CARF Working Paper

CARF-F-486

Average Inflation Targeting and the Interest Rate Lower Bound

Flora Budianto
Bank for International Settlements

Taisuke Nakata
University of Tokyo

Sebastian Schmidt
European Central Bank and CEPR

April 2020

CARF is presently supported by The Dai-ichi Life Insurance Company, Limited, Nomura Holdings, Inc., Sumitomo Mitsui Banking Corporation, Mizuho Financial Group, Inc., MUFG Bank, Ltd., The Norinchukin Bank and The University of Tokyo Edge Capital Partners Co., Ltd. This financial support enables us to issue CARF Working Papers.

Average Inflation Targeting and the Interest Rate Lower Bound*

Flora Budianto†
Bank for International Settlements

Taisuke Nakata‡
University of Tokyo

Sebastian Schmidt§
European Central Bank and CEPR

April 2020

Abstract

Assigning a discretionary central bank a mandate to stabilize an average inflation rate—rather than a period-by-period inflation rate—increases welfare in a New Keynesian model with an occasionally binding lower bound on nominal interest rates. Under rational expectations, the welfare-maximizing averaging window is infinitely long, which means that optimal average inflation targeting (AIT) is equivalent to price level targeting (PLT). However, AIT with a finite, but sufficiently long, averaging window can attain most of the welfare gain from PLT. Under boundedly-rational expectations, if cognitive limitations are sufficiently strong, the optimal averaging window is finite, and the welfare gain of adopting AIT can be small.

Keywords: Monetary Policy Objectives, Makeup Strategies, Liquidity Trap, Deflationary Bias, Expectations
JEL-Codes: E31, E52, E58, E61, E71

*We thank Wouter den Haan, Mike Kiley and seminar participants at the ECB for helpful comments. The views expressed in this paper should be regarded as those solely of the authors, and are not necessarily those of the Bank for International Settlements, or the European Central Bank.

†Bank for International Settlements, Centralbahnplatz 2, 4051 Basel, Switzerland; Email: flora.budianto@bis.org.
‡Faculty of Economics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-0033; Email: taisuke.nakata@e.u-tokyo.ac.jp.
§European Central Bank, Monetary Policy Research Division, 60640 Frankfurt, Germany; Email: sebastian.schmidt@ecb.int.

1 Introduction

For most of the last decade, monetary policy in major parts of the industrialized world has been constrained by a lower bound on nominal interest rates, and inflation rates have been hovering around levels below central banks' targets. Against this backdrop, current monetary policy frameworks, which were typically instituted when the possibility of being constrained by the lower bound seemed small, have come under increased scrutiny. Some central banks—notably the U.S. Federal Reserve, the European Central Bank and the Bank of Canada—are currently reviewing their monetary policy strategies and discussing whether some modifications are warranted in light of the challenges associated with the lower bound.

This paper contributes to this discussion by analyzing the effects of average inflation targeting (AIT) on macroeconomic stabilization and society's welfare in the presence of a lower bound on nominal interest rates. AIT has recently attracted increasing attention as a possible alternative to currently prevailing inflation targeting frameworks (e.g. Brainard (2019); Svensson (2020)), notably because of its 'makeup' feature whereby past inflation shortfalls are made up for by temporarily higher future inflation and vice versa.

In the spirit of the policy delegation literature (e.g. Rogoff (1985)), we consider the optimization problem of a central bank that acts under discretion and whose objective function features the volatility of average inflation rates over a pre-specified time period, as opposed to the volatility of the current inflation rate. The analysis is based on two variants of the standard New Keynesian model with a lower bound on nominal interest rates. In one variant, agents form expectations rationally. In the other variant, agents have boundedly-rational expectations, as in Gabaix (2019). We include a model with boundedly-rational expectations in our analysis because some have questioned the suitability of the standard rational-expectations model for analysis of monetary policy strategies on the ground that it can give rise to implausibly large effects of forward guidance—a promised interest rate change in the future—on current inflation and economic activity. Bounded rationality is one way to attenuate this so-called forward guidance puzzle because it implies that agents are unable to fully internalize information about future economic conditions when forming expectations.[1] Consequently, the private sector's consumption and pricing decisions are less dependent on model-consistent expectations of future inflation and economic activity than in the standard model. We specify the central bank's AIT objective in the form of an exponential moving average, which allows us to solve both model variants nonlinearly using global methods.[2]

We find that AIT improves welfare considerably when agents form expectations rationally. Following a large recessionary shock that drives the policy rate to the lower bound, a central bank

[1] This implication of the model with bounded rationality is consistent with results from a large-scale randomized control trial on U.S. consumers by Coibion et al. (2020). They find that providing information about interest rates at longer horizons has relatively small effects on consumers' expectations over future interest rates.

[2] Specifying the AIT objective in the form of an arithmetic moving average would be prohibitively expensive from a computational point of view when considering averaging windows that are sufficiently long. For instance, if the averaging window is 4 years (16 quarters), there are 15 endogenous state variables, making it nearly infeasible to solve the model accurately using global methods in a reasonable amount of time.

with an AIT objective keeps the policy rate low for longer than a central bank with a standard inflation targeting objective, thereby engineering a temporary overshooting in future inflation that helps to mitigate the decline of output and inflation at the lower bound via the expectations channel. This 'history dependence motive' of monetary policy under AIT is complemented by a 'lower bound risk motive' that makes current inflation under AIT an increasing function of a model-consistent measure of the risk of hitting the lower bound in the future. The lower bound risk motive contributes to society's welfare by counteracting the so-called deflationary bias of discretionary monetary policy, i.e. the phenomenon that the mere possibility that the constraint binds in the future—as opposed to the constraint being actually binding—results in a systematic inflation shortfall when the policy rate is away from the lower bound (Adam and Billi, 2007; Nakov, 2008; Nakata and Schmidt, 2019a).

The welfare-maximizing averaging window in the rational-expectations model is infinitely long, and the finding is robust to various alternative parameterizations of the model.[3] The AIT objective with an infinitely long averaging window—the optimal AIT in the rational-expectations model—coincides with a price-level-targeting (PLT) objective. However, we find that most of the welfare improvement associated with the optimal AIT can be attained by an AIT objective with a finite, but sufficiently long, averaging window. In our baseline calibration, AIT with an averaging window capturing a few years can attain most of the welfare gain associated with the optimal AIT.

AIT also improves welfare in the model with boundedly-rational expectations, but the welfare gain from AIT in this model is smaller than in the rational-expectations model. For a range of values of the cognitive discounting parameters in the model's Euler equation and Philips curve used in the literature the optimal averaging window remains infinite. That is, the results from the rational-expectations model are robust to including plausible degrees of bounded rationality. However, if the degree of cognitive discounting is sufficiently large, marginal increases in the discounting parameters lower the optimal averaging window. In such cases, welfare under PLT may be even lower than welfare under standard inflation targeting. The effectiveness of AIT and PLT thus hinges on the extent to which people understand how these strategies make future monetary policy and macroeconomic outcomes contingent on current economic conditions.

In both models, welfare can be further increased by assigning a relative weight on output gap stabilization that is smaller than the one in society's objective function ('inflation conservatism'). When the only source of uncertainty is a natural real rate shock, it is optimal to assign zero weight on the output gap. This holds true independently of whether the central bank's nominal target variable is period-by-period inflation, an average inflation rate or the price level. Strict (average) inflation targeting eliminates the deflationary bias away from the lower bound which raises inflation expectations in all states and thereby improves stabilization outcomes at the lower bound. The gains from correcting the deflationary bias by adjusting the central bank's relative weight on output gap stabilization are particularly large under standard inflation targeting—the monetary policy regime

[3] When distinguishing between 'finitely long' and 'infinitely long' averaging windows, we use terminology from the more common arithmetic-moving-average specification of AIT, and treat our exponential-moving-average specification—an infinite impulse response filter—as an approximation of the former. See Section 3 for more details.

under which the deflationary bias is most pronounced to start with. When people have boundedly-rational expectations and their cognitive abilities are sufficiently low, adjusting the central bank's relative weight on output gap stabilization can lead to a larger welfare gain than changing the inflation objective.

Our paper is related to two strands of the literature on monetary policy and the interest rate lower bound. First, Eggertsson and Woodford (2003), Jung et al. (2005), Adam and Billi (2006), Nakov (2008) and Bilbiie (2019) characterize optimal monetary policy under commitment and show that the central bank uses communication about its future interest rate policy to steer the economy when the contemporaneous policy rate cannot be lowered any further.[4] Nakata et al. (2019) and Levin and Sinha (2019) analyze the optimal commitment policy in a model similar to the model with boundedly-rational agents used here, and find that it is typically optimal for the central bank to partially compensate for the reduced effect of a future rate cut by keeping the policy rate at the lower bound for longer than in the benchmark rational-expectations setup. Our paper differs from these papers in that we assume that the central bank, while committed to its assigned objective(s), sets its policy instruments with discretion. Within that framework, we show that assigning an average inflation target to a central bank is a practical way to reap most of the benefits of the optimal commitment policy without requiring the central bank to engage in time-inconsistent policies.

Second, in the spirit of the policy delegation literature, some papers have proposed modifications to the central bank objective function in order to improve welfare in models with a lower bound when policymakers act under discretion. For instance, Nakata and Schmidt (2019a,b) show that the discretionary equilibrium in models with an occasionally binding lower bound constraint can be improved by the appointment of an inflation conservative central banker and by the assignment of an interest-rate smoothing term to the central bank objective function, respectively. Similarly, Billi (2017) compares price level targeting and nominal GDP targeting to standard inflation targeting in a model with an interest rate lower bound. Nessen and Vestin (2005) assess the desirability of (arithmetic) average inflation targeting using the policy delegation approach in a standard New Keynesian model without a lower bound on nominal interest rates.[5] To our knowledge, we are the first to formally assess how assigning an average inflation objective to a discretionary central bank affects stabilization outcomes and welfare in models with an interest rate lower bound.

The remainder of the paper is organized as follows. Section 2 describes the model. Section 3 presents the results for the rational-expectations variant of the model, and Section 4 for the variant of the model with boundedly-rational expectations. Section 5 concludes.

[4] Several other papers study models where the central bank is committed to follow an interest-rate feedback rule with 'makeup' features that implement policies akin to the optimal commitment policy, e.g. Reifschneider and Williams (2000) and, more recently Bernanke et al. (2019), Mertens and Williams (2019), and Coenen et al. (2020).

[5] Our paper is also related to Vestin (2006) who compares standard inflation targeting to price level targeting in a standard New Keynesian model without a lower bound constraint. Walsh (2019) evaluates price level targeting and average inflation targeting using the policy delegation framework, but in a model without an interest rate lower bound.

