

# How Inflation Affects Macroeconomic Performance: An Agent-Based Computational Investigation\*

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**Abstract.** We use an agent-based computational approach to show how inflation can worsen macroeconomic performance by disrupting the mechanism of exchange in a decentralized market economy. We find that increasing the trend rate of inflation above 3 percent has a substantial deleterious effect, but lowering it below 3 percent has no significant macroeconomic consequences. Our finding remains qualitatively robust to changes in parameter values and to modifications to our model that partly address the Lucas critique. Finally, we contribute a novel explanation for why cross-country regressions may fail to detect a significant negative effect of trend inflation on output even when such an effect exists in reality.

*Keywords:* Agent-based computational model, inflation, price dispersion, firm turnover

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# 1 Introduction

Inflation-targeting central banks frequently justify their narrow focus on inflation by arguing that maintaining a low and stable rate of inflation is the best way for them to promote consistently high levels of GDP and low levels of unemployment, an argument that has been expressed by such eminent economists as Friedman (1977) and Laidler (1997). Yet, neither mainstream economic theory nor existing empirical studies offer much support for the belief that a country's real economic performance is significantly improved by reducing the trend rate of inflation, except in extreme circumstances. Indeed, Fortin (1996) and Akerlof et al. (1996) argue that reducing inflation too close to zero worsens economic performance because, at low rates of inflation, downward nominal wage rigidity raises the natural rate of unemployment. Moreover, too low a rate of inflation can result in real instability because of the zero lower bound on nominal interest rates.

Given the lack of support from economic science, and because of the dangers posed by nominal wage rigidity and the zero lower bound, inflation-targeting central banks are reluctant to reduce their targets below 2 or 3 percent. However, the commonly acknowledged weakness of the microfoundations of mainstream monetary theory leaves many wondering whether there might still be significant gains from reducing inflation that theorists have not yet discovered.

The research reported here goes somewhat beyond mainstream monetary economics to investigate this issue of how economic performance might be enhanced by reducing the trend rate of inflation. The paper explores an idea that has been advanced by economists such as Heymann and Leijonhufvud (1995), namely that inflation might impede the market mechanisms responsible for coordinating economic activities (see also Ragan, 1998). Strictly speaking, this idea cannot be investigated in a conventional rational-expectations-equilibrium framework because the concept of a rational expectations equilibrium presupposes that peoples' actions and beliefs are always perfectly coordinated without the need for any explicit mechanism. We therefore deploy a somewhat unconventional method, namely agent-based computational economics (ACE).<sup>1</sup>

More specifically, we use a modified version of the ACE model that we developed in Ashraf et al. (2011), henceforth AGH (2011), for addressing the role of banks in an economic system. In this model economy, all trades are coordinated by a self-organizing network of trade specialists just as they are in reality by shops, brokers, middlemen, banks, realtors,

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<sup>1</sup>A survey of the ACE literature is provided by Tesfatsion and Judd (2006). Examples of recent applications of the ACE approach to macroeconomics include Deissenberg et al. (2008), Delli Gatti et al. (2008), Dosi et al. (2010), and Ashraf et al. (2011).

and so forth. Here, we simplify the model by ignoring the existence of banks. The model is calibrated to U.S. data and simulated many times under different target inflation rates to see what difference the inflation target makes to the average level and variability of GDP, the variability of inflation, and the average rate of unemployment.

The basic reason for thinking that this model may help to account for significant costs of inflation is that it provides a propagation mechanism through which inflation might impede the market processes that coordinate economic activity. The mechanism involves the entry and exit of business firms that collectively constitute the network of trade specialists. Because price changes are not perfectly coordinated, a higher trend rate of inflation should imply, on average, more dispersion in the relative prices offered by the different specialists. Such extraneous relative-price variability introduces more volatility into the demand faced by any individual specialist, thus raising the incidence of shop failures throughout the economy. As a result, abstracting from any effects of wage rigidity and the problem of the zero lower bound on nominal interest rates, increased trend inflation should reduce average GDP by impeding the transactions process.

Our main finding from this investigation is that the trend inflation rate has a powerful adverse effect on economic performance, but only when it rises above 3 percent. For example, an increase of trend inflation from 3 to 10 percent reduces the average level of GDP across all 40 years in the median simulation by more than 5 percent. It has a similar effect on the other macroeconomic indicators that we examine.

