvalues: $\lambda_{1,2}=0$, $\lambda_{3,4}=\frac{\left(1+\beta+\kappa\sigma^{-1}+\beta\sigma^{-1}\phi_x\right)}{2\beta}\pm\frac{\sqrt{\left(1-\beta+\kappa\sigma^{-1}+\beta\sigma^{-1}\phi_x\right)^2-4\beta\left(\kappa\sigma^{-1}(\phi_\pi-1)+\sigma^{-1}\phi_x(1-\beta)\right)}}{2\beta}$. The infinite eigenvalues correspond to $A_1^{-1}A_2\mathbf{v}=0$; i.e., they correspond to eigenvectors $\left[1,0,-\kappa\sigma^{-1}\phi_\pi,-\sigma^{-1}\phi_\pi\right]'$ and $\left[0,1,-\kappa\sigma^{-1}\phi_x,-\sigma^{-1}\phi_x\right]'$. The equilibrium is locally determinate if and only if $|\lambda_{2,3}|>1$, or equivalently if $\phi_\pi+\phi_x\frac{1-\beta}{\kappa}>1$. This is also known as the Taylor principle.[1] The fact that the stable eigenvalue that is equal to zero implies that E_tx_{t+1} and $E_t\pi_{t+1}$ does not depend on the endogenous state variables π_{t-1}^e, x_{t-1}^e, but only on the exogenous state variable. Hence the solution is

$$\begin{bmatrix}\pi_t\\ x_t\end{bmatrix}=-\sigma^{-1}\begin{bmatrix}\kappa\phi_\pi & \kappa\phi_x\\ \phi_\pi & \phi_x\end{bmatrix}\begin{bmatrix}\pi_{t-1}^e\\ x_{t-1}^e\end{bmatrix}+\begin{bmatrix}B_\pi\\ B_x\end{bmatrix}r_t^n$$

this implies that

$$E_t\begin{bmatrix}\pi_{t+1}\\ x_{t+1}\end{bmatrix}=\begin{bmatrix}\Phi_\pi\\ \Phi_x\end{bmatrix}\rho_r r_t^n$$

where

$$\begin{aligned}\begin{bmatrix}\Phi_\pi\\ \Phi_x\end{bmatrix} &= \Delta^{-1}\begin{bmatrix}\left(\sigma^2+\phi_x\sigma\right)B_\pi-\sigma\phi_xB_x\\ -\sigma\phi_\pi B_\pi+\sigma\left(\sigma+\kappa\phi_\pi\right)B_x\end{bmatrix}\\ \text{and }\Delta &= \sigma^2+\sigma\left(\phi_x+\kappa\phi_\pi\right)+(\kappa-1)\,\phi_\pi\phi_x\end{aligned}$$

[1] See Woodford (2003, Chapter 4).

Plug the solution into the system and use the method of undetermined coefficients:

$$\begin{aligned} B_x &= \Delta^{-1}\left(-\sigma\phi_\pi B_\pi + \sigma\left(\sigma+\kappa\phi_\pi\right)B_x\right)\rho_r \\ &\quad -\sigma^{-1}\left(-\Delta^{-1}\left(\left(\sigma^2+\phi_x\sigma\right)B_\pi - \sigma\phi_x B_x\right)\rho_r - 1\right) \\ B_\pi &= \kappa B_x + \beta\Delta^{-1}\left(\left(\sigma^2+\phi_x\sigma\right)B_\pi - \sigma\phi_x B_x\right)\rho_r \end{aligned}$$

This gives

$$\begin{bmatrix} B_\pi \\ B_x \end{bmatrix} = \Gamma \begin{bmatrix} \kappa\left(1+\left(\phi_\pi\kappa+\phi_x\right)\sigma^{-1}\right) + \phi_x\sigma^{-1}\left(\kappa\left(\kappa-1\right)\phi_\pi\sigma^{-1} - \beta\rho_r\right) \\ 1+\left(\phi_\pi\kappa+\phi_x\right)\sigma^{-1} - \beta\rho_r + \phi_x\sigma^{-1}\left(\left(\kappa-1\right)\phi_\pi\sigma^{-1} - \beta\rho_r\right) \end{bmatrix}$$

where $\Gamma = \frac{\sigma^{-1}}{(1-\beta\rho_r)(1-\rho_r)+\sigma^{-1}\kappa(\phi_\pi-\rho_r)+\sigma^{-1}\phi_x((\kappa-1)(\phi_\pi-\rho_r)\sigma^{-1}+1-\beta\rho_r)}$.

The decision rules are

$$\begin{aligned} \begin{bmatrix} \pi_t \\ x_t \end{bmatrix} &= -\sigma^{-1}\begin{bmatrix} \kappa\phi_\pi & \kappa\phi_x \\ \phi_\pi & \phi_x \end{bmatrix}\begin{bmatrix} \pi^e_{t-1} \\ x^e_{t-1} \end{bmatrix} \\ &\quad +\Gamma\begin{bmatrix} \kappa\left(1+\left(\phi_\pi\kappa+\phi_x\right)\sigma^{-1}\right) + \phi_x\sigma^{-1}\left(\kappa\left(\kappa-1\right)\phi_\pi\sigma^{-1} - \beta\rho_r\right) \\ 1+\left(\phi_\pi\kappa+\phi_x\right)\sigma^{-1} - \beta\rho_r + \phi_x\sigma^{-1}\left(\left(\kappa-1\right)\phi_\pi\sigma^{-1} - \beta\rho_r\right) \end{bmatrix} r^n_t \end{aligned}$$

which also implies the following forecasting rules:

$$E_t\begin{bmatrix} \pi_{t+1} \\ x_{t+1} \end{bmatrix} = \begin{bmatrix} \Phi_\pi \\ \Phi_x \end{bmatrix}\rho_r r^n_t$$

B. Model solution under non-rational expectations

In the model, agents make decisions according to the decision rules as functions of the past history of exogenous events (shocks). These decision rules characterize optimal choices regarding consumption, savings and prices, given how agents form expectations with respect to future economic outcomes. Under rational expectations, these expectations are a statistical mean over all possible outcomes implied by decisions conditional on every future history of events. This implies that agents always behave in a way consistent with their decision rules, and that this behaviour is based on the most likely turn of random events. Therefore, deviation from rational expectations implies that agents do not behave consistently or that they make systematic errors in forecasting random events.

Although rational expectations represent a useful benchmark for how agents form their expectations, we need to understand the implications of assuming alternative expectations formation functions for the design of monetary policy. In general, the expected values of the output gap and inflation, $E_t^* x_{t+1}$ and $E_t^* \pi_{t+1}$, are linear functions of the state history, $\{r_s^n\}_{s=0}^t$. As we showed in section A of this appendix, under rational expectations these functions are only functions of r_t^n. These functions imply that agents' forecast errors are zero, on average. To understand the effect of alternative expectations formation functions on outcomes (and the expectations channel), assume that period-t forecast errors co-vary with the state in periods t and $t-1$; i.e., that

$$E_t \left(E_t^* \begin{bmatrix} \pi_{t+1} \\ x_{t+1} \end{bmatrix} - \begin{bmatrix} \pi_{t+1} \\ x_{t+1} \end{bmatrix} \right) = \sigma^{-1} \rho_r \left(\begin{bmatrix} \kappa L_{0\pi} \\ L_{0x} \end{bmatrix} r_t^n + \begin{bmatrix} \kappa L_{1\pi} \\ L_{1x} \end{bmatrix} \rho_r r_{t-1}^n \right)$$

where $L_{0\pi}$, L_{0x}, $L_{1\pi}$, L_{1x} are real numbers representing the elasticity of forecast errors on inflation and the output gap with respect to shock realizations in periods t and $t-1$. The above specification of the forecast errors implies that agents' expectations are inconsistent with rational expectations during the first two quarters after the shock and are, on average, zero afterwards. The case with

$L_{0\pi} = L_{0x} = L_{1\pi} = L_{1x} = 0$ corresponds to rational expectations. Hence, the above specification allows us to study deviations from rational expectations that occur only with respect to current or last-period state realizations. We consider another specification in which forecast errors correlate with the longer history of shocks afterwards.