2 Model

We use an infinite-horizon New Keynesian model formulated in discrete time. The economy is inhabited by identical households who consume and work, goods-producing firms that act under monopolistic competition and are subject to price rigidities, and a central bank. We consider two alternative expectations formation mechanisms. In the benchmark setup, agents have rational expectations (see Galí, 2015), and in the alternative setup agents have boundedly-rational expectations as in Gabaix (2019). In the latter setup, agents do not fully understand the world as represented by the model. When they contemplate the future, their expectations are geared to the steady state of the economy, which serves as a simple benchmark.

2.1 Private sector behavior and welfare

Aggregate private sector behavior is described by a Phillips curve and a Euler equation

$$\pi_t = \kappa y_t + \beta(1-\alpha_{PC})\mathrm{E}_t\pi_{t+1} \tag{1}$$

$$y_t = (1-\alpha_{EE})\mathrm{E}_t y_{t+1} - \sigma\left(i_t - \mathrm{E}_t\pi_{t+1} - r_t^n\right) \tag{2}$$

The private sector behavioral constraints have been (semi) log-linearized around the intended zero-inflation steady state.[6] π_t is the inflation rate between periods $t-1$ and t, y_t denotes the output gap, i_t is the *level* of the riskless nominal interest rate between periods t and $t+1$, r_t^n is the exogenous natural real rate of interest, and E_t is the rational expectations operator conditional on information available in period t. Parameters α_{PC} and α_{EE} capture the degree of cognitive discounting by firms and households, respectively. In the rational expectations benchmark, $\alpha_{PC} = \alpha_{EE} = 0$. Under boundedly rational expectations, α_{PC} and α_{EE} are functions of the cognitive discounting parameter denoted $\bar{m}$ in Gabaix (2019)

$$1-\alpha_{EE} = \bar{m} \tag{3}$$

$$1-\alpha_{PC} = \bar{m}\left[\varphi + \frac{1-\beta\varphi}{1-\beta\varphi\bar{m}}(1-\varphi)\right], \tag{4}$$

where $\beta \in (0,1)$ is the pure rate of time preference and $\varphi \in (0,1)$ denotes the share of firms that cannot reoptimize their price in a given period.

The other parameters in the private sector aggregate behavioral constraints are defined as follows: $\sigma > 0$ is the intertemporal elasticity of substitution in consumption, and κ represents the slope of the Phillips curve.[7]

[6] See Nakata (2016, 2017) for analyses of optimal policy in fully nonlinear New Keynesian models. Key insights on optimal policy do not depend on whether private sector behavioral equations are put in nonlinear or in log-linearized form.

[7] κ is itself a function of several structural parameters of the economy: $\kappa = \frac{(1-\varphi)(1-\varphi\beta)}{\varphi(1+\eta\theta)}(\sigma^{-1}+\eta)$, where $\eta > 0$ is the inverse of the labor-supply elasticity, and $\theta > 1$ denotes the price elasticity of demand for differentiated goods.

Households' welfare at time t is given by the expected discounted sum of current and future utility flows. Following Gabaix (2019), boundedly-rational agents are assumed to experience utility from consumption and leisure like rational agents. Hence, the welfare criterion is invariant to the expectations formation mechanism. A second-order approximation to household preferences leads to

$$V_t = -\frac{1}{2}\mathrm{E}_t \sum_{j=0}^{\infty} \beta^j \left[\pi_{t+j}^2 + \lambda y_{t+j}^2\right], \tag{5}$$

where $\lambda = \kappa/\theta$.[8]

2.2 Central bank objective, monetary policy strategies and equilibrium

The central bank controls the one-period nominal interest rate i_t, which we will also refer to as the policy rate. It does not have a commitment technology, that is, it acts under discretion. The monetary policy objective function in some generic period t is given by

$$V_t^{CB} = -\frac{1}{2}\mathrm{E}_t \sum_{j=0}^{\infty} \beta^j \left[\hat{\pi}_{t+j}^2 + \lambda^{CB}(\omega y_{t+j})^2\right], \tag{6}$$

where

$$\hat{\pi}_{t+j} = \omega \pi_{t+j} + (1-\omega)\hat{\pi}_{t+j-1}, \tag{7}$$

$\omega \in [0,1]$ and $\lambda^{CB} \geq 0$. For most of our analysis, and unless stated otherwise, we assume $\lambda^{CB} = \lambda$.

This central bank objective function nests three monetary policy strategies:

- *Standard inflation targeting (IT)*: When $\omega = 1$, monetary policy follows a standard flexible inflation targeting strategy whereby the central bank aims to stabilize the period-by-period inflation rate π_t and the output gap y_t. For $\lambda^{CB} = \lambda$, the central bank's objective function coincides with society's objective function (5).

- *Average inflation targeting (AIT)*: When $\omega \in (0,1)$, the central bank aims to stabilize an exponential moving average inflation rate $\hat{\pi}$, as defined in equation (7).[9] Weighting the output gap term in the central bank's objective function with the moving-average parameter ω ensures that variations in ω do not affect the weight on y_t^2 relative to the weight on π_t^2, the two terms that also show up in society's objective function.[10]

- *Price level targeting (PLT)*: When $\omega = 0$, the central bank aims to stabilize the price level

[8] We assume that the steady state distortions arising from monopolistic competition are offset by a wage subsidy so that the steady state is the first best.

[9] As briefly mentioned in the Introduction, defining average inflation in terms of an exponential moving average rather than an arithmetic moving average economizes on the number of state variables and thereby facilitates the solution of the model using global methods.

[10] To see this, note that $\hat{\pi}_t^2 + \lambda^{CB}(\omega y_t)^2 = \omega^2\left[\pi_t^2 + \lambda^{CB} y_t^2\right] + (1-\omega)\left((1-\omega)\hat{\pi}_{t-1}^2 + 2\omega\pi_t\hat{\pi}_{t-1}\right)$.

$p_t \equiv \pi_t + p_{t-1}$. To see this, note that

$$\frac{\hat{\pi}_t}{\omega} = \pi_t + (1-\omega)\frac{\hat{\pi}_{t-1}}{\omega} \tag{8}$$

$$= \sum_{j=0}^{t}(1-\omega)^j \pi_{t-j} + (1-\omega)^{t+1}\frac{\hat{\pi}_{-1}}{\omega} \tag{9}$$

Assuming $\hat{\pi}_{-1} = 0$, and re-scaling by $1/\omega^2$, the central bank's objective function can be written as

$$-\frac{1}{2}\mathrm{E}_t \sum_{j=0}^{\infty} \beta^j \left[\left(\sum_{k=0}^{t+j} (1-\omega)^k \pi_{t+j-k} \right)^2 + \lambda^{CB} y_{t+j}^2 \right], \tag{10}$$

which, for $\omega = 0$, becomes

$$-\frac{1}{2}\mathrm{E}_t \sum_{j=0}^{\infty} \beta^j \left[(p_{t+j} - p_{-1})^2 + \lambda^{CB} y_{t+j}^2 \right], \tag{11}$$

where p_{-1} is the log of the initial price level, which can be normalized to zero.

The policy problem of a generic central bank is as follows. Each period t, it chooses the inflation rate (π_t), the average inflation rate ($\hat{\pi}_t$), the output gap, and the nominal interest rate to maximize its objective function (6) subject to the behavioral constraints of the private sector (1)–(2), the definition of the inflation average (7), and the lower bound constraint $i_t \geq 0$, with the value and policy functions at time $t+1$ taken as given. Formally,

$$\begin{aligned} V^{CB}(\hat{\pi}_{t-1}, r_t^n) = \max_{\pi_t, y_t, i_t, \hat{\pi}_t} & -\frac{1}{2}\left[\hat{\pi}_t^2 + \lambda^{CB}(\omega y_t)^2\right] + \beta \mathrm{E}_t V^{CB}(\hat{\pi}_t, r_{t+1}^n) \\ & + \phi_t^{PC}\left[\pi_t - \beta(1-\alpha_{PC})\mathrm{E}_t \pi(\hat{\pi}_t, r_{t+1}^n) - \kappa y_t\right] \\ & + \omega^2 \phi_t^{EE}\left[y_t - (1-\alpha_{EE})\mathrm{E}_t y(\hat{\pi}_t, r_{t+1}^n) + \sigma(i_t - \mathrm{E}_t \pi(\hat{\pi}_t, r_{t+1}^n) - r_t^n)\right] \\ & + \omega^2 \phi_t^{LB} i_t \\ & + \phi_t^{AI}\left[\hat{\pi}_t - \omega \pi_t - (1-\omega)\hat{\pi}_{t-1}\right], \end{aligned} \tag{12}$$

where $\phi_t^{PC}, \omega^2\phi_t^{EE}, \omega^2\phi_t^{LB} \geq 0, \phi_t^{AI}$ are Lagrange multipliers and $\pi(\hat{\pi}_t, r_{t+1}^n), y(\hat{\pi}_t, r_{t+1}^n)$ characterize the equilibrium that the central bank expects to occur in period $t+1$, conditional upon the level of the natural real rate r_{t+1}^n.

A *Markov-Perfect equilibrium* is defined as a set of time-invariant value and policy functions $\{V^{CB}(\cdot), \pi(\cdot), \hat{\pi}(\cdot), y(\cdot), i(\cdot)\}$ that solves the central bank's problem (12).

We report social welfare of an economy for a particular monetary policy strategy ω in terms of the perpetual consumption transfer—expressed as a share of its steady state—that would make households in the hypothetical economy without any shocks indifferent to living in the actual stochastic economy

$$W := (1-\beta)\,\frac{\theta}{\kappa}\left(\sigma^{-1}+\eta\right)\mathrm{E}[V], \tag{13}$$

where the mathematical expectation is taken with respect to the unconditional distribution of r_t^n, and V is defined in equation (5).