Our paper is aimed at demonstrating not just how an ACE approach can address questions not readily amenable to treatment by conventional equilibrium analyses but also how to tackle some of the common objections to the methodology of ACE itself. One such objection is that simulations can be sensitive to numerical values assigned to parameters. We deal with this objection, first, by attempting to calibrate our parameter values to data on the U.S. economy and, second, by performing a sensitivity analysis, which shows that our main finding is qualitatively robust to changes in parameter values.

Another common objection to an analysis like ours arises from the famous “Lucas critique.” That is, when trend inflation rises, one would expect peoples’ behavioral rules to adapt to this change in the environment, and a model with exogenous behavioral rules does not allow this kind of adaptation as fully as a rational-expectations analysis would. To deal with this issue, we use the above-mentioned sensitivity analysis to identify which behavioral parameters are most important for our results. Specifically, we find that the markup applied by a firm when setting its retail price is particularly critical – the effect of inflation is magnified by having a small markup. We then modify our model to allow

markups to adapt to the environment through the selection mechanism implicit in the firm exit process. We find that the economy-wide average surviving markup ends up being higher when inflation is higher, but we also find that our main result remains intact when we take this endogenous behavior of markups into consideration.

One question raised by our numerical results concerns the absence of conclusive evidence from existing empirical studies, which, for the most part, have failed to find a sizable and robust effect of long-run inflation on a country's GDP. Interestingly, we show that if the baseline calibrated model were true, then there would still be a 15 percent chance that a cross-country regression of log GDP on inflation would reveal a statistically insignificant effect. The reason is that our model implies a novel endogeneity issue, which arises from a positive Phillips-type relationship between output and inflation that tends to mask the underlying negative long-run causal effect of trend inflation on output.

The paper is organized as follows. In Section 2, we briefly survey some of the relevant literature on the real effects of inflation. Section 3 lays out the basic structure of our agent-based model. Section 4 discusses the workings of the model. Section 5 presents our method for calibrating the model's parameters. Section 6 reveals our main results and those from our sensitivity analysis. In Section 7, we discuss our technique for dealing with the Lucas critique. Section 8 shows the implications of our model for cross-country regressions of output on inflation.

## 2 Literature on the real effects of inflation

There is an extensive literature on the potential real effects and costs of inflation.<sup>2</sup> One strand of the literature has focused on effects that work through the opportunity cost of holding non-interest-bearing money holdings. Raising this opportunity cost can reduce output by lowering capital accumulation and labor supply (Stockman, 1981; Cooley and Hansen, 1989; Gomme, 1993) or by altering search intensity (Rocheteau and Wright, 2005; Lagos and Rocheteau, 2005). It is hard to make the case, however, that such effects are empirically important given that non-interest-bearing money is such a small item in people's portfolios. For example, Chari et al. (1995) calculate the effects of inflation on growth in a variety of endogenous growth models where the opportunity cost of holding money is the only channel through which inflation matters, and they find that a 10 percentage point increase in inflation has a negative effect of at most 0.027 percentage points on the steady-state growth rate. Similarly,

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<sup>2</sup>For overviews, see Fischer and Modigliani (1978), Driffil et al. (1990), and Haslag (1997).

Gomme (1993) reports a very modest impact of inflation on the steady-state growth rate of output.

Another line of research has argued that non-indexation of private accounting systems distorts savings decisions and the allocation of capital under high rates of inflation and, moreover, that inflation diverts talent away from real productive activity and into less socially productive financial activity designed simply to cope with or profit from changes in the value of money (Leijonhufvud, 1977; Howitt, 1990; Summers, 1991). However, these possible costs of inflation are difficult to quantify, and we are not aware of any attempts to estimate their effects on the path of real output. On the other hand, Feldstein (1999) has argued that reducing inflation from 2 percent to 0 would raise output by 4 to 6 percentage points because of the non-indexation of capital income taxation. Nevertheless, this effect seems more like a problem to be dealt with by tax authorities than central bankers.