To solve our equilibrium system (1)-(3) under a given specification for the expectations (see section 2 of the main text), expectations must be of the form

$$E_t^* \begin{bmatrix} \pi_{t+1} \\ x_{t+1} \end{bmatrix} = \begin{bmatrix} \theta_\pi \\ \theta_x \end{bmatrix} r_t^n + \begin{bmatrix} \eta_\pi \\ \eta_x \end{bmatrix} \rho_r r_{t-1}^n$$

To find the unknown coefficients θ_π, θ_x, η_π, η_x, plug this equation into (1)–(3) to get the outcomes as

$$\begin{aligned} \begin{bmatrix} \pi_t \\ x_t \end{bmatrix} = & \left(\begin{bmatrix} -\kappa\sigma^{-1}\phi_\pi + \kappa\sigma^{-1}\rho_r + \beta\rho_r & -\kappa\sigma^{-1}\phi_x + \kappa\rho_r \\ -\sigma^{-1}\phi_\pi + \sigma^{-1}\rho_r & -\sigma^{-1}\phi_x + \rho_r \end{bmatrix} \begin{bmatrix} \theta_\pi \\ \theta_x \end{bmatrix} \right. \\ & \left. + \begin{bmatrix} \beta\rho_r + \kappa\sigma^{-1}\rho_r & \kappa\rho_r \\ \sigma^{-1}\rho_r & \rho_r \end{bmatrix} \begin{bmatrix} \eta_\pi \\ \eta_x \end{bmatrix} + \sigma^{-1}\rho_r \begin{bmatrix} \kappa \\ 1 \end{bmatrix} \right) r_{t-1}^n \\ & + \begin{bmatrix} -\kappa\sigma^{-1}\phi_\pi\rho_r & -\kappa\sigma^{-1}\phi_x\rho_r \\ -\sigma^{-1}\phi_\pi\rho_r & -\sigma^{-1}\phi_x\rho_r \end{bmatrix} \begin{bmatrix} \eta_\pi \\ \eta_x \end{bmatrix} r_{t-2}^n \\ & + \left(\begin{bmatrix} \kappa\sigma^{-1} + \beta & \kappa \\ \sigma^{-1} & 1 \end{bmatrix} \begin{bmatrix} \theta_\pi \\ \theta_x \end{bmatrix} + \sigma^{-1} \begin{bmatrix} \kappa \\ 1 \end{bmatrix} \right) \varepsilon_t \end{aligned}$$

Use the method of undetermined coefficients to find θ_π, θ_x, η_π, η_x. Denoting $h_0 = \frac{\rho_r}{1+\kappa\sigma^{-1}\phi_\pi+\kappa\sigma^{-1}\phi_x(1+(\kappa-1)\sigma^{-1}\phi_\pi)}$, we get

$$\begin{bmatrix} \eta_\pi \\ \eta_x \end{bmatrix} = \Gamma_{\eta 1} \begin{bmatrix} \kappa L_{1\pi} \\ L_{1x} \end{bmatrix}$$

and

$$\begin{bmatrix} \theta_\pi \\ \theta_x \end{bmatrix} = \Gamma_{\theta 0} \begin{bmatrix} \kappa \left(1 + L_{0\pi}\right) \\ 1 + L_{0x} \end{bmatrix} + \Gamma_{\theta 1} \begin{bmatrix} \kappa L_{1\pi} \\ L_{1x} \end{bmatrix}$$

where

$$\begin{aligned}
\Gamma_{\eta 1} &= \sigma^{-1} h_0 \begin{bmatrix} 1 + \kappa \phi_x \sigma^{-1} & -\kappa \sigma^{-1} \phi_x \\ -\sigma^{-1} \phi_\pi & 1 + \kappa \sigma^{-1} \phi_\pi \end{bmatrix} \\
\Gamma_{\theta 0} &= \Gamma \rho_r \begin{bmatrix} 1 - \rho_r + \phi_x \sigma^{-1} & \kappa \left(\rho_r - \phi_x \sigma^{-1}\right) \\ -\sigma^{-1} \left(\phi_\pi - \rho_r\right) & 1 + \kappa \sigma^{-1} \left(\phi_\pi - \rho_r\right) - \beta \rho_r \end{bmatrix} \\
\Gamma_{\theta 1} &= \Gamma h_0 \begin{bmatrix} 1 - \rho_r + \phi_x \sigma^{-1} & \kappa \left(\rho_r - \phi_x \sigma^{-1}\right) \\ -\sigma^{-1} \left(\phi_\pi - \rho_r\right) & 1 + \kappa \sigma^{-1} \left(\phi_\pi - \rho_r\right) - \beta \rho_r \end{bmatrix} \\
&\quad \times \begin{bmatrix} \left(\beta \rho_r + \frac{\kappa}{\sigma} \rho_r\right) \left(\frac{\kappa}{\sigma} \phi_x + 1\right) - \frac{\kappa}{\sigma} \phi_\pi \rho_r & \kappa \rho_r \left(\frac{\kappa}{\sigma} \phi_\pi + 1\right) - \frac{\kappa}{\sigma} \phi_x \left(\beta \rho_r + \frac{\kappa}{\sigma} \rho_r\right) \\ \frac{1}{\sigma} \rho_r \left(\frac{\kappa}{\sigma} \phi_x + 1\right) - \frac{1}{\sigma} \phi_\pi \rho_r & \rho_r \left(\frac{\kappa}{\sigma} \phi_\pi + 1\right) - \frac{\kappa}{\sigma^2} \rho_r \phi_x \end{bmatrix}
\end{aligned}$$

Sensitive and static expectations

We consider two cases of forecast-error specification: one in which forecast errors are positively correlated with recent state history and the other with negative correlation. To build intuition for such non-rational expectations, we note that the specification of expectations implies that $E_t^* r_{t+1}^n \neq E_t r_{t+1}^n$; i.e., agents make consistent errors in correctly forecasting the future realization of the state. Moreover, we assume that agents' expectations $E_t^* \pi_{t+1}$ and $E_t^* x_{t+1}$ may not be consistent with a single underlying stochastic process for r_t^n, or, in other words, that their inflation and output-gap expectations are based on different perceptions for the r_t^n process. To emphasize this feature, we will use notation $\overrightarrow{E_t^* r_{t+1}^n}$ for this 2-vector. We obtain the expression for $\overrightarrow{E_t^* r_{t+1}^n}$ by plugging the solution from the previous section into the forecast specification and assuming for concreteness that $L_{1\pi} = L_{1x} = 0$:

$$\left(\sigma^{-1}\begin{bmatrix}\kappa F_\pi \\ F_x\end{bmatrix} + \sigma^{-1}\begin{bmatrix}\kappa \\ 1\end{bmatrix}\right)\left(E_t^* r_{t+1}^n - \rho_r r_t^n\right) = \sigma^{-1}\rho_r\begin{bmatrix}\kappa L_{0\pi} \\ L_{0x}\end{bmatrix} r_t^n$$