2.3 Analytical insights

Before turning to the numerical analysis, it is useful to explore analytically some of the key properties of AIT. Solving the central bank's optimization problem gives rise to the following first-order condition[11]

$$\pi_t = -(1-\omega)\frac{\hat{\pi}_{t-1}}{\omega} + \frac{\beta(1-\omega)}{\kappa\sigma}\left(\mathrm{E}_t\phi_{t+1}^{LB} + \lambda^{CB}\sigma\mathrm{E}_t y_{t+1}\right) + A_{LB}(\hat{\pi}_t)\phi_t^{LB} + A_y(\hat{\pi}_t)y_t \tag{14}$$

where

$$A_y(\hat{\pi}_t) \equiv \left(\beta(1-\alpha_{PC})\frac{\partial \mathrm{E}_t\pi_{t+1}}{\partial(\hat{\pi}_t/\omega)} - 1\right)\frac{\lambda^{CB}}{\kappa} \tag{15}$$

$$A_{LB}(\hat{\pi}_t) \equiv \left(\frac{\beta}{\kappa}(1-\alpha_{PC})\frac{\partial \mathrm{E}_t\pi_{t+1}}{\partial(\hat{\pi}_t/\omega)} - \frac{1}{\kappa} + (1-\alpha_{EE})\frac{\partial \mathrm{E}_t y_{t+1}}{\partial(\hat{\pi}_t/\omega)} + \sigma\frac{\partial \mathrm{E}_t\pi_{t+1}}{\partial(\hat{\pi}_t/\omega)}\right)\sigma^{-1}. \tag{16}$$

For $\omega = 1$, (14) collapses to $\pi_t = -(\lambda^{CB}/\kappa)y_t - (\sigma^{-1}/\kappa)\phi_t^{LB}$, the well-known first-order condition under standard inflation targeting. When $\omega < 1$, monetary policy is influenced by two motives that are absent under standard inflation targeting. The *history dependence motive* is represented by the first term on the right-hand side of equation (14), and makes the inflation rate in period t an increasing function of past inflation shortfalls, as memorized by the previous period's average inflation rate $\hat{\pi}_{t-1}$. The *lower bound risk motive* is represented by the second term on the right-hand side of equation (14) and makes the inflation rate an increasing function of the expected lower-bound multiplier in the next period, $\mathrm{E}_t\phi_{t+1}^{LB}$, a measure of the risk of hitting the lower bound in the next period.[12]

To better understand these two channels, let us temporarily assume that $\lambda^{CB} = 0$ in (14).[13] In a period in which the lower bound constraint is not binding, $\phi_t^{LB} = 0$, the central bank's first-order condition reads

$$\pi_t = -(1-\omega)\frac{\hat{\pi}_{t-1}}{\omega} + \frac{\beta(1-\omega)}{\kappa\sigma}\mathrm{E}_t\phi_{t+1}^{LB}. \tag{17}$$

Suppose, $\hat{\pi}_{t-1} < 0$, perhaps because the lower bound constraint was binding in period $t-1$.

[11]Under price level targeting, i.e. when $\omega = 0$, $\hat{\pi}_t/\omega$ in (14)-(16) has to be replaced with p_t.

[12]Another motive, which is not the focus of our analysis, is related to the occurrence of the expected output gap term on the right-hand side of (14). The Phillips curve describes a potential trade-off between inflation and output gap stabilization which, in turn, can give rise to a trade-off between average inflation and the output gap. When the central bank expects a trade-off between average inflation and the output gap to materialize in the next period, it can improve this trade-off by adjusting the current inflation rate in the opposite direction of expected next period's inflation rate.

[13]In the parlance of the policy delegation literature, $\lambda^{CB} = 0$ describes an inflation-conservative central bank.

Then, all else equal, the central bank aims for a higher inflation rate π_t than it would do if average inflation had been at target in the previous period. When agents expect higher period-t inflation in period $t-1$, this has a stimulative effect on inflation in period $t-1$, and mitigates the average inflation shortfall in period $t-1$.

Now suppose $\hat{\pi}_{t-1} \approx 0$, commensurate with a situation where the lower bound constraint has not been binding for a long time. Then, current period-by-period inflation depends only on the expected Lagrange multiplier associated with the lower bound constraint. When there is a positive probability that the lower bound constraint becomes binding in the future, $\mathrm{E}_t \phi_{t+1}^{LB} > 0$, the central bank aims for a higher inflation rate than it would do in the absence of such lower bound risk. By implementing a strictly positive inflation rate when the lower bound is not binding, the central bank mitigates the decline in next period's average inflation rate in case the lower bound constraint becomes binding. These two motives will also be at play in the numerical analysis presented in the next section.

3 Results under rational expectations

We now turn to the numerical analysis of how the assignment of an average inflation targeting objective affects society's welfare and economic dynamics when the lower bound on nominal interest rates is an occasionally binding constraint. This section presents results for the model under rational expectations. Results for the model under boundedly-rational expectations are presented in the next section. Throughout, we use some terminology from the more common arithmetic-moving-average specification of AIT to frame the results. Specifically, when $\omega = 0$, we may say that the averaging window is 'infinitely long', and when $\omega > 0$, we may say that the averaging window is 'finitely long'. When doing so, we interpret the exponential-moving-average, which is an infinite impulse response filter, as an—admittedly imperfect—approximation of an arithmetic moving average.

Table 1 reports our baseline parameterization, which is based on Nakata and Schmidt (2019b), for both variants of the model. The natural real rate shock r_t^n is governed by a stationary AR(1)

Table 1: **Parameterization**

Parameter	Value	Economic interpretation
β	0.99	Subjective discount factor
σ	2	Intertemporal elasticity of substitution in consumption
η	0.47	Inverse labor supply elasticity
θ	10	Price elasticity of demand
φ	0.8106	Share of firms per period keeping prices unchanged
ρ_r	0.85	AR coefficient natural real rate process
σ_r	$\frac{0.4}{100}$	Standard deviation natural real rate shock

Note: These parameter values imply $\kappa = 0.0079$ and $\lambda = 0.00079$.

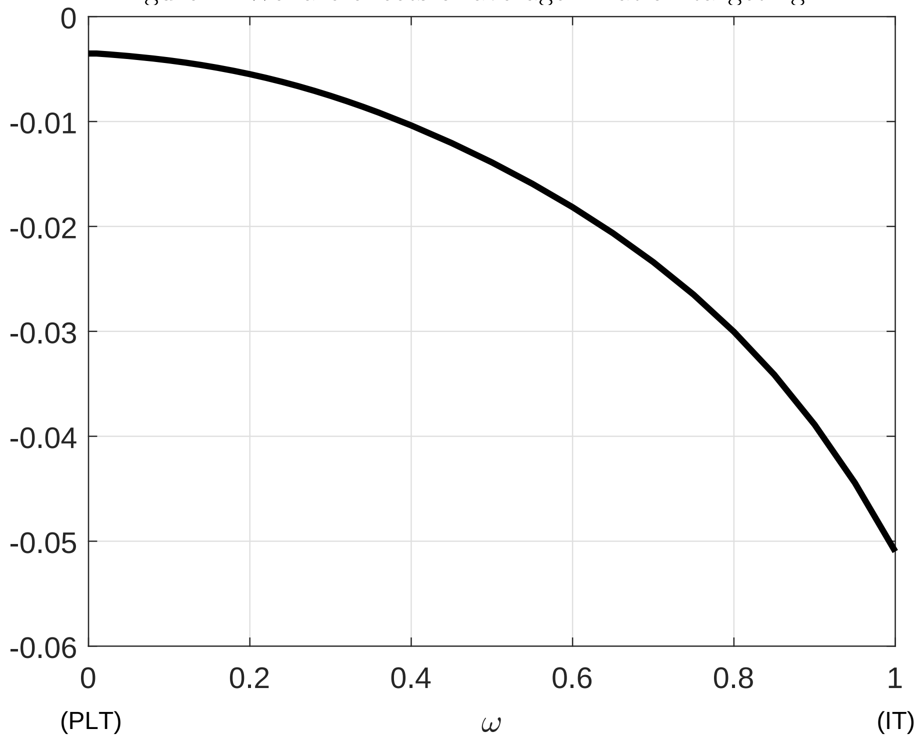
process, which has been estimated using U.S. data.[14] The Online Appendix contains a sensitivity analysis with respect to the values of key parameters.

We solve the model using the collocation method. The algorithm is explained in the Online Appendix.

3.1 Optimal averaging window

Figure 1 shows how society's welfare (13) varies with the inflation-averaging parameter ω in the model with rational expectations ($\alpha_{EE}, \alpha_{PC} = 0$).

Figure 1: Welfare effects of average inflation targeting



Note: Welfare is defined in equation (13).

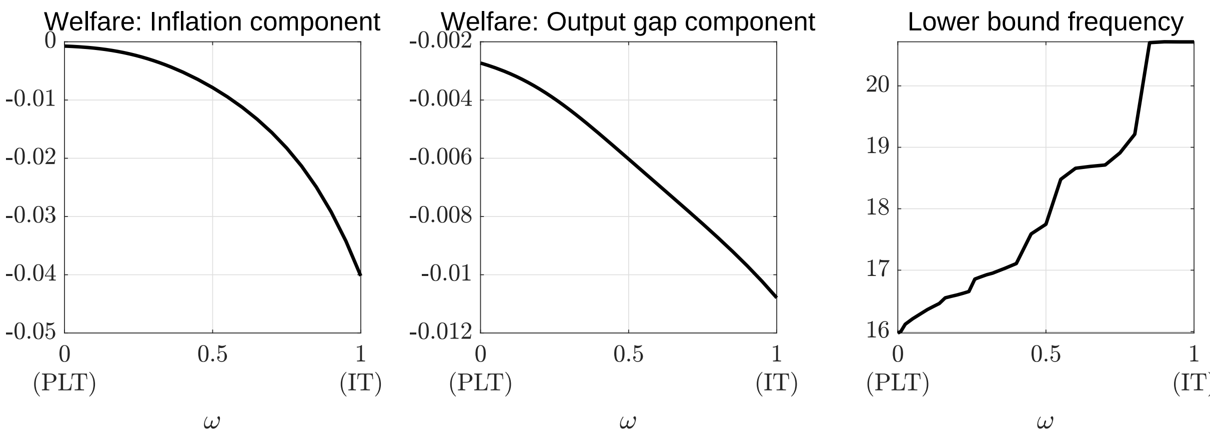
According to the figure, welfare increases monotonically as ω declines from 1 (the IT case) to 0 (the PLT case). Hence, PLT is the optimal monetary policy strategy in the class of considered frameworks and the optimal averaging window is infinitely long, in arithmetic-moving-average parlance. Interestingly, a rather modest, finite averaging window for the inflation objective $\hat{\pi}$ can lead to substantial welfare gains when compared to standard IT. For instance, for $\omega = 0.7$, the welfare costs are only half as large as under IT. In our model, these welfare gains from choosing $\omega < 1$ arise solely because of the presence of the lower bound on nominal interest rates. In the absence of the lower bound constraint, optimal monetary policy would replicate the efficient equilibrium for any value of ω.

Figure 2 decomposes society's overall welfare into the inflation-volatility and output-volatility

[14] See Appendix B in Nakata and Schmidt (2019b) for the details of the estimation.

components—shown in the left and middle panel, respectively. Both welfare components are monotonically decreasing in ω. Hence, there is no trade-off in the choice of ω between inflation and output gap stabilization. Finally, the right panel of Figure 2 shows that the frequency of a binding lower bound is either unchanged or declines as we lower ω.