In New Keynesian dynamic stochastic general equilibrium models (e.g., Woodford, 2003), trend inflation affects output mainly by affecting the equilibrium degree of price dispersion. This is especially true in those versions that use the Calvo (1983) price-setting model. Ascari (2004) and Yun (2005) show the effect to be very large and, in fact, much larger than one would guess from log-linearized approximations. However, this seems to be sensitive to the two features of the Calvo model that most economists would not want to rely on, namely the assumptions that producers are constrained to always satisfy whatever demand is forthcoming at their posted prices and that the opportunity to change one's price is delivered by a state-independent Poisson process providing no upper bound to the length of time between price changes.<sup>3</sup>

The rise in price dispersion due to inflation can also have real effects by increasing the amount of resources devoted to search on the part of buyers, as emphasized in the search-theoretic literature (Bénabou, 1988, 1992; Head and Kumar, 2005). It will also play a crucial role in our framework, which highlights the detrimental effect of rising price dispersion on business failures.

On the empirical side, there is virtually no robust evidence on the effects of inflation on real outcomes. The literature on the effects of trend inflation on the growth rate of output, as surveyed in Ragan (1998), has produced little evidence of a significant effect, except in extreme circumstances. Nor is there much evidence that countries whose central banks adopted inflation targets starting in the early 1990s had better macroeconomic performance

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<sup>3</sup>Using a standard New Keynesian model, Howitt and Milionis (2007) show that when trend inflation is 10 percent, 36 percent of output is produced by firms selling at a marginal loss, and that once one eliminates this counterintuitive prediction by replacing the Poisson process with either fixed price-change intervals or optimally chosen state-dependent intervals, the output cost of inflation falls by a factor of 20.

than those that did not. There is also almost no direct evidence of an effect of trend inflation on the level of real output as opposed to its growth rate or volatility (e.g., Bullard and Keating, 1995). Later in the paper, we provide a novel explanation for why it may be hard to detect a significant negative effect of trend inflation on output.

Despite the absence of robust reduced-form evidence on the real effects of inflation, there is considerable direct evidence on the relationship between inflation and relative-price dispersion, which plays a major role not only in New Keynesian and search-theoretic models but also in our agent-based framework. For example, Vining and Elwertowski (1976), Parks (1978), Parsley (1996), Debelle and Lamont (1997), and Lastrapes (2006) provide robust evidence on the positive association between inflation and price dispersion using data for the U.S. In addition, similar findings have been reported for Israel (Lach and Tsiddon, 1992) and Canada (Binette and Martel, 2005).

### 3 The model

Our model is a special case of the one developed in AGH (2011). Here, for simplicity, we abstract from the banking sector. The model attempts to portray, in an admittedly crude form, the mechanism by which economic activities are coordinated in a decentralized economy.

The model starts from the proposition that, in reality, almost all exchanges in an advanced economy involve a specialized trader (“shop owner”) on one side or the other of the market. On this foundation, we have built a model whose structure and macroeconomic aggregates are comparable to the canonical New Keynesian analysis of Woodford (2003). That is, prices are set by competing firms acting under monopolistic competition, the rate of interest is set by a monetary authority following a Taylor rule, and consumer demands depend, *inter alia*, on current wealth. However, it is quite different from the standard New Keynesian framework in three important respects. First, we have introduced elements of search in both goods (retail) markets and labor markets. Second, instead of having a fixed population of firms, we assume that firms are subject to failure and that the process of replacing failed firms is a costly one that disrupts established trading patterns. Third, rather than assuming complete contingent financial markets, we assume that the only available financial instruments are government-issued money and bonds.

To simplify the model and abstract from questions of inflation expectations, we assume throughout that peoples’ expectations of inflation are firmly anchored by the central bank. Thus, expected inflation is always equal to the announced inflation target.

### 3.1 The conceptual framework

There is a fixed number  $N$  of people, a fixed number  $n$  of different durable goods, and the same number  $n$  of different types of labor. Labor of type  $i$  can be used only to produce good  $i$ . Time is discrete, indexed by “weeks”  $t = 1, \dots, T$ . There are 48 weeks per “year.” In addition to the  $n$  goods, there are two nominal assets: fiat money and bonds. A bond is a promise by the government to pay one unit of money (“dollar”) next week.

Each person has a fixed type  $(i, j)$ , where  $i \neq j$  and  $i \neq j + 1 \pmod{n}$ , meaning that each week he is endowed with one unit of labor of type  $i$  (his “production good”) and can eat only goods  $j$  and  $j + 1 \pmod{n}$  (his primary and secondary “consumption goods”). There is exactly one person of each type. Thus, the population of the economy is  $N = n(n - 2)$ . In everything that follows, we set the number of goods  $n$  equal to 50, implying a population of  $N = 2400$  people.