where

$$\begin{bmatrix}F_\pi \\ F_x\end{bmatrix} = \sigma\Gamma\rho_r\begin{bmatrix}a_1 & a_2 \\ a_3 & a_4\end{bmatrix} \times \begin{bmatrix}1 + L_{0\pi} \\ 1 + L_{0x}\end{bmatrix}$$

and where

$$\begin{aligned}
a_1 &= \left(\beta + \frac{\kappa}{\sigma}\right)\left(\frac{1}{\sigma}\phi_x - \rho_r + 1\right) - \frac{\kappa}{\sigma}\left(\phi_\pi - \rho_r\right) \\
a_2 &= \left(\frac{\kappa}{\sigma}\left(\phi_\pi - \rho_r\right) - \beta\rho_r + 1\right) + \left(\beta + \frac{\kappa}{\sigma}\right)\left(\rho_r - \frac{1}{\sigma}\phi_x\right) \\
a_3 &= \kappa\left(\frac{1}{\sigma}\left(\frac{1}{\sigma}\phi_x - \rho_r + 1\right) - \frac{1}{\sigma}\left(\phi_\pi - \rho_r\right)\right) \\
a_4 &= \frac{\kappa}{\sigma}\left(\phi_\pi - \rho_r\right) - \beta\rho_r + \frac{\kappa}{\sigma}\left(\rho_r - \frac{1}{\sigma}\phi_x\right) + 1
\end{aligned}$$

The above equation implies that the perceived persistence of the fundamental shock, $\frac{cov\left(\overrightarrow{E_t^* r_{t+1}^n}, r_t^n\right)}{var(r_t^n)}$, is not equal to ρ_r, and moreover, that the shock's persistence depends on whether it is inferred from inflation or output-gap dynamics. Let us denote the persistence of the shock consistent with inflation (output-gap) dynamics by $\rho_r^{*\pi}$ (ρ_r^{*x}); i.e.,

$$\overrightarrow{E_t^* r_{t+1}^n} = \begin{bmatrix}\rho_r^{*\pi} \\ \rho_r^{*\pi}\end{bmatrix} r_t^n$$

Then we obtain that

$$\rho_r^{*\pi} = \rho_r \left(1 + \frac{L_{0\pi}}{1 + F_\pi}\right)$$
$$\rho_r^{*x} = \rho_r \left(1 + \frac{L_{0x}}{1 + F_x}\right)$$

Under rational expectations, $L_{0\pi} = L_{0x} = 0$, agents correctly infer that

$$\rho_r^{*\pi} = \rho_r^{*x} = \rho_r$$

Alternatively, if $L_{0\pi} > 0$ and $L_{0x} > 0$, then

$$\rho_r^{*\pi} > \rho_r$$
$$\rho_r^{*x} > \rho_r$$

i.e., forecast errors are equivalent to perceiving the shock as more persistent than it is. This case implies that period-t forecasts of inflation and the output gap (relative to their rational forecasts) are positively correlated with period-t shock realizations. This is equivalent to saying that period-$(t+1)$ forecast errors are negatively correlated with period-t shocks. For example, if in period t there is a positive shock to the real interest rate, $r_t^n > 0$, then agents' forecasts tend to be more elastic with respect to rational forecasts. For this reason, we term such expectations formation as *sensitive expectations*.

If, instead, the deviation from the rational expectations goes in the opposite direction (i.e., if $L_{0\pi} < 0$ and $L_{0x} < 0$), then the perceived shock persistence is lower than it is:

$$\rho_r^{*\pi} < \rho_r$$

$$\rho_r^{*x} < \rho_r$$

In this case, period-$(t+1)$ forecast errors are *positively* correlated with period-t shocks. For example, if in period t there is a positive shock to the real interest rate, $r_t^n > 0$, then agents' forecasts tend to be *less* elastic with respect to rational forecasts. We therefore term these expectations *static expectations*. For a particular case with $L_{0\pi} = L_{0x} = -1$, agents perceive that the fundamental shock is i.i.d., $\rho_r^{*\pi} = \rho_r^{*x} = 0$, so that $E_t^* x_{t+1} = E_t^* \pi_{t+1} = 0$.

Adaptive expectations

So far, we have studied deviations from rational expectations that implied that agents' forecast errors do no persist for a long period of time. In particular, we have considered the case where those errors were consistent with rational expectations, but for only the first two periods after the shock. To investigate the implications of forecast errors that persist for a long time, we turn to another specification of non-rational expectations. We draw on the experimental literature and assume that the expected values of inflation and the output gap are functions of past realizations of inflation and the output gap. Specifically, we assume that

$$E_t^* \begin{bmatrix} \pi_{t+1} \\ x_{t+1} \end{bmatrix} = (1-\omega) E_t \begin{bmatrix} \pi_{t+1} \\ x_{t+1} \end{bmatrix} + \omega \begin{bmatrix} \pi_{t-l} \\ x_{t-l} \end{bmatrix}, \quad \omega \in [0,1]$$

i.e., that period-t expected values of inflation and the output gap in period-$(t+1)$ are weighted averages of statistical expectations of inflation and the output gap in period-$(t+1)$ (with weight

$1-\omega$) and their realizations in period $t-l$. The implied expected forecast errors are

$$E_t\left(E_t^*\begin{bmatrix}\pi_{t+1}\\ x_{t+1}\end{bmatrix}-\begin{bmatrix}\pi_{t+1}\\ x_{t+1}\end{bmatrix}\right)=-\omega\left(E_t\begin{bmatrix}\pi_{t+1}\\ x_{t+1}\end{bmatrix}-\begin{bmatrix}\pi_{t-l}\\ x_{t-l}\end{bmatrix}\right)$$

Therefore, in period t agents use period $t-l$ realization of inflation and the output gap to form expectations of period-$(t+1)$ inflation and the output gap. If realized inflation or the output gap in period $t-l$ is high (low), then agents' forecasts of inflation and the output gap tend to be higher (lower) than would be implied under rational expectations. We therefore term such expectations *adaptive expectations.*

One important implication of adaptive expectations is that, unlike in the case of static or sensitive expectations, agents' forecast errors persist forever. To see this, note that the solution to (1)–(3) under the above condition on expectations takes the AR form

$$\begin{bmatrix}\pi_t\\ x_t\end{bmatrix}=\begin{bmatrix}A_\pi\\ A_x\end{bmatrix}r_{t-1}^n+\begin{bmatrix}B_\pi\\ B_x\end{bmatrix}r_t^n+\begin{bmatrix}C_\pi\\ C_x\end{bmatrix}\begin{bmatrix}\pi_{t-1}\\ x_{t-1}\end{bmatrix},\qquad \text{if } l=0$$

and

$$\begin{bmatrix}\pi_t\\ x_t\end{bmatrix}=\begin{bmatrix}A_\pi\\ A_x\end{bmatrix}\begin{bmatrix}\pi_{t-l-1}\\ x_{t-l-1}\end{bmatrix}+\begin{bmatrix}B_\pi\\ B_x\end{bmatrix}r_t^n+\begin{bmatrix}C_\pi\\ C_x\end{bmatrix}\begin{bmatrix}\pi_{t-l}\\ x_{t-l}\end{bmatrix},\qquad \text{if } l=1,2,...$$

Unlike sensitive expectations, for which such effects last a finite number of periods, period-t shock realization has long-lasting effects on agents' forecast errors.

Figure A.1 shows impulse responses in the model with rational expectations.

Figure A.2 provides the fraction of inflation variance decreased via expectations in the model with rational expectations, for a range of key parameter values.

Figure A.3 gives that fraction for alternative expectations formations.

Figure A.4 compares forecasts and forecast errors estimated for the experiment with those estimated for the model with sensitive, adaptive(2) and adaptive(3) forms of expectations.