Figure 2: Welfare decomposition and lower bound frequency



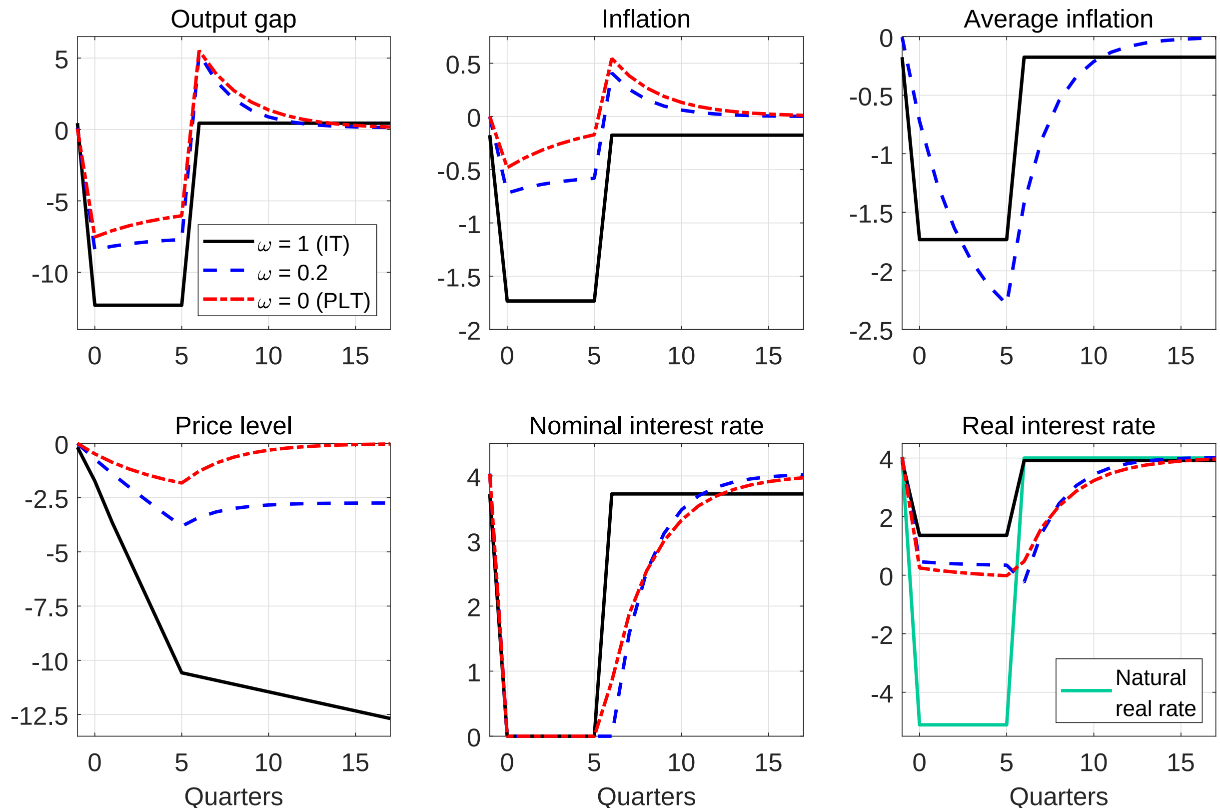
Note: Lower bound frequency is reported as the percentage share of simulated periods in which the lower bound constraint was binding.

3.2 Why average inflation targeting is welfare-improving

To better understand the benefits of a monetary policy strategy that entails $\omega < 1$, consider the following liquidity trap scenario. The economy is initially in the risky steady state. In period 0, the economy is hit by a shock that drives the natural real rate into negative territory where it stays for six quarters. Thereafter, it jumps back to its steady state level. At each point in time, agents are unaware of the future path of the natural real rate, expecting it to gradually return to its steady state according to the AR(1) process. This exemplary natural real rate path is of course rather extreme, but is useful in demonstrating the implications of $\omega < 1$ for output, inflation and interest rate dynamics in a transparent way. Figure 3 plots the evolution of key variables in this scenario for standard inflation targeting ($\omega = 1$), average inflation targeting (here for $\omega = 0.2$) and price level targeting ($\omega = 0$).

Under IT, the central bank lowers the policy rate to zero when the shock occurs, but the real interest rate only falls to a level somewhat below two percent, reflecting a large decline in inflation expectations. The gap between the natural real rate and the actual real interest rate, in turn, leads to large declines in output and inflation. When the natural real rate finally jumps back to its steady state, the central bank immediately raises the policy rate back to its pre-shock level. The inflation rate increases but remains negative. This so-called 'deflationary bias' arises because agents are aware that the lower bound might be binding again in the future, which puts downward pressure on conditional inflation expectations. When $\lambda^{CB} > 0$, as is the case under our assumption that $\lambda^{CB} = \lambda$, subdued inflation expectations result in a trade-off for the central bank between

Figure 3: Liquidity trap scenario



Note: All variables except for output have been annualized. Average inflation is normalized by $1/\omega$.

inflation and output gap stabilization. In equilibrium, the inflation rate is negative and the output gap is positive whenever the lower bound constraint is slack.[15] Finally, because of the deflationary bias, the price level remains on a downward trajectory after the liquidity trap episode.

Under AIT, the central bank also lowers the policy rate to zero when the shock occurs. However, when the shock recedes after 6 quarters the central bank raises the policy rate only gradually. This interest rate gradualism arises because average inflation is still negative when the natural real rate jumps back to its steady state level, and to stabilize average inflation, the central bank has to set the policy rate so that period-by-period inflation temporarily overshoots its long-run level. This is the history dependence motive described in Section 2.3 in operation. Households' and firms' inflation expectations at the lower bound are thus higher than under standard inflation targeting, and hence the real interest rate gap is smaller than under standard inflation targeting, resulting in improved outcomes for output and inflation at the lower bound. After the temporary overshooting, inflation is stabilized close to zero. Improved stabilization outcomes at the lower bound mitigate the downward pressure on conditional inflation expectations away from the lower bound, and the remaining deflationary pressures from these subdued inflation expectations are fully offset by the

[15]This trade-off between inflation and output gap stabilization arising from lower bound risk is analyzed in more detail in Nakata and Schmidt (2019a) and Hills et al. (2019).

central bank's lower bound risk motive.[16] Therefore, the price level is eventually stabilized, although at a lower level than prior to the shock.

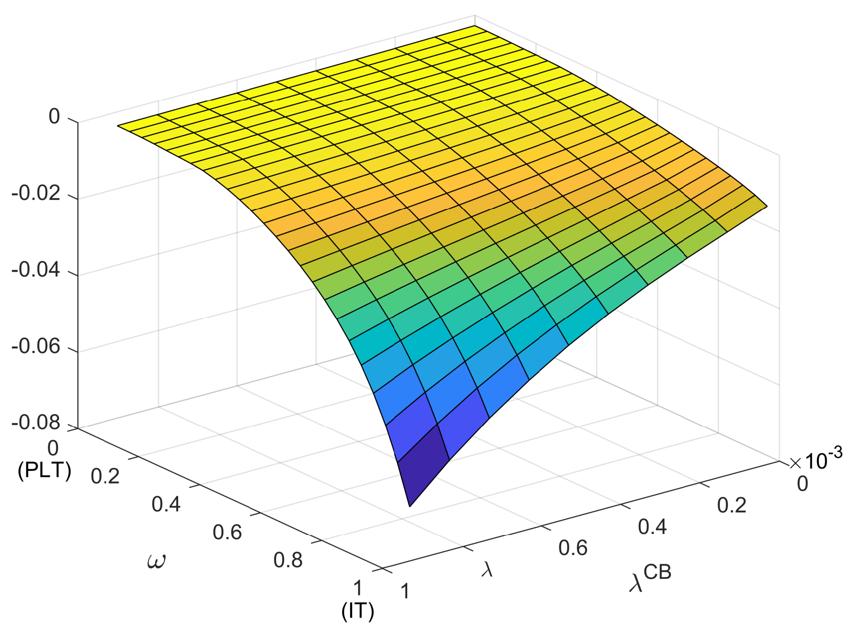
Finally, dynamics under PLT are qualitatively similar to those under AIT (with $\omega = 0.2$), except for the dynamics of the price level. Under PLT, the price level is stabilized at its pre-shock level after the liquidity trap episode. Any previous shortfall in period-by-period inflation is thus made up for one-for-one under PLT, whereas previous inflation shortfalls are made up for less than one-for-one under AIT. The stronger form of history dependence under PLT further mitigates the decline in the output gap and inflation at the lower bound.

3.3 Optimal relative weight on output gap stabilization

So far, we have presented results for the case where the central bank's objective function puts the same weight on output gap stabilization relative to period-by-period inflation stabilization as society's objective function, $\lambda^{CB} = \lambda$. In principle, however, the value assigned to λ^{CB} does not have to coincide with the value of λ. Therefore, we now relax the assumption that $\lambda^{CB} = \lambda$.

Figure 4 plots society's welfare as a function of both ω and λ^{CB}. We can make several obser-

Figure 4: Welfare effects of average inflation targeting and inflation conservatism



Note: Welfare is defined in equation (13). Here, $\lambda = 0.00079$.