Because no person can eat his own production good, everyone must trade to consume. Trading can take place only through facilities called “shops.” Each shop is a combined production/trading operation. There are  $n$  different types of shops. A shop of type  $i$  is capable of buying type  $i$  labor with money, converting type  $i$  labor into good  $i$ , and selling good  $i$  for money. The number of shops of each type will evolve endogenously.

To trade with a shop, a person must form a trading relationship with it. Each person may have a trading relationship with at most one shop that deals in his production good, in which case that shop is his “employer” and he is one of its “employees,” and at most one shop that deals in each of his consumption goods, in which case that shop is one of his “stores” and he is one of its “customers.” Each person’s trading relationships will evolve endogenously.

Each shop of type  $i$  has a single owner whose production good is  $i$ . Operating the shop entails a fixed overhead cost of  $F$  units of type  $i$  labor per week and a variable cost of one unit of type  $i$  labor per unit of good  $i$  produced. All trade takes place at prices that are posted in advance by the shop. Specifically, each shop posts a retail price and a weekly wage rate, each of which may be adjusted periodically.

There is no depreciation or other physical storage cost. Goods produced but not sold in a week are kept in inventory. Former shop owners continue to hold their “legacy inventories” until these are sold in special “firesale” markets.

The government does not purchase goods or labor but it does issue money and bonds, and it services the interest on bonds through a sales tax on every retail transaction. It adjusts the ad valorem tax rate  $\tau$  once per year. The central bank pegs the interest rate  $i$  on bonds by open market operations. It adjusts this rate every 4 weeks according to a Taylor

rule. In addition, the central bank is engaged in the forecasting of future GDP, inflation, and interest rates, and it releases this information to the public.

### 3.2 Protocol and behavioral rules

Each week our model economy proceeds through the same sequence of actions consisting of nine stages: 1) entry; 2) search and matching; 3) bond market trading; 4) labor and goods market trading; 5) monetary policy; 6) match breakups; 7) fiscal policy; 8) exit; and 9) wage and price setting. We believe that each of these 9 stages represents a process that is of central importance to the functioning of a market economy. Our underlying strategy is to model each process as simply as possible, that is, with unsophisticated behavioral rules that maintain the spirit of ACE modeling, while attempting to maintain at least a minimal degree of plausibility and of rough consistency with mainstream macroeconomics. The rest of this section sketches the protocol and behavioral rules of the model. We refer the reader to AGH (2011) for the exhaustive details of the algorithm that implements the model, further discussion of the behavioral rules, and the way to incorporate a banking sector in the model. The complete C++ code is available at [http://www.econ.brown.edu/fac/Peter\\_Howitt/working/Inflation.zip](http://www.econ.brown.edu/fac/Peter_Howitt/working/Inflation.zip).

**Entry.** In the first stage, each person who is not already a shop owner becomes a potential entrant (“entrepreneur”) with a fixed probability  $\theta/N$ , where the parameter  $\theta$  represents the supply of entrepreneurship or the weekly frequency of innovation. Each entrepreneur goes through the following decision process to decide whether to enter.

First, the entrepreneur formulates a business plan for his prospective shop, which consists of a wage rate  $w$  and a sales target  $y^{\text{trg}}$ . He sets the initial wage rate equal to the previous week’s (publicly known) economy-wide average wage  $W$ , adjusted for the central bank’s target inflation rate during the prospective wage contract period of  $\Delta$  weeks. He then picks his sales target  $y^{\text{trg}}$  randomly from a uniform distribution over  $[1, n]$  and plans to post the retail price  $p = (1 + \mu)w/(1 - \tau)$ , which is a fixed markup  $\mu$  over after-tax marginal cost (in Section 7 we endogenize  $\mu$ ). These choices imply a profit flow  $\Pi$  that the firm would earn if it opened and if its sales target were realized.

Given this business plan, the entrepreneur will allow the opportunity for entry to lapse if his financial wealth  $A$  (the sum of his money and bond holdings) is not enough to pay for the fixed cost of operating the shop during the first month. He will also allow the entry opportunity to lapse if his prospective profit  $\Pi$  is less than his currently estimated permanent income, which is discussed further below.