C. Calibration of model parameters

All data are at a quarterly frequency, spanning the inflation-targeting period in Canada, from 1992Q1 to 2012Q2. The output gap and all trends are calculated by the Bank of Canada.[2] Inflation is based on Statistics Canada's v41690914 series: "Consumer price index (CPI) seasonally adjusted 2005 basket - Canada; All-items." The nominal interest rate is based on the Bank of Canada's v39078 series "Bank rate."

The standard deviation of inflation is 0.44 per cent. Standard deviation of the output gap is 1.95 per cent, or 4.4 times the standard deviation of inflation. The persistence of the output gap in the data, 0.79, is much higher than the inflation persistence, 0.09. Since the model does not include mechanisms to account for differences in the persistence of inflation and the output gap, it predicts virtually the same persistence for the output gap and inflation. We therefore calibrate the model to match the persistence of inflation to 0.4, which is at the midpoint between inflation and output-gap persistence in the data. It is also close to inflation persistence over the longer historical time period, 1973Q3-2012Q2. In the end, three model parameters (standard deviation and the serial correlation of the r_t^n shock process, σ_r and ρ_r, and the slope of the New Keynesian Phillips curve, κ), are calibrated to match the following three calibration targets: standard deviation and the serial correlation of inflation deviations, 0.44 per cent and 0.4, and the ratio of standard deviations of the output gap and inflation, 4.4. Table A.1 summarizes the calibrated parameters and calibration targets.

[2] Trend values for the output gap, inflation and the interest rate can be provided upon request.

2. Experiments

Boxes A.1 and A.2 provide snapshots of the forecast and history screens.

Boxes A.3 and A.4 contain the texts of non-technical and technical instructions, respectively.

A. Pilot sessions

Prior to conducting our final experiment, we ran seven pilot sessions. These sessions allowed us to refine our instructions and design. We tried a number of variations on the instructions. In some pilots, we provided participants with highly numerical descriptions of the economy (i.e., full calibrations of the system). Subjects complained about the perceived technical nature of the environment, and commented that they were overwhelmed with too much information.

We also conducted pilot sessions that involved minimal instructions similar to thase of Bao et al. (2012) and Pfajfar and Žakelj (2012, 2013), where a qualitative description of the economy was given to subjects during the instruction phase of the experiment. While we explained how different variables interacted and in what direction they would influence one another, there was no discussion of their relative importance. The qualitative description resulted in less confusion during the instructions and experiment, and subjects appeared much more receptive to participating.

In addition, we also made technical instructions available to subjects who would be interested in knowing more details about the set-up. Finally, during the pilots, we found that subjects were far more receptive to the experiment when we walked them through qualitative examples of how each of the different factors affected inflation, output and the nominal interest rate.

In our earlier pilot sessions, participants viewed the last period's outcomes (inflation and output) as well as the implied forecast errors on the main screen. In this case, subjects' forecasts of future outcomes were greatly biased by the past outcomes that they saw on their screens. To avoid priming participants to exhibit such behaviour, in our final design we removed that information from the main screen, and instead allowed subjects to access that information by clicking on the history screen.

B. Communication treatment

In our main experiment, we have assumed no role for the communication of monetary policy. This assumption is consistent with our theoretical framework, in which it is assumed that agents have complete information about the model and, in particular, the way in which monetary policy is set. Specifically, conditional on the realized history of the shock, agents' expectations of inflation and the output gap are consistent with future policy actions implied by the Taylor rule specification in the model.

In this treatment, we test this assumption by adding to our experiment an explicit announcement of the expected path of future nominal interest rates. In period t, subjects will see on the main screen, in addition to the same information as before, conditional expected values of nominal interest rates in the following T_i periods: $E_{t-1}i_{t+1}$, $E_{t-1}i_{t+2}$, ..., $E_{t-1}i_{t+T_i}$. We assume that, to compute the expected path of nominal interest rates after period t, the central bank uses the solution of the model with rational expectations, conditional on history through $t-1$.

In that solution, the interest rate in period t is the following function of the shock:

$$\begin{aligned} i_t &= 1.5\left(0.141 r^n_{t-1}\right) + 0.5\left(0.472 r^n_{t-1}\right) \\ &= 0.448 r^n_{t-1} \end{aligned}$$

This implies that

$$E_{t-1}i_{t+s} = 0.57^s i_t, \quad s = 1, ..., T_i$$

with one-standard-deviation bands given by adding/subtracting from those point values $\sqrt{s}\sigma_r, \;\; s = 1, ..., T_i$.

Assuming that subjects make their decisions with a complete understanding of the model (and monetary policy), the communication of future expected monetary policy actions in this treatment *should not* have significant effects on the outcomes, particularly on how effective monetary policy is in stabilizing inflation and output-gap fluctuations. Table A.2 reports experimental results for this treatment.

References

[1] Bao, T., Hommes, C., Sonnemans, and J., Tuinstra, J. 2012. "Individual expectations, limited rationality and aggregate outcomes," *Journal of Economic Dynamics and Control*, 36(8), 1101-1120.

[2] Blanchard, O. and Kahn, C. 1980. "The Solution of Linear Difference Models under Rational Expectations," *Econometrica*, 48(5), 1305-1311.

[3] Pfajfar, D. and Zakelj, B. 2012. "Uncertainty and Disagreement in Forecasting Inflation: Evidence from the Laboratory," Working Paper, Tilburg University.

[4] Pfajfar, D. and Zakelj, B. 2013. "Inflation Expectations and Monetary Policy Design: Evidence from the Laboratory," Working Paper, Tilburg University.

[5] Woodford, M. 2003. *Interest and prices: Foundations of a theory of monetary policy.* Princeton University Press.

Table A.1: Model parameterization

A. Calibrated Parameters

σ_r	st dev of $r^n{}_t$ innovations, %	1.13
ρ_r	ser corr of $r^n{}_t$	0.57
κ	slope of NKPC	0.13

B. Targets

	Data	Model
st dev of π_t, %	0.44	0.44
ser corr of π_t	0.40	0.40
$std(x_t)/std(\pi_t)$	4.4	4.4

C. Assigned Parameters

	period	1 quarter
β	discount factor	$0.96^{1/4}$
σ	risk aversion	1
ϕ_π	Taylor rule coef, inflation	1.5
ϕ_x	Taylor rule coef, output gap	0.5

Table A.2: Experimental evidence, communication treatment

Treatment	Fraction of conditional variance decreased via expectations channel		std(π_t)	ser.cor.(π_t)	std(x_t)/std(π_t)
	π_t	x_t			
<u>**Benchmark**</u>					
Model (Rational)	**0.73**	**0.65**	**0.44**	**0.40**	**4.4**
Model (Adaptive 1)	**0.20**	**0.32**	**1.00**	**0.74**	**2.6**
Experiments (Benchmark)					
median	0.51	0.45	0.79	0.56	3.8
min	0.25	0.03	0.54	0.49	3.0
max	0.56	0.56	0.92	0.69	4.1
Experiments (Communication)					
median	0.19	0.10	1.18	0.75	2.9
min	-0.94	-3.47	0.75	0.66	2.5
max	0.59	0.64	2.24	0.82	4.1

<u>Note:</u> Statistics for each treatment in the experiments are computed for five (six) sessions of repetition 2 for the benchmark (communication) treatment.