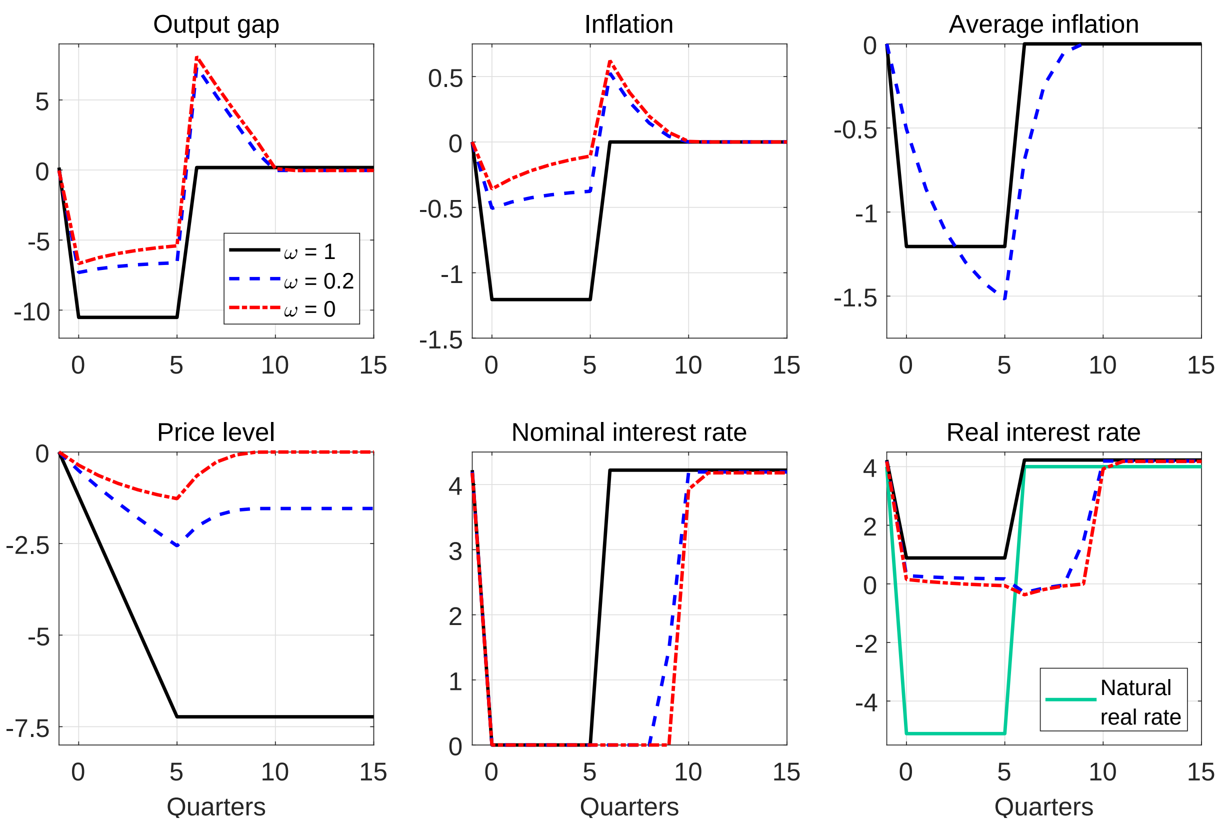
vations. First, when maximizing society's welfare over both $\omega \in [0, 1]$ and $\lambda^{CB} \geq 0$, strict PLT ($\omega = 0, \lambda^{CB} = 0$) is optimal. Second, for any $\omega \in [0, 1]$ welfare increases monotonically as λ^{CB} declines. This numerical finding extends the analytical result in Nakata and Schmidt (2019a) on

[16] Elimination of the deflationary bias is not a generic feature of average inflation targeting. Numerically, we find that the deflationary bias vanishes under AIT only if the value of ω is sufficiently small. In the Online Appendix, we show that the lower bound risk motive contributes to welfare under AIT.

the desirability of 'inflation conservatism' ($\lambda^{CB} < \lambda$) under standard IT to the case where $\omega < 1$. Third, for any $\lambda^{CB} \geq 0$, welfare increases monotonically as ω declines, which means that our result on the desirability of AIT/PLT holds for any values of λ^{CB}. Finally, optimizing one of the two policy parameters alone—either ω or λ^{CB}—can improve welfare quite a bit. In the current model with rational expectations, welfare is higher in the PLT regime with $\lambda^{CB} = \lambda$ than in the IT regime with $\lambda^{CB} = 0$. However, as we will see shortly, this result does not need to hold in the model with boundedly-rational expectations.

To understand how the assignment of a smaller relative weight on output gap stabilization in the central bank's objective function affects stabilization outcomes and welfare, let us reconsider the liquidity trap scenario, but with $\lambda^{CB} = 0$. Figure 5 shows the evolution of key model variables under IT, AIT and PLT. Under all three monetary policy strategies, the decline in the output gap

Figure 5: Liquidity trap scenario ($\lambda^{CB} = 0$)



Note: All variables except for output have been annualized. Average inflation is normalized by $1/\omega$.

and inflation in response to the shock is smaller than is the case when $\lambda^{CB} = \lambda$ (see Figure 3). Furthermore, the deflationary bias away from the lower bound—previously observed under standard inflation targeting with $\lambda^{CB} > 0$—disappears. When the central bank cares only about inflation stabilization, the subdued inflation expectations arising from lower bound risk no longer create a trade-off between stabilization of the nominal target variable and economic activity. Finally, the absence of such a trade-off implies that when $\omega < 1$—when the central bank pursues AIT or

PLT—the central bank not only raises interest rates more gradually after the liquidity trap episode than under IT—as is the case when $\lambda^{CB} = \lambda$—it now keeps the nominal interest rate at the lower bound for longer. This more accommodative interest rate policy heightens the overshooting in the output gap relative to the case where $\lambda^{CB} = \lambda$ and speeds up the return of the average inflation rate/price level to its target.

4 Results under boundedly-rational expectations

We now turn to the analysis of AIT in the model with boundedly-rational expectations.

As pointed out by Del Negro et al. (2015) and Carlstrom et al. (2015), the effects on inflation and output of an interest rate cut in the future are implausibly large in the standard New Keynesian model (so-called "forward guidance puzzle").[17] Many papers recently have proposed modifications to the standard New Keynesian model to attenuate this forward guidance puzzle, with the introduction of boundedly-rational expectations being one of them. Because AIT improves allocations by promising interest rate cuts in the future, it is important to investigate the effectiveness of AIT using a model with attenuated forward guidance effects.

The baseline parameterization is summarized in Table 1. The Online Appendix contains a sensitivity analysis with respect to the values of key parameters.

4.1 Optimal averaging window

Figure 6 shows how welfare varies with the value of ω for various values of $\bar{m}$, the cognitive discounting parameter.[18] According to the figure, the optimal value of ω remains zero—i.e. the optimal averaging window remains infinitely long—as long as $\bar{m}$ is sufficiently close to one. However, when the value of $\bar{m}$ is sufficiently below one, a further decline in $\bar{m}$ increases the optimal ω, and the optimal averaging window becomes finite. In an extreme case in which $\bar{m} = 0$, the decisions of households and firms are almost static, and the optimal omega is close to one.

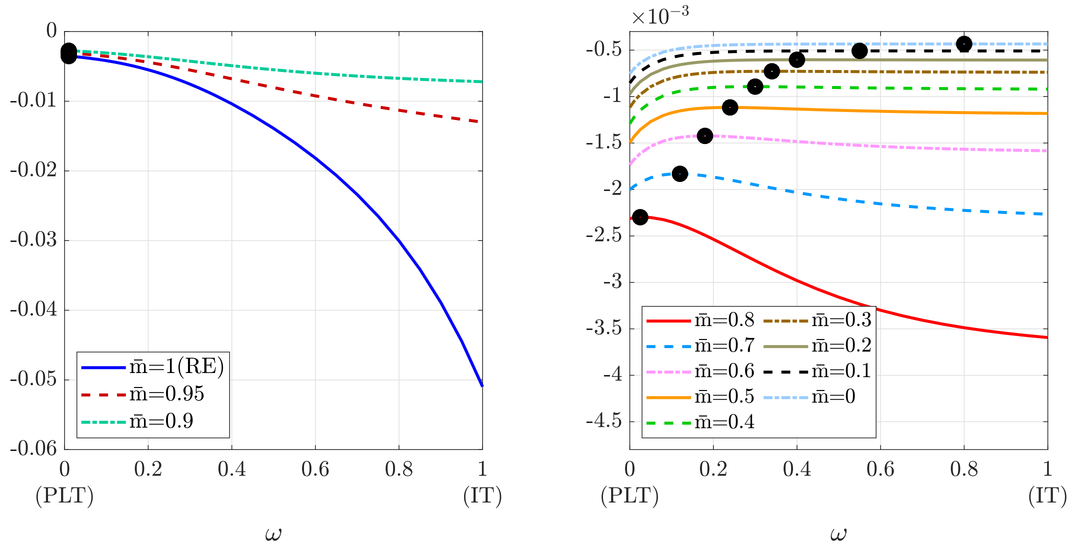
Another feature of Figure 6 is that the welfare gain from adopting the optimally calibrated AIT policy declines as $\bar{m}$ declines. This feature makes sense because AIT improves allocations relative to standard IT by taking advantage of the forward-looking behavior of households and firms. When $\bar{m}$ is less than 0.5, welfare under the optimally calibrated AIT is about the same as welfare under standard IT. Finally, it is also notable that, when $\bar{m}$ is low, welfare under PLT (that is, $\omega = 0$) is lower than welfare under standard IT. In our numerical example, this occurs when $\bar{m}$ is below 0.7.

Given the sensitivity of the welfare results with respect to the degree of bounded rationality, we would ideally base our paramterization of the discounting parameters on available empirical

[17] In evaluating the effects of forward guidance shocks, it is typically assumed that the promise of an interest-rate cut far into the future is perfectly credible, but this assumption might not be realistic. For example, Haberis et al. (2019) show that, once the assumption of perfect credibility is relaxed, the effects of forward guidance shocks become smaller.

[18] Recall that a higher $\bar{m}$ means a higher cognitive ability. When $\bar{m} = 1$, the model corresponds to the rational-expectations model. As $\bar{m}$ becomes lower, agents' decisions today depend less on expected future inflation and output.

Figure 6: Welfare effects of average inflation targeting with boundedly-rational expectations



Note: Welfare is defined in equation (13).

evidence. Gabaix (2019) uses values for the discounting parameters consistent with $\bar{m} = 0.85$, based on several empirical estimates of (hybrid) Phillips curves and Euler equations available in the literature. However, these estimates do not provide direct evidence on the micro parameter $\bar{m}$. As emphasized by Gabaix (2019), additional well-identified empirical work is needed to better inform the parameterization of the model with bounded rationality.[19] Thus, we report results for a wide range of values of the cognitive discounting parameter.