The entrepreneur also conducts “market research” before deciding whether to enter. In particular, he sends invitations to two people, one a potential employee and the other a potential customer, to form trading relationships with him if the shop opens. The potential employee accepts if the shop’s wage  $w$  exceeds his current “effective wage,” and the potential customer accepts if the shop’s planned retail price  $p$  is less than his current “effective price.”<sup>4</sup> If either invitee declines, the entrepreneur allows the opportunity to lapse.

If all these tests pass, the entrepreneur opens a shop with an “input target” equal to  $x^{\text{trg}} = y^{\text{trg}} + F + \lambda_I (y^{\text{trg}} - I)$ , where  $\lambda_I$  is the weekly inventory adjustment speed and  $I$  is current inventories, which, for a new shop, are just equal to the entrant’s legacy inventories. Implicit in this equation is a desired inventory level equal to one week’s sales.

**Search and matching.** Next, each person is given an opportunity to search for possible trading relationships. Each person who is not a shop owner engages in job search with probability  $\sigma$ . Job search consists in asking one “comrade” (someone with the same production good) what his effective wage is. If this exceeds the searcher’s current effective wage, then the searcher will ask the comrade’s employer for a job. The employer will take on the new worker if his last period’s labor input does not exceed his current input target.

Store search is undertaken by every person. The searcher first asks a “soulmate” (someone with the same consumption goods) for his effective retail prices, and then asks a randomly chosen shop if it has a posted price for one of the searcher’s consumption goods. For each of his consumption goods, the searcher decides to switch, to either the soulmate’s shop or to the randomly located shop, or decides to stay with his current shop, depending on which choice yields the lowest effective price.

**Bond market trading.** Next, everyone goes to the bond market. First, the government redeems all bonds. At this point, all the financial wealth  $A$  of any transactor is in the form of money. Then, each person decides on this week’s planned consumption expenditures  $E$ . He first adjusts his permanent income according to the adaptive rule  $\Delta Y^p = \lambda_p (Y - Y^p)$ , where  $Y$  is actual income (either wages or profit) from the previous period and  $\lambda_p$  is the weekly permanent income adjustment speed. He then adjusts permanent income for estimated weekly inflation. Finally, he sets planned consumption equal to a fixed fraction  $v$  of total wealth.<sup>5</sup> Total wealth is  $A$  plus any legacy inventories plus the expected present value of his

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<sup>4</sup>The notions of effective wage and effective price are defined further below.

<sup>5</sup>In AGH (2011), we point out that such an expenditure function would apply if the person knew for certain his future incomes and interest rates, and if he were choosing  $E$  to maximize an intertemporally additive logarithmic utility function with a weekly rate of time preference  $\rho_w = v/(1 - v)$ , subject to the usual lifetime budget constraint. We use this interpretation of the expenditure function when calibrating the model, and will calibrate it in terms of the annual rate of time preference  $\rho$ , defined by  $(1 + \rho) = (1 + \rho_w)^{48}$ .

estimated permanent income. In calculating the latter, he makes use of inflation and interest rate projections provided by the central bank.

People then adjust their portfolios. Someone that does not own a shop retains  $E$  in the form of money and invests  $A - E$  in bonds. However, if  $E > A$ , he holds all of  $A$  in money. A shop owner goes through a similar procedure except that his desired money holding is the amount needed to cover not only his planned consumption expenditure but also his target wage bill, which is his current wage rate times his input target  $x^{\text{trg}}$ .

**Labor and goods market trading.** This stage starts with trade in the firesale markets, where inventories can be purchased at a discounted price from former shop owners. Next, each person in turn engages in labor market trading (with his employer) and goods market trading (with his stores). Labor market trading proceeds as follows. If the person has an employer with positive money holdings, he offers to trade his endowment in exchange for the effective wage  $w^{\text{eff}} = \min\{w, M\}$ , where  $w$  is the employer's posted wage and  $M$  is the employer's money holdings just prior to this trade. The employer accepts the offer unless the shop's labor input already exceeds its input target and the ratio of inventory to sales target exceeds a critical threshold value  $IS > 1$ .

Goods market trading happens in the following manner. First, the customer learns the price  $p_i$  currently posted by each of his two stores ( $i = 1, 2$ ). Then, when a person visits a store with positive inventory  $I$ , he can place an order for some amount  $c_i$ , subject to a cash-in-advance constraint. The store then sells the person an amount  $c_i^{\text{eff}} = \min\{c_i, I\}$ . The person's effective price for that good is defined as  $p_i^{\text{eff}} = p_i c_i / c_i^{\text{eff}}$ . However, if  $I = 0$  or the person does not have a store for that good, the person's effective price is set to infinity.