Figure A.1: Responses to 113 bps impulse to r_t^n shock

Rational expectations

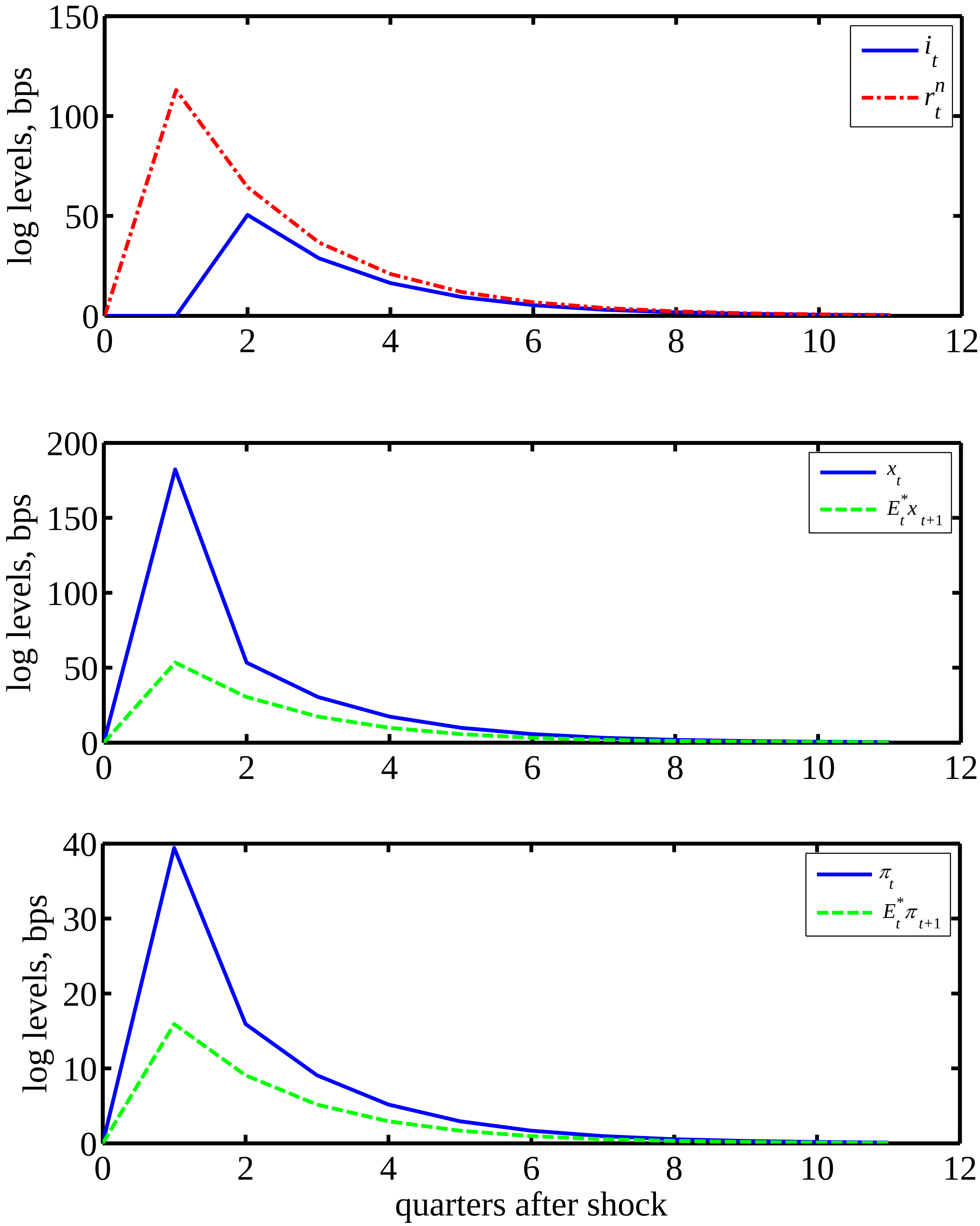


Figure A.2: Fraction inflation variance decreased via expectations,
Rational expectations (o - baseline calibration)

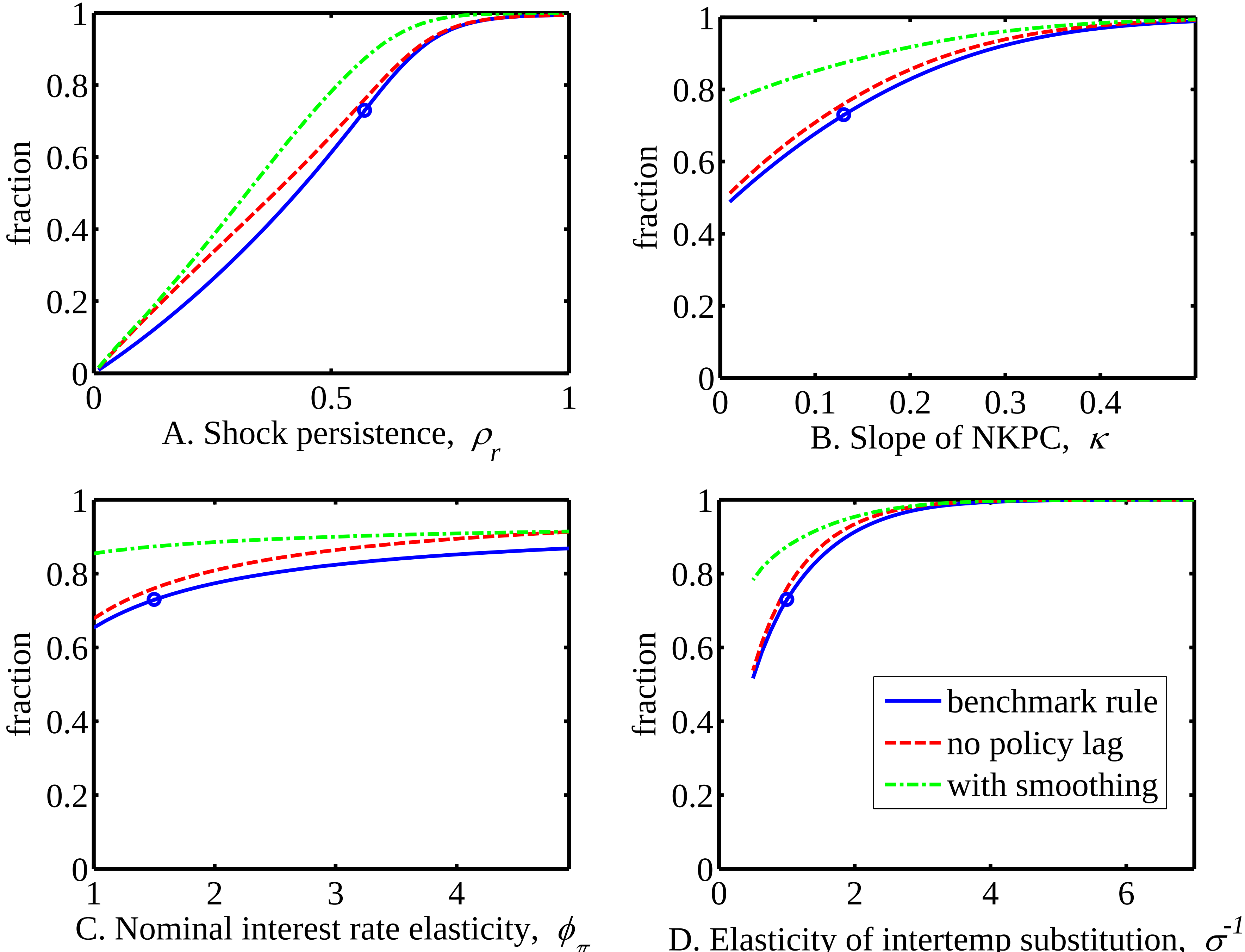


Figure A.3: Fraction of inflation variance decreased via expectations,
(o - baseline calibration)