4.2 Why bounded rationality diminishes the welfare gain from AIT

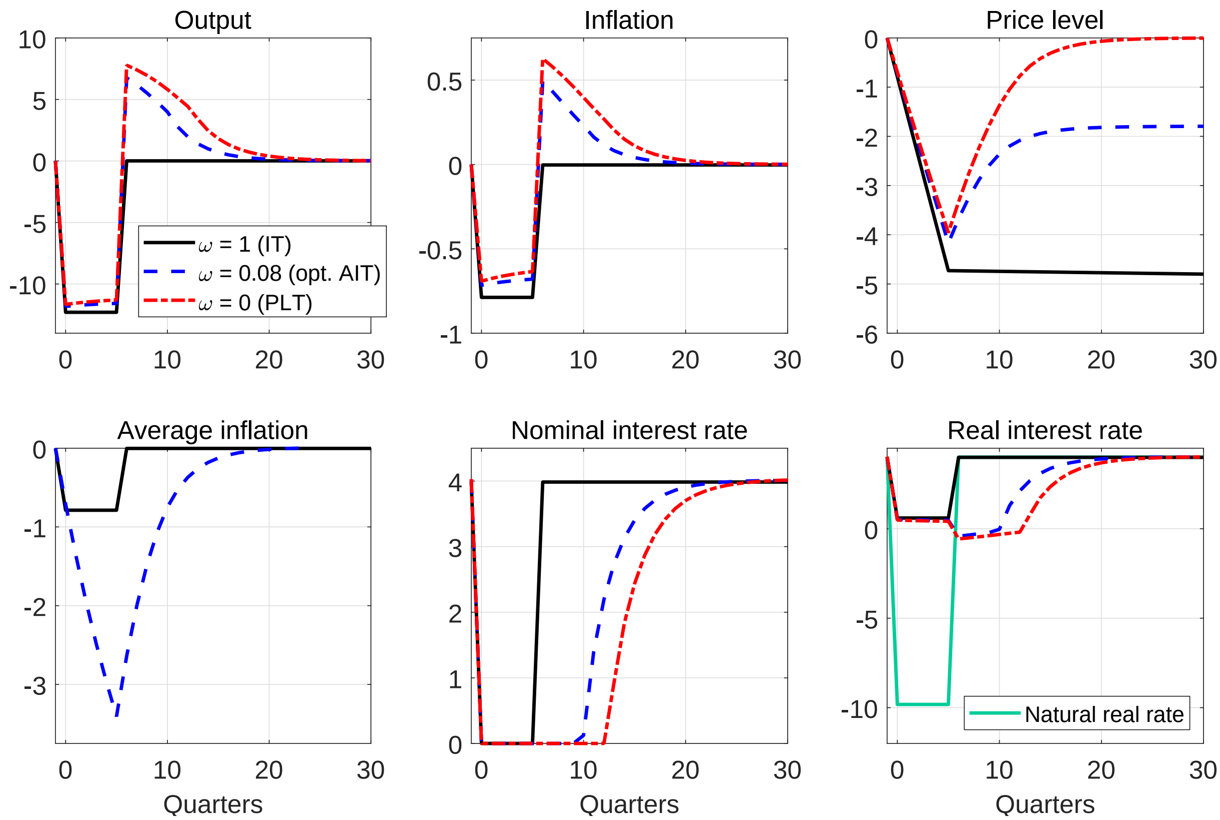
To understand why the optimal ω declines with $\bar{m}$, we show in Figure 7 how the economy with $\bar{m} = 0.75$ evolves in a recession scenario comparable to the one in Figure 3, for selected values of ω. The size of the shock is chosen so that, when $\omega = 1$, the decline in output is the same as that in the model with rational expectations.[20]

Consider first the case with PLT (that is, the case with $\omega = 0$)—shown by dash-dotted red lines. Under PLT, the policy rate is kept at the lower bound for several quarters after the natural real rate turns positive, creating a temporary overheating of the economy. However, relative to the case with $\bar{m} = 1$, the benefit of the temporary overheating for economic activity when the natural rate is negative are small, as future economic conditions have a smaller impact on today's allocations when $\bar{m} = 0.75$. As a result, both inflation and output decline by more during the crisis in the model with boundedly-rational expectations than in the model with rational expectations. At the same time,

[19]Other structural approaches to mitigate the forward guidance puzzle consistent with discounting the Euler equation and/or Phillips curve typically use values for the discounting parameters that are not too far below one. See Nakata et al. (2019) for an overview.

[20]If we kept the shock size unchanged, the declines in output and inflation would be much smaller in the model with boundedly-rational expectations for any value of ω than in the model with rational expectations, and it is difficult to see the effects of adopting the AIT.

Figure 7: Liquidity trap scenario with boundedly-rational expectations



Note: All variables except for output have been annualized. Average inflation is normalized by $1/\omega$.

a lower inflation path during the crisis implies that the inflation overshoot—and as a result the output overshoot—in the aftermath of the crisis is larger than in the rational-expectations model.

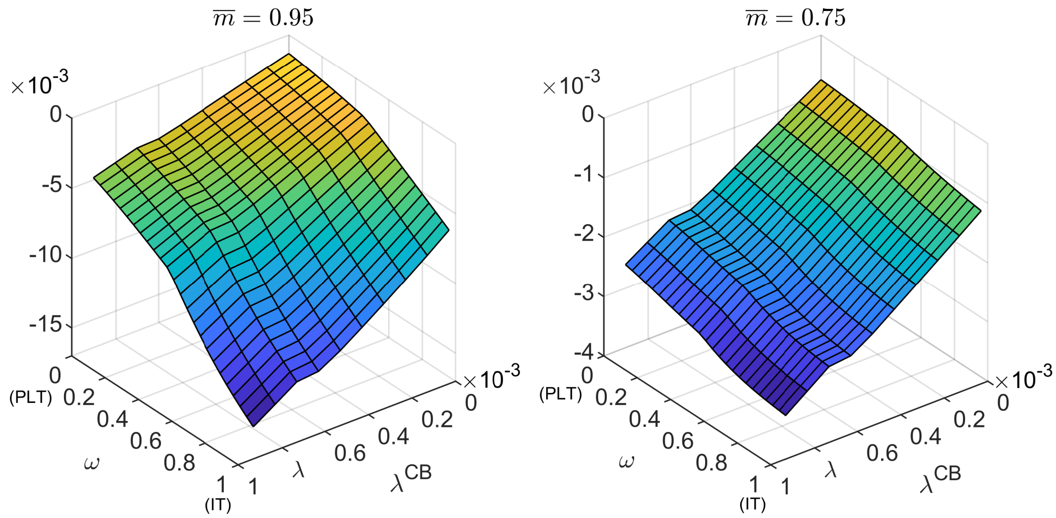
Next, consider an AIT regime with $\omega = 0.08$. In this case—shown by dashed blue lines—the policy rate is at the lower bound for a shorter duration and the inflation and output overshoots are smaller than under $\omega = 0$. While inflation and output decline by more in the crisis under $\omega = 0.08$ than under $\omega = 0$, the differences are small. That is, an increase of ω from 0 to 0.08 lowers the cost of AIT nontrivially, while lowering the benefit of AIT only by a small amount, increasing the overall welfare. For our model calibration with $\bar{m} = 0.75$, $\omega = 0.08$ is indeed the optimal value.

4.3 Optimal relative weight on output gap stabilization

We now relax again the assumption that $\lambda^{CB} = \lambda$. Figure 8 plots society's welfare as a function of both ω and λ^{CB}. The left panel shows results when the cognitive discounting parameter $\bar{m}$ equals 0.95, and the right panel shows results when $\bar{m} = 0.75$, as in the liquidity trap scenario considered in the previous subsection.

When cognitive limitations are moderate, as in the left panel of Figure 8, strict PLT ($\omega = 0, \lambda^{CB} = 0$) is optimal, as in the rational-expectations model. Optimizing one of the two policy parameters alone—either ω or λ^{CB}—can improve welfare quite a bit, which is also in line with the

Figure 8: Welfare effects of AIT and inflation conservatism with boundedly-rational expectations



Note: Welfare is defined in equation (13).

results obtained for the rational-expectations model.

When cognitive limitations are more severe, as in the right panel, strict PLT is no longer optimal. Specifically, for $\bar{m} = 0.75$, the optimal values for the policy parameters are $\omega = 0.1$ and $\lambda^{CB} = 0$.[21] Unlike in both the rational-expectations model and the boundedly-rational expectations model with values of $\bar{m}$ close to one, the welfare gain from optimizing over λ^{CB} is much larger than the gain from optimizing over ω. The reason is as follows. With boundedly-rational expectations, policies that improve macroeconomic outcomes at the lower bound by raising expectations about future output gap and inflation are less effective than in the case of rational expectations. The benefits from both AIT and inflation conservatism—i.e. lowering the weight on output gap stabilization—are thus smaller under boundedly-rational expectations. AIT, unlike inflation conservatism, also comes at a cost, which is the temporary output gap and inflation rate overshooting in the future. Due to an adverse feedback loop, this cost is increasing in the degree of agents' cognitive limitations. A given increase in expected future output gap and inflation at the lower bound has a smaller stabilizing effect on current output gap and inflation, which, because of the history dependence

[21] In the previous subsection, we optimized only over ω, keeping λ^{CB} fixed at λ. Therefore, the optimized value for ω reported here is slightly different from the one reported in the previous subsection.

motive, requires a larger future overshooting. Inflation conservatism, instead, does not induce a history dependence motive and is thus not prone to the same adverse feedback loop.

5 Conclusion

We have studied the implications of average inflation targeting—a monetary policy strategy that aims to stabilize an average inflation rate as opposed to a period-by-period inflation rate—for macroeconomic outcomes and welfare, using a New Keynesian model with a lower bound on nominal interest rates. We have considered two variants of the model, one with rational expectations and one with boundedly-rational expectations. Following the policy delegation approach, we have analyzed the optimization problem of a central bank that takes the assigned objective function as given and sets the short-term nominal interest rate under discretion.

Under rational expectations, assigning an average inflation targeting objective to the central bank improves macroeconomic outcomes and increases people's welfare when compared to standard inflation targeting. While the optimal averaging window is infinitely long, most of the welfare gain can be attained by a finite, but sufficiently long, averaging window.

These results from the rational-expectations model continue to hold true in the model with boundedly-rational expectations as long as cognitive limitations remain small. However, if cognitive limitations are sufficiently strong, the optimal averaging window is finite, and the welfare improvement from abandoning standard inflation targeting in favor of average inflation targeting can be small. The effectiveness of makeup strategies such as average inflation targeting thus hinges on the extent to which people understand how these strategies make future monetary policy and macroeconomic outcomes contingent on current economic conditions.

References

Adam, K. and R. M. Billi (2006): "Optimal Monetary Policy under Commitment with a Zero Bound on Nominal Interest Rates," *Journal of Money, Credit and Banking*, 38, 1877–1905.

——— (2007): "Discretionary Monetary Policy and the Zero Lower Bound on Nominal Interest Rates," *Journal of Monetary Economics*, 54, 728–752.

Bernanke, B., M. Kiley, and J. Roberts (2019): "Monetary Policy Strategies for a Low-Rate Environment," Finance and Economics Discussion Series 2019-009, Board of Governors of the Federal Reserve System (U.S.).

Bilbiie, F. O. (2019): "Optimal Forward Guidance," *American Economic Journal: Macroeconomics*, 11, 310–45.

Billi, R. M. (2017): "A Note on Nominal GDP Targeting and the Zero Lower Bound," *Macroeconomic Dynamics*, 21, 2138–2157.

Brainard, L. (2019): "Federal Reserve Review of Monetary Policy Strategy, Tools, and Communications: Some Preliminary Views," *Remarks at the Presentation of the 2019 William F. Butler Award New York Association for Business Economics, New York.*

Carlstrom, C. T., T. S. Fuerst, and M. Paustian (2015): "Inflation and Output in New Keynesian Models with a Transient Interest Rate Peg," *Journal of Monetary Economics*, 76, 230–243.

Coenen, G., C. Montes-Galdon, and F. Smets (2020): "Effects of State-Dependent Forward Guidance, Large-Scale Asset Purchases and Fiscal Stimulus in a Low-Interest-Rate Environment," Working Paper Series 2352, European Central Bank.