Each customer chooses his desired consumption bundle  $(c_1, c_2)$  to maximize his utility function  $u(c_1, c_2) = c_1^{\varepsilon/(\varepsilon+1)} + c_2^{\varepsilon/(\varepsilon+1)}$  with a "demand parameter"  $\varepsilon > 0$ , subject to his budget constraint. If he has established relationships with stores for both of his consumption goods, the budget constraint is  $p_1 c_1 + p_2 c_2 = E$ . However, if he has a relationship with only one store, he spends the entire amount  $E$  on that shop's good.

**Monetary policy.** Every fourth week, the central bank sets the rate of interest  $i$  according to the Taylor rule,  $\ln(1 + i) = \max\{\ln(1 + i^*) + \gamma_\pi [\ln(1 + \pi) - \ln(1 + \pi^*)] + \gamma_y [y - \tilde{y}], 0\}$ , where  $\gamma_\pi$  and  $\gamma_y$  are fixed coefficients,  $1 + \pi$  is the inflation factor over the past 12 months,  $\pi^*$  is the fixed inflation target,  $y$  is the current 3-months moving average for the weekly average log GDP,  $\tilde{y}$  is the central bank's evolving estimate of weekly log potential output, and  $i^* \equiv r^* + \pi^*$ , where  $r^*$  is the evolving target for the long-run real interest rate.

Since the central bank cannot be presumed to know the economy's natural interest rate or potential output, it must estimate them adaptively. Accordingly, it adjusts  $r^*$  up or down

depending on whether the current inflation rate exceeds or falls short of the inflation target  $\pi^*$ , with an adjustment speed  $\eta_r$ . It also estimates  $\tilde{y}$  as the long-run expected value of  $y$  under an AR(1) process whose parameters are re-estimated right after  $r^*$  is adjusted. To provide people with interest rate projections to use in planning their consumption, it also estimates an AR(1) process for inflation and feeds the predictions of its estimated AR(1) processes for  $y$  and  $\pi$  into its Taylor rule.<sup>6</sup>

**Match breakups.** Established trading relationships may break up randomly. In particular, each person in the economy who does not own a shop is subjected to a probability  $\delta$  of quitting the labor and goods markets, which entails the unconditional severance of all current trading relationships by the person with his employer and his stores.

**Fiscal policy.** Next, once a year, and in the last week of the year, the retail sales tax rate  $\tau$  is adjusted. The government sets the tax rate equal to a value  $\tau^*$ , which is the value that would leave the debt-to-GDP ratio undisturbed in the no-shock equilibrium outlined in Section 4, plus an adjustment factor that is proportional to the difference between the actual and the target debt-to-GDP ratio  $b^*$ , with a fiscal adjustment coefficient  $\lambda_\tau$ .

**Exit.** Now, each shop has an opportunity to exit. First, each shop exits for exogenous reasons with probability  $\delta$ . Second, each remaining shop can choose voluntarily to exit if the shop owner is “hopeless,” that is, if his financial wealth  $A$  is not enough to pay for the coming week’s fixed overhead cost. Third, each unprofitable shop exits with probability  $\phi$ . In computing profitability, the shop owner takes into account the opportunity cost of his labor services, that could be earning a wage, and the interest-opportunity cost of maintaining the shop’s inventory. Once a shop exits for any reason, all trading relationships (with both employees and customers) are dissolved.

**Wage and price setting.** Finally, each shop has an opportunity to update its posted wage and retail price. The shop first sets its sales target equal to the current week’s actual sales and adjusts its input target accordingly. Then, it proceeds to update its wage but only if the last wage change was  $\Delta$  weeks ago. Its wage adjustment will be a proportion  $\beta$  of the percentage deviation of the shop’s input target from the amount of labor it has been offered in the trading process, plus an adjustment for expected inflation. Its retail price can be adjusted each period to retain its markup over marginal cost. The “normal” retail price involves the fixed markup  $\mu$ . However, if the shop’s inventories are too far from its target

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<sup>6</sup>There are 4 parameters that are used to initialize the central bank’s adaptive learning processes. These include the initial target real interest rate,  $r_0^*$ , the initial estimate of log potential output,  $\tilde{y}_0$ , and the initial estimates of the autocorrelation coefficients for output and inflation,  $\hat{\lambda}_{y0}$  and  $\hat{\lambda}_{\pi0}$ . In addition, we assume that the central bank begins to adjust all estimates and targets after  $T_{cb}$  years.

sales, that is, if the inventory-to-sales ratio passes one of the critical thresholds  $IS$  and  $1/IS$ , it will adjust its price below and above, respectively, by the fixed factor  $\delta_p$ .