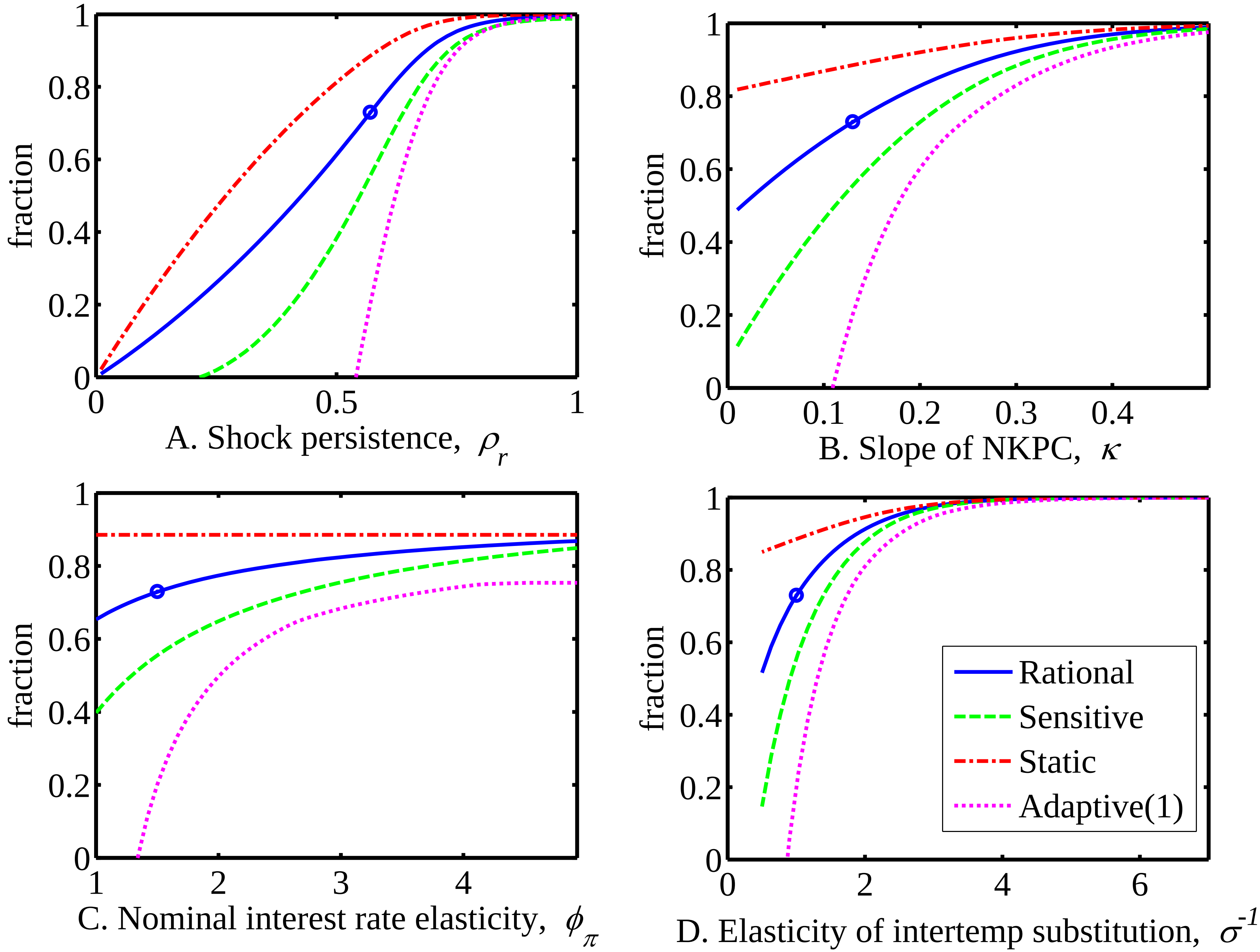
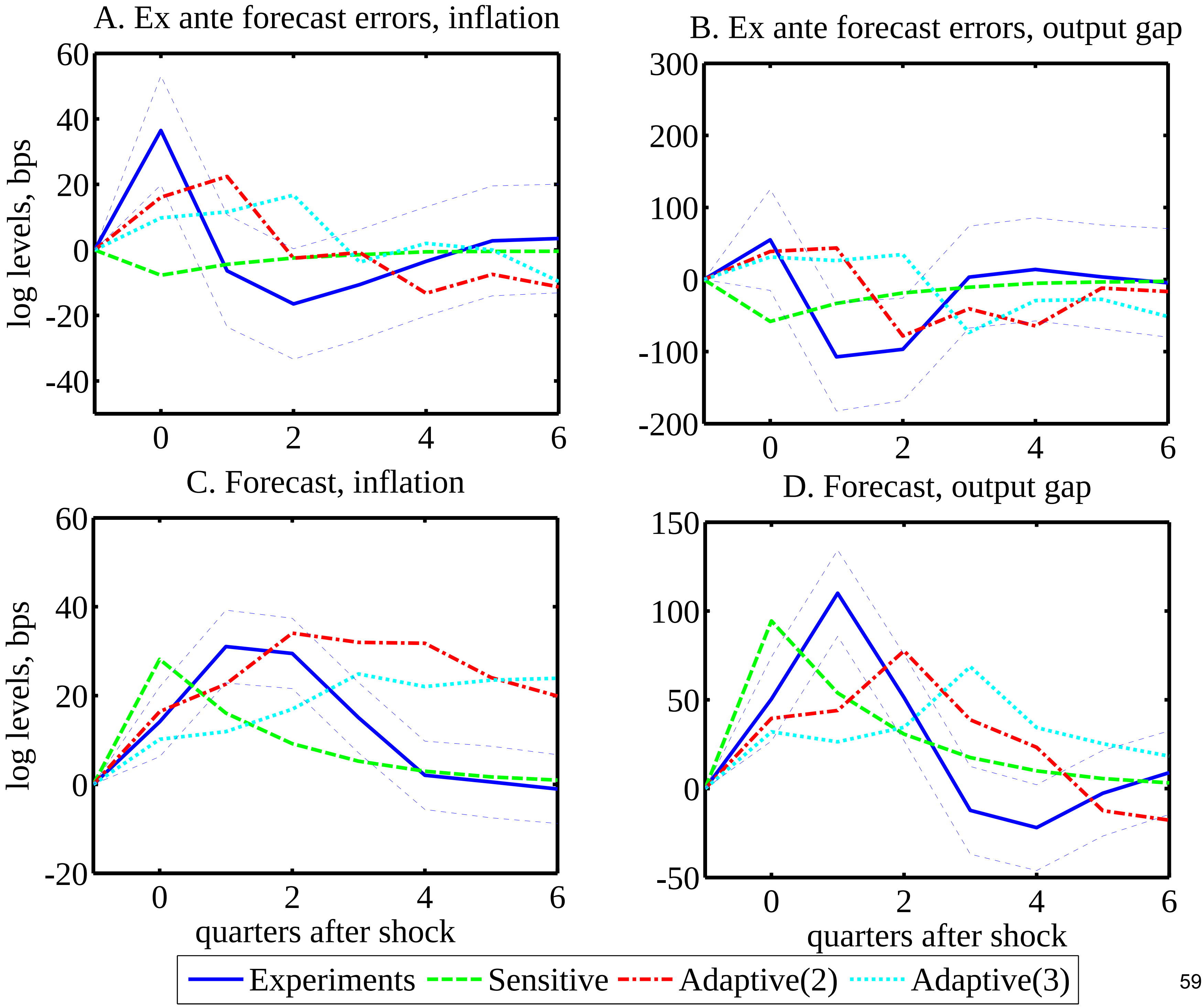
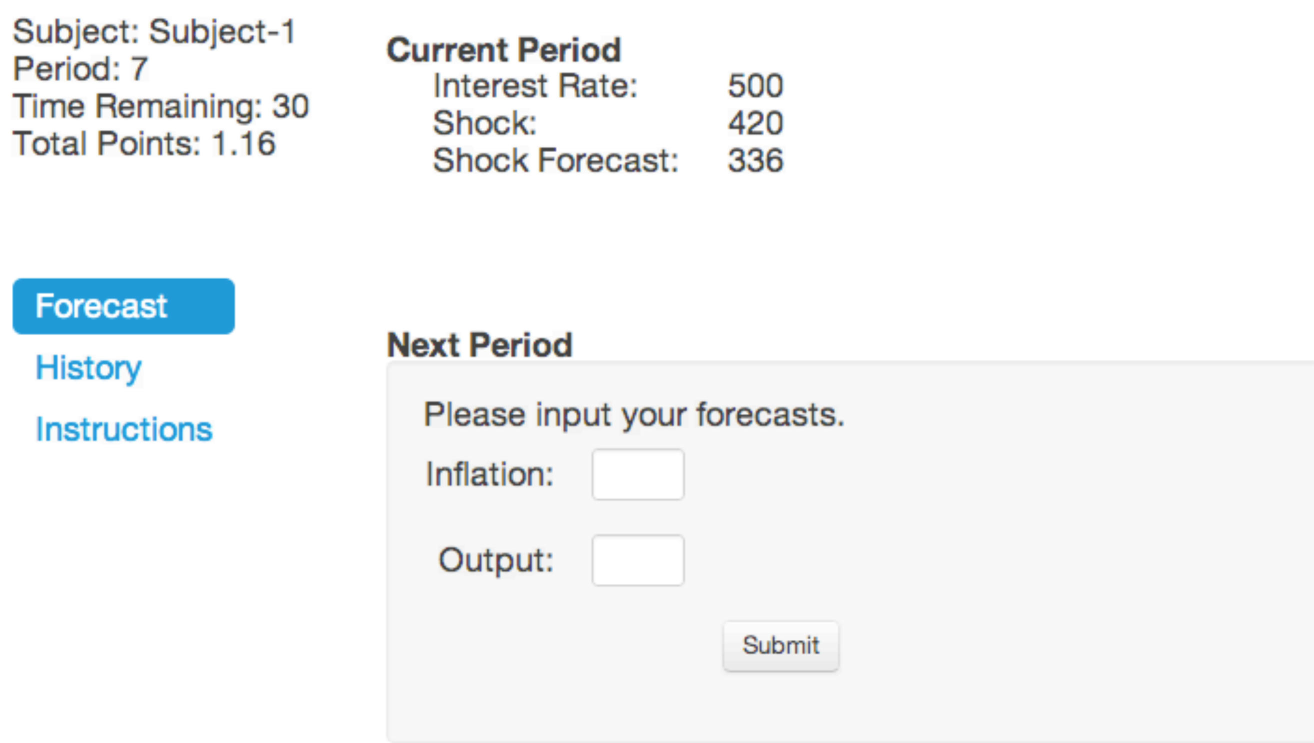