Coibion, O., D. Georgarakos, Y. Gorodnichenko, and M. Weber (2020): "Forward Guidance and Household Expectations," Working Paper 26778, National Bureau of Economic Research.

Del Negro, M., M. Giannoni, and C. Patterson (2015): "The Forward Guidance Puzzle," Staff reports, Federal Reserve Bank of New York.

Eggertsson, G. B. and M. Woodford (2003): "The Zero Bound on Interest Rates and Optimal Monetary Policy," *Brookings Papers on Economic Activity*, 34, 139–235.

Gabaix, X. (2019): "A Behavioral New Keynesian Model," Working Paper 22954, National Bureau of Economic Research.

Galí, J. (2015): *Monetary Policy, Inflation, and the Business Cycle*, Princeton: Princeton University Press.

Haberis, A., R. Harrison, and M. Waldron (2019): "Uncertain Policy Promises," *European Economic Review*, 111, 459–474.

Hills, T. S., T. Nakata, and S. Schmidt (2019): "Effective Lower Bound Risk," *European Economic Review*, 120, 103321.

Jung, T., Y. Teranishi, and T. Watanabe (2005): "Optimal Monetary Policy at the Zero-Interest-Rate Bound," *Journal of Money, Credit and Banking*, 37, 813–35.

Levin, A. and A. Sinha (2019): "Pitfalls of Make-Up Strategies for Mitigating the Effective Lower Bound," *Cato Journal*, forthcoming.

Mertens, T. and J. Williams (2019): "Tying Down the Anchor: Monetary Policy Rules and the Lower Bound on Interest Rates," Staff Reports 887, Federal Reserve Bank of New York.

Nakata, T. (2016): "Optimal Fiscal and Monetary Policy with Occasionally Binding Zero Bound Constraints," *Journal of Economic Dynamics and Control*, 73, 220–240.

——— (2017): "Uncertainty at the Zero Lower Bound," *American Economic Journal: Macroeconomics*, 9, 186–221.

Nakata, T., R. Ogaki, S. Schmidt, and P. Yoo (2019): "Attenuating the Forward Guidance Puzzle: Implications for Optimal Monetary Policy," *Journal of Economic Dynamics and Control*, 105, 90 – 106.

Nakata, T. and S. Schmidt (2019a): "Conservatism and Liquidity Traps," *Journal of Monetary Economics*, 104, 37 – 47.

——— (2019b): "Gradualism and Liquidity Traps," *Review of Economic Dynamics*, 31, 182 – 199.

Nakov, A. (2008): "Optimal and Simple Monetary Policy Rules with Zero Floor on the Nominal Interest Rate," *International Journal of Central Banking*, 4, 73–127.

Nessen, M. and D. Vestin (2005): "Average Inflation Targeting," *Journal of Money, Credit, and Banking*, 37(5), 837–863.

Reifschneider, D. and J. C. Williams (2000): "Three Lessons for Monetary Policy in a Low-Inflation Era," *Journal of Money, Credit and Banking*, 32(4), 936–966.

Rogoff, K. (1985): "The Optimal Degree of Commitment to an Intermediate Monetary Target," *The Quarterly Journal of Economics*, 100, 1169–89.

Svensson, L. (2020): "Monetary Policy Strategies for the Federal Reserve," *International Journal of Central Banking*, 16, 133–193.

Vestin, D. (2006): "Price-level versus Inflation Targeting," *Journal of Monetary Economics*, 53(7), 1361–1376.

Walsh, C. E. (2019): "Alternatives to Inflation Targeting in Low Interest Rate Environments," IMES Discussion Paper Series 19-E-13, Institute for Monetary and Economic Studies, Bank of Japan.

Online Appendix:

Average Inflation Targeting and the Interest Rate Lower Bound

A Numerical algorithm

We approximate the policy functions for the inflation rate, output, the policy rate and the average inflation rate with a finite elements method using collocation. For the basis functions we use cubic splines. The algorithm uses fixed-point iteration and proceeds in the following steps:

1. Construct the collocation nodes. Use a Gaussian quadrature scheme to discretize the normally distributed innovation to the natural real rate shock.

2. Start with a guess for the basis coefficients.

3. Use the current guess for the basis coefficients to approximate the expectation terms.

4. Solve the system of equilibrium conditions for inflation, output, the policy rate and average inflation at the collocation nodes, assuming that the zero lower bound is not binding. For those nodes where the zero bound constraint is violated solve the system of equilibrium conditions associated with a binding zero bound.

5. Update the guess for the basis coefficients. If the new guess is sufficiently close to the old one, the algorithm has converged. Otherwise, go back to step 3.

B Welfare effects of lower bound risk motive

To assess the role of the lower bound risk motive for welfare, we solve the benchmark rational-expectations model under a version of the central bank's first order condition (14) without the term capturing the lower bound risk motive[22]

$$\pi_t = -(1-\omega)\frac{\hat{\pi}_{t-1}}{\omega} + \frac{\beta(1-\omega)\lambda^{CB}}{\kappa}\mathrm{E}_t y_{t+1} + A_{LB}(\hat{\pi}_t)\phi_t^{LB} + A_y(\hat{\pi}_t)y_t, \tag{B.1}$$

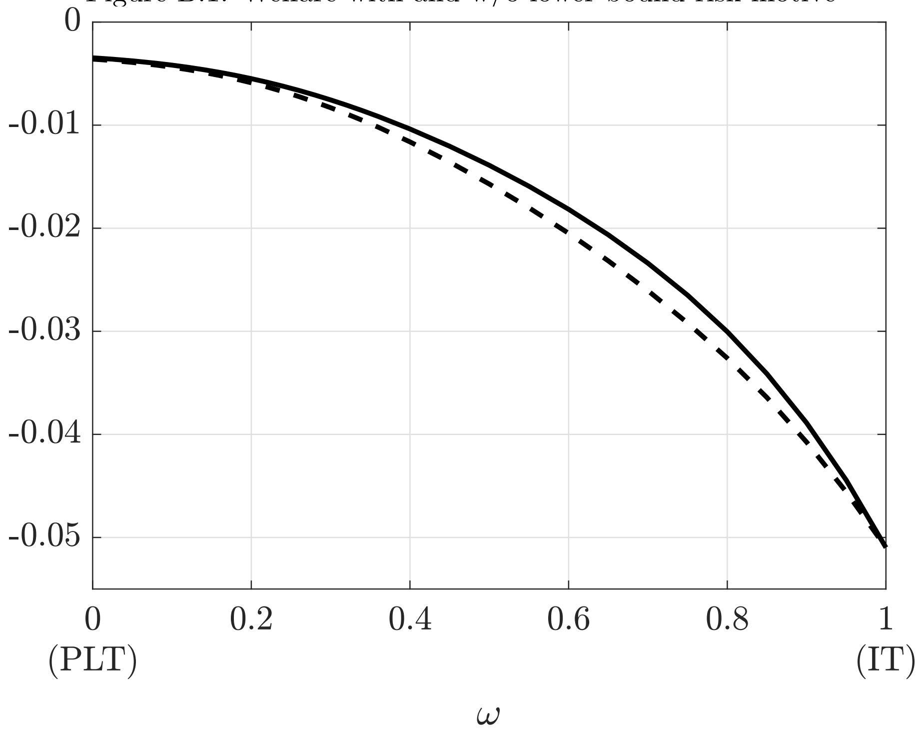
where $A_{LB}(\hat{\pi}_t)$ and $A_y(\hat{\pi}_t)$ are defined in equations (15) and (16).

Figure B.1 shows how society's welfare (13) varies with the inflation-averaging parameter ω in the rational-expectations model ($\alpha_{EE}, \alpha_{PC} = 0$) when monetary policy is characterized by (i) equation (14) (solid line), and (ii) equation (B.1) (dashed line).

Welfare is lower when monetary policy is not guided by the lower bound risk. Quantitatively, however, the difference between the two welfare curves is relatively small. One explanation could be that for values of ω close to one, the coefficient on the expected next-period Lagrange multiplier associated with the lower bound constraint $\mathrm{E}_t\phi_{t+1}^{LB}$ is very small, because it entails the term $(1-\omega)$.

[22] The lower bound risk motive in (14) is captured by the term $\frac{\beta(1-\omega)}{\kappa\sigma}\mathrm{E}_t\phi_{t+1}^{LB}$.

Figure B.1: Welfare with and w/o lower bound risk motive



Note: Welfare is defined in equation (13).

For values of ω further below one, the coefficient on the expected Lagrange multiplier becomes larger but lower bound risk itself—i.e. the size of the expected Lagrange multiplier—is mitigated because when ω is small, the decline in the output gap and inflation at the lower bound is less severe, which itself is a result of the history dependence motive.

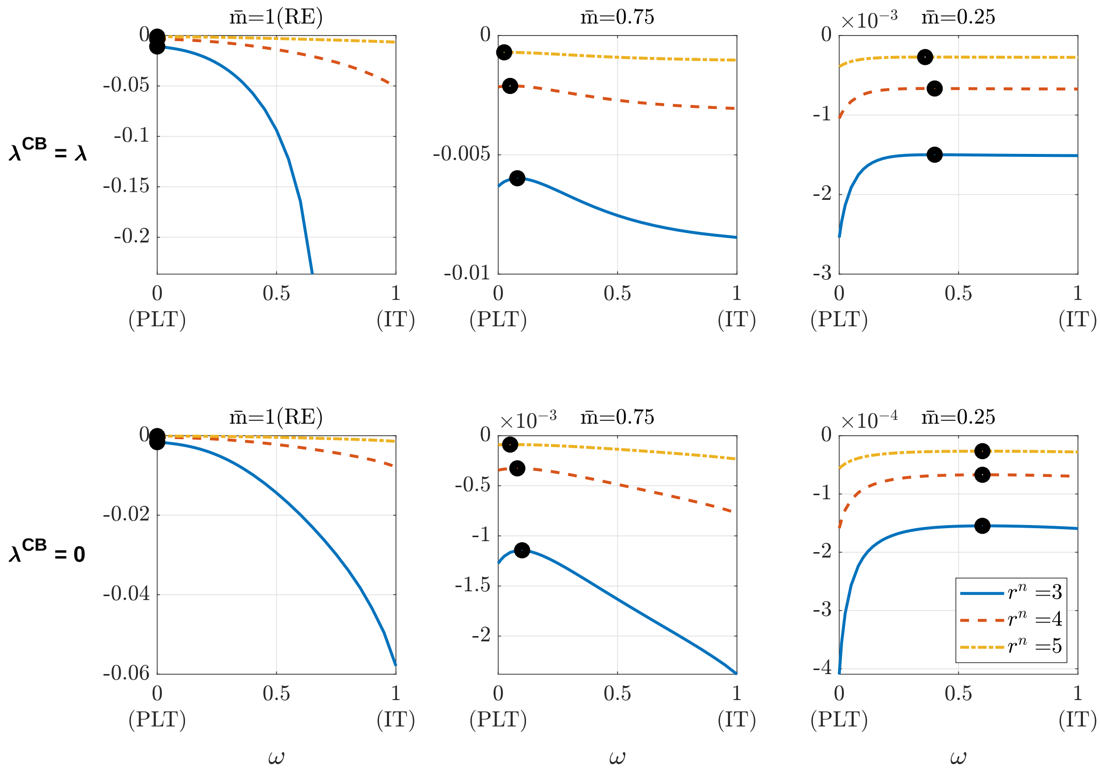
C Sensitivity analysis

In this section, we investigate the sensitivity of the welfare results to changes in selected parameter values, specifically the steady state level of the natural real rate r^n, the share of firms keeping prices unchanged per period φ, and the intertemporal elasticity of substitution in consumption σ.