Figure A.4: Responses to 113 bps impulse to natural rate of interest, r_t^n



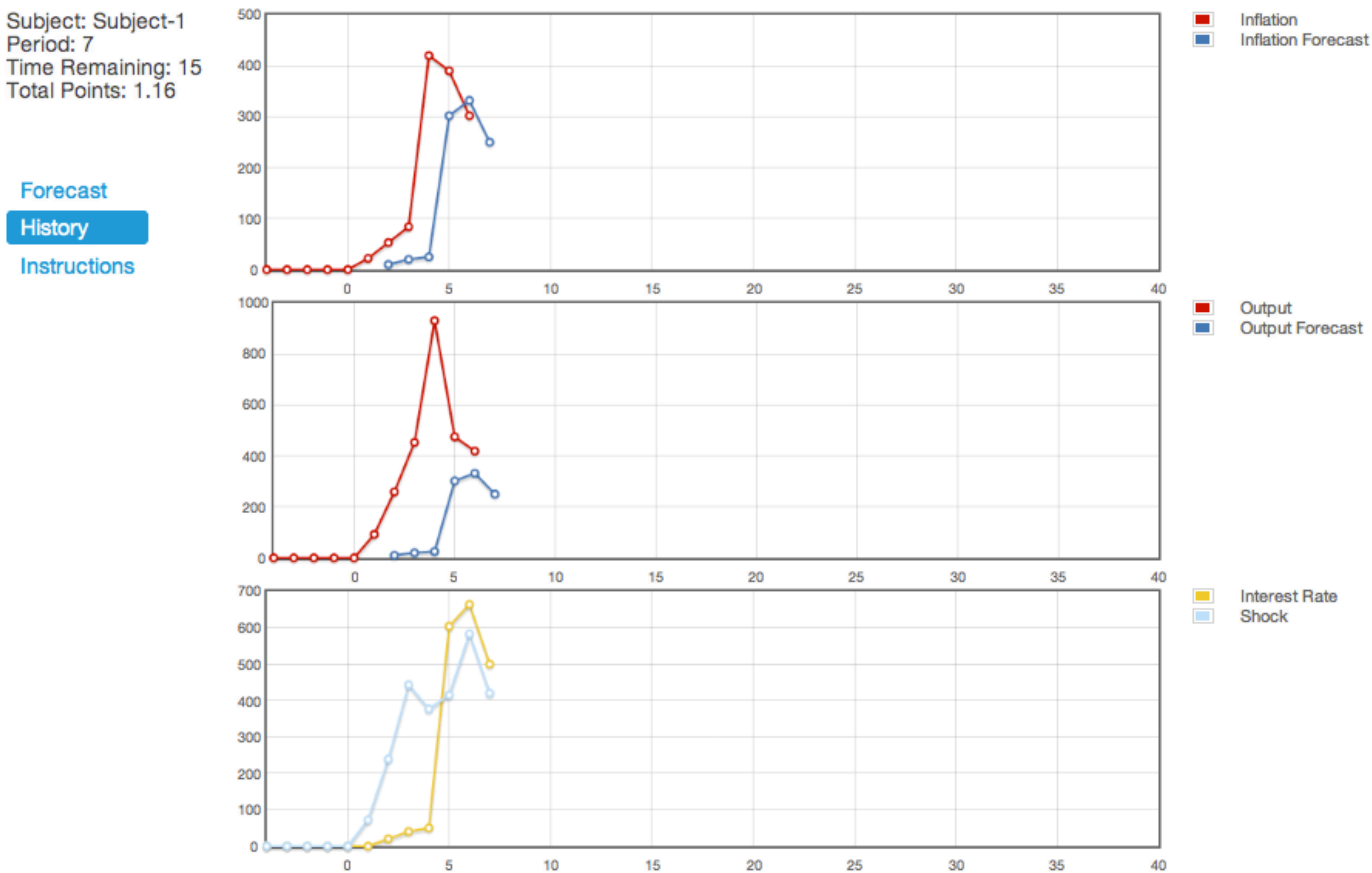
Box A.1: Experimental interface, forecast screen

Forecast Screen



Box A.2: Experimental interface, history screen

History Screen



Box A.3: Non-Technical Instructions

Experimental Instructions

Welcome! You are participating in an economics experiment at CIRANO Lab. In this experiment you will participate in the experimental simulation of the economy. If you read these instructions carefully and make appropriate decisions, you may earn a considerable amount of money that will be immediately paid out to you in cash at the end of the experiment.