We find that in the rational-expectations model, PLT is the optimal strategy for all considered parameter values. In the model with boundedly-rational expectations, the optimal value of ω, and hence the optimal monetary policy strategy, can depend on the specific values of r^n, φ and σ.

Figure C.1 shows how welfare depends on ω for different values of r^n. For the panels in the first row, it is assumed that $\lambda^{CB} = \lambda$, and for the panels in the second row it is assumed that $\lambda^{CB} = 0$. The panels in the left, middle, and right columns are for $\bar{m} = 1$, $\bar{m} = 0.75$, and $\bar{m} = 0.25$, respectively. A lower value of r^n reduces the room for monetary policy to cut the nominal interest rate in response to adverse shocks before reaching the lower bound and, all else equal, increases the frequency of a binding lower bound. A reduction in r^n thus leads to a decline in welfare regardless of the values for λ^{CB}, $\bar{m}$, and ω.

Figure C.1: Welfare effects of AIT and the steady state natural real interest rate



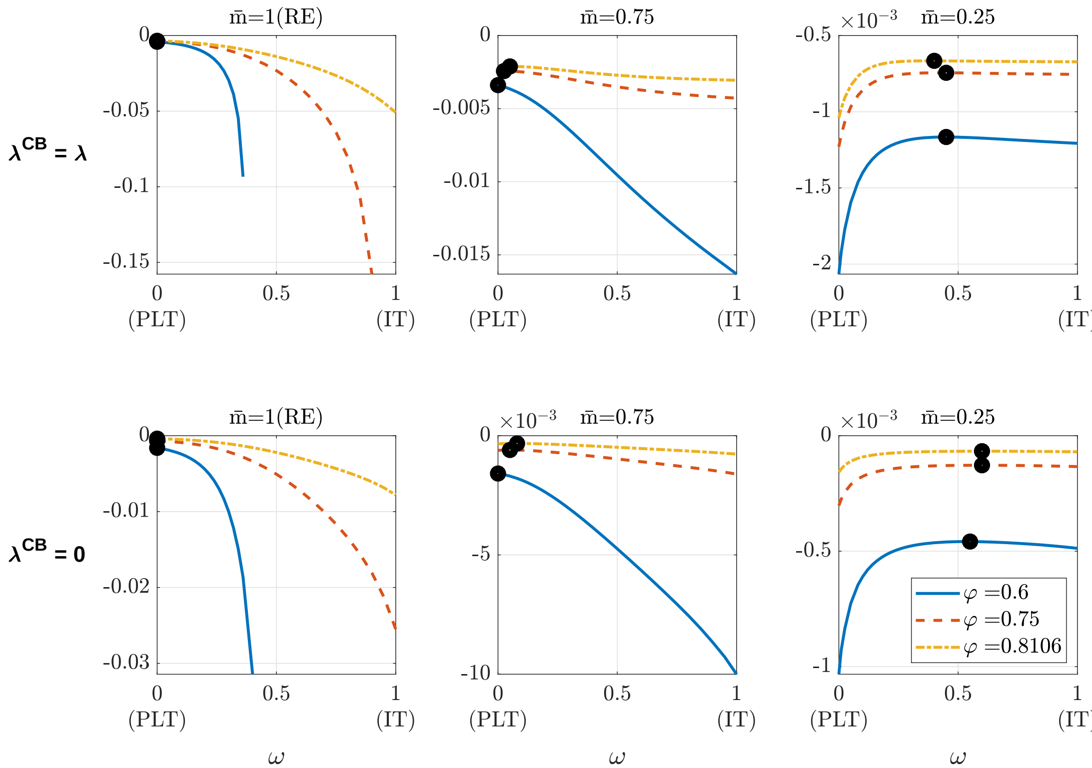
Note: Welfare is defined in equation (13). The steady state natural real interest rate r^n is expressed in annualized percent. The top panels show the results for $\lambda^{CB} = \lambda$, the bottom panels show the results for $\lambda^{CB} = 0$. Here, $\lambda = 0.00078$ if $r^n = 3\%$, $\lambda = 0.00079$ if $r^n = 4\%$ and $\lambda = 0.000793$ if $r^n = 5\%$.

Under rational expectations PLT is the optimal strategy for all three values of r^n, regardless of the value for λ^{CB}. Under rational expectations, when r^n equals 3 percent (annualized) and $\lambda^{CB} = \lambda$, no model solution exists for values of ω larger than 0.7, as shown by the solid blue line in the top-left panel. Under boundedly-rational expectations, when the degree of bounded rationality is sufficiently strong, a lower r^n raises the optimal ω, as can be seen in the panels in the middle and right columns. This result reflects the fact that the suboptimality of PLT becomes more pronounced when the lower bound frequency is higher.

Figure C.2 shows how welfare depends on ω for different degrees of price rigidity, with a higher φ implying more rigid prices. Due to the so-called 'paradox of flexibility' an increase in price flexibility, i.e. a decline in φ, lowers welfare for any values of λ^{CB}, $\bar{m}$, and ω. As in the sensitivity analysis with respect to r^n, under rational expectations ($\bar{m} = 1$)—shown in the left column—PLT is the optimal strategy for all three values of φ, regardless of the values of λ^{CB}. Under bounded rationality with $\lambda^{CB} = 0$—shown in the bottom-middle and bottom-right panels—the optimal ω increases as prices become more sticky.[23]

[23]Since a change in the value of φ also changes λ, this result does not necessarily hold true when $\lambda^{CB} = \lambda$. Specifically, this result does not hold when $\lambda^{CB} = \lambda$ and $\bar{m} = 0.25$, as shown in the top-right panel.

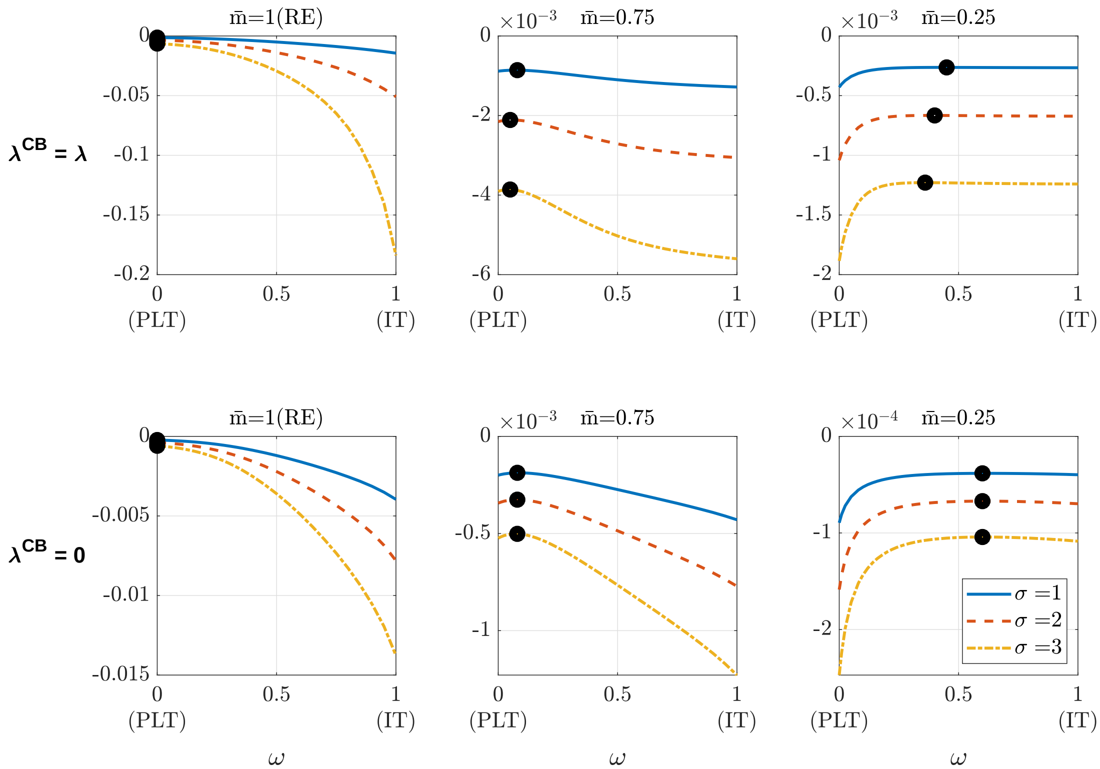
Figure C.2: Welfare effects of AIT and the degree of price rigidity



Note: Welfare is defined in equation (13). The top panels show the results for $\lambda^{CB} = \lambda$, the bottom panels show the results for $\lambda^{CB} = 0$. Here, $\lambda = 0.0046$ if $\varphi = 0.6$, $\lambda = 0.00146$ if $\varphi = 0.75$ and $\lambda = 0.00079$ if $\varphi = 0.8106$.

Finally, Figure C.3 shows how welfare depends on ω for different values of the intertemporal elasticity of substitution. Since the natural real rate shock in the Euler equation is multiplied by the intertemporal elasticity of substitution, a higher σ, all else equal, implies that the lower bound constraint binds more often. Hence, an increase in the intertemporal elasticity of substitution lowers welfare for any values of λ^{CB}, $\bar{m}$, and ω. As before, under rational expectations PLT is the optimal strategy for all three values of ω, regardless of the values of λ^{CB}.

Figure C.3: Welfare effects of AIT and the intertemporal elasticity of substitution



Note: Welfare is defined in equation (13). The top panels show the results for $\lambda^{CB} = \lambda$, the bottom panels show the results for $\lambda^{CB} = 0$. Here, $\lambda = 0.0012$ if $\sigma = 1$, $\lambda = 0.00079$ if $\sigma = 2$ and $\lambda = 0.00065$ if $\sigma = 3$.