Each participant is paid CDN$10 for attending. Throughout this experiment you will also earn points based on the decisions you make. Every point you earn is worth $0.75.

During the experiment you are not allowed to communicate with other participants. If you have any questions, the experimenter will be glad to answer them privately. If you do not comply with these instructions, you will be excluded from the experiment and deprived of all payments aside from the minimum payment of CDN $10 for attending.

The experiment is based on a simple simulation that approximates fluctuations in the real economy. Your task is to serve as private forecasters and provide real-time forecasts about future output and inflation in this simulated economy. The instructions will explain what output, inflation, and the interest rate are and how they move around in this economy, as well as how they depend on forecasts. You will also have a chance to try it out in a practice demonstration.

In this simulation, households and firms (whose decisions are automated by the computer) will form forecasts identically to yours. So to some degree, outcomes that you will see in the game will depend on the way in which all of you form your forecasts. Your earnings in this experiment will depend on the accuracy of your individual forecasts.

Below we will discuss what inflation and output are, and how to predict them. All values will be given in basis points, a measurement often used in descriptions of the economy. All values can be positive, negative, or zero at any point in time.

INFORMATION SHARED WITH ALL PARTICIPANTS

Each period, you will receive the following information to help you make forecasts.

Interest Rate

The interest rate is the rate at which consumers and firms borrow and save in this experimental economy. The central bank that sets the interest rate is forward-looking in that it responds to forecasts of future inflation and output. It will aim to keep inflation and output equal to zero.

Depends on: **Forecasted inflation for current period (+)**
Example: If the median subject forecasts inflation to be positive in the next period, the interest rate next period will be positive. If the median forecast for inflation is negative, the interest rate will be negative.

Depends on: **Forecasted output for current period (+)**
Example: If the median subject forecasts output to be positive in the next period, the interest rate next period will be positive. If the median forecast for inflation is negative, the interest rate will be negative.
Question: If the median forecasts for inflation and output are -10 and -20, respectively, what sign will the interest rate be? _________. What if the median forecast for inflation is -10 and output is 20?________

Current Shock

A shock is a random "event" that affects output. E.g. A natural disaster can suddenly destroy crops, or a technological discovery immediately improves productivity.

Depends on: **Random Draw**

The shock will be relatively small most of the time. Two-thirds of the time it will fall between -138 and 138 points, and 95% of the time it will fall between -276 and 276 points. On average, it will be 0. (But rarely will it ever be exactly zero!)

Every shock takes some time to dissipate. Suppose the shock in the current period is 100. Next period, that shock will now be 57% of 100, or 57 points. Assuming no new shocks were to occur, the value of the shock next period is 57 points. Some shock is likely to occur.

Shock Forecast

The shock forecast is a prediction of what the shock will be next period. It assumes that, on average, next period's shock is zero.

Example: If the current shock is -200 points, the forecasted value of the shock tomorrow is -200(0.57) = -114

HOW INFLATION AND OUTPUT ARE DETERMINED

You will be making forecasts about what you believe inflation and output will be tomorrow.

1. ***Inflation***

Inflation is the rate at which overall prices change between two periods.

Depends on: **Forecasted inflation in the next period (+)**

Example: If the median subject forecasts future inflation to be positive, current inflation will be positive, and vice versa.

Question: Holding all else constant, will current inflation be positive or negative if the median forecast for future inflation is -20? __________________.

Current output (+)

Example: If current output is positive, current inflation will be positive. If current output is negative, current output will be negative.

Question: Holding all else constant, what sign is current inflation if current output is 50?______0?__________

2. ***Output***

Output refers to a measure of the quantity of goods produced in a given period.

Depends on: **Forecasted output in the next period (+)**

Example: If the median subject forecasts future output to be positive, current output will also be positive.

Question: Holding all else constant, will output be positive or negative if the median subject forecasts output to be -15 points next period?______________

Forecasted inflation in the next period (+)

Example: If the median subject forecasts inflation to be positive next period, current output will be positive.

Question: Holding all else constant, what sign will output be if the median subject forecasts inflation to be 250 points next period?______________. What sign will inflation have? ____________.

Current interest rate (-)

Example: If the current interest rate is positive, current output will be positive.

Question: Holding all else constant, what sign will output be if interest rates are 10? _______________ What sign will inflation have? ______________

Random Shocks (+)

Example: Positive shocks will have a positive effect on output. Negative shocks will have a negative effect on output.

Question: Holding all else constant, what sign will output be if the shock is -50?__________ . What sign will inflation have? _________________

Score

Your score will depend on the accuracy of your forecasts. The absolute difference between your forecasts and the actual values for output and inflation are your absolute forecast errors.

Absolute Forecast Error = absolute (Your Forecast – Actual Value)
Total Score = 0.30(2^-0.01 (Forecast Error for Output)) + 0.30(2^-0.01 (Forecast Error for Inflation))

The maximum score you can earn each period is 0.60.
Your score will decrease as your forecast error increases. Suppose your forecast errors for each of output and inflation are:

0	-Your score will be 0.6	300	-Your score will be 0.075
50	-Your score will be 0.42	500	-Your score will be 0.02
100	-Your score will be 0.30	1000	-Your score will be 0
200	-Your score will be 0.15	2000	-Your score will be 0

Information about the Interface, Actions, and Payoffs

During the experiment, your main screen will display information that will help you make forecasts and earn more points.

At the top left of the screen, you will see your subject number, the current period, time remaining-, and the total number of points earned.

Below that you can click on different tabs to access different information. These tabs are the Forecast Tab, History Tab, and Instructions Tab.

On the Forecast Tab, you will see information that is common to all participants: the current interest rate, the size of the shock to output, and the forecasted shock for next period.

When the period begins, you will have 60 seconds to submit new forecasts for the next period's inflation and output levels. You may submit both negative and positive forecasts. Please review your forecasts before pressing the SUBMIT button. Once the SUBMIT button has been clicked, you will not be able to revise your forecasts until the next period. You will earn zero points if you do not submit both forecasts. The amount of time will be reduced to 45 seconds in later periods.

On the History tab, you will see three history plots. The top history plot displays your past forecasts of output and the realized output levels. The second plot displays your past forecast of inflation and realized inflation levels. The difference between your forecasts and the actual realized levels constitutes your forecast errors. Your forecasts will always be shown in blue while the realized value will be shown in red. The final plot displays past interest rates and the shock to output. You can see the exact value for each point on a graph by placing your mouse at that point.

On the Instructions Tab, you may view a more technical version of these instructions.

Each economy will last for between 50-60 periods. The environment will then be reset such that inflation, output, and interest rates return to zero. A new economy will begin and your previous decisions will not play a role. Your scores from each of the economies plus the show up fee will be paid to you in cash at the end of the experiment.

Box A.4: Technical Instructions

The economy consists of four main variables:

- Inflation
- Output
- Interest rate
- Shocks

At any time, *t*, the values of these variables will be calculated as follows:

Interest Rate_t = 1.5(Median forecast of Inflation_t formed last period)
+0.5(Median forecast of Output_t formed last period)

Inflation_t = 0.989(Median forecast of Inflation_{t+1})+0.13(Output_t)

Output_t = Median forecast of Output_{t+1} + Median forecast of Inflation_{t+1} - Interest rate_t + Shock_t

Shock_t = 0.57(Shock_{t-1})+Random component_t

- The random component is 0 on average.
- Roughly two out of three times the shock will be between -138 and 138 basis points.
- 95 per cent of the time the shock will be between -276 and 276 basis points.