## 4 The workings of the model

As the preceding discussion has made clear, all shocks in this economy are individual shocks. Nevertheless, the individual shocks that cause matches to break up and shops to enter or leave particular markets do have aggregate consequences because there is only a finite number of agents. So, in general, the economy will not settle down to a deterministic steady state unless we turn off these shocks. If we do turn off all shocks, there is a deterministic equilibrium that the economy would stay in if left undisturbed by entry and breakups, with wages being adjusted each week ( $\Delta = 1$ ). This equilibrium will serve as an initial position for all the experiments we perform on the model below.

The equilibrium is one in which all the potential gains from trade are realized. Each person is matched with one employer and two stores. There are  $n$  shops, one trading in each of the  $n$  goods. To preserve symmetry across goods, we suppose that each good is the primary consumption good for exactly one shop owner. Each shop begins every week with actual, potential, and target input all equal to  $n - 2$ , which is the number of suppliers of each good, and with actual and target sales equal to inventory holdings equal to actual output:  $n - 2 - F$ . Thus, the economy's total output equals full capacity:  $y^* = n(n - 2 - F)$ .

In AGH (2011), we characterize the rest of this equilibrium, which will repeat itself indefinitely, with all nominal magnitudes – money and bond holdings, actual and effective wages and prices, and permanent incomes – rising each week at the constant target rate of inflation, provided that the fixed cost of operation  $F$  is small enough that shops always pass the profitability test during the exit stage.

Inflation has almost no effect in this flexible-price equilibrium without any shocks. There will be a minor effect on the equilibrium tax rate  $\tau$  because, with higher inflation, the government is collecting more seigniorage and, hence, can maintain its target real debt level with a lower sales tax. However, aggregate output and employment will be unaffected, the real rate of interest will remain equal to the rate of time preference, and the volatility of output and inflation will remain equal to zero.

When the shocks are turned on, the economy ceases to track full employment and full capacity. In particular, GDP falls whenever a shop that was satisfying some consumers goes out of business or a customer loses a store because of a random breakup. GDP also falls whenever a new shop enters and diverts workers from old shops that were satisfying some

customers, because some of these workers' efforts will now be used up in deferring the fixed cost of the new shop rather than producing goods that can be consumed by customers of the old shop.

These events that reduce GDP are constantly being offset to some degree by the entry of new shops that are able to satisfy customers in markets where there had previously been no viable shop, and by the exit of shops that were using up fixed costs but not producing enough to satisfy their customers. Thus, both entry and exit are critical to the system's ability to approximate full-capacity utilization. However, although entry of new shops is useful in markets where there are no incumbents, or where the incumbents are not hiring all the potential workers because of layoffs or because of financial problems that prevent them from meeting their payroll, entry can be harmful (to the level of real GDP) in cases where incumbent shops were hiring most of the potential workers and satisfying most of the potential customers. Likewise, although exit is important in cases where the shop has ceased to play an active intermediation role, whether because of financial difficulties, a surfeit of inventories, or a too high markup, exit can also be very harmful in cases where the incumbent was previously doing well, because it can cascade across markets causing a cumulative loss of output (Howitt, 2006).

The effects of the shocks will tend to be larger when inflation is higher because inflation introduces an extra source of dispersion in relative prices, given that individual prices are changed at random times, and it does so by a larger percentage amount the higher is the trend inflation rate. This dispersion in relative prices induces variability in each shop's sales and, hence, in profitability, and the concomitant widening of the distribution of profitability ends up putting more firms near the edge of failure, making it more likely for firms to fail due to a random shock to innovation or match breakup. The bigger is the fixed cost and the smaller is the markup, the more likely is such a shock to trigger the failure of the shop. Thus, a higher target rate of inflation intensifies the propagation of shocks through the failure of trading enterprises. To explore this mechanism in more detail, however, we need first to calibrate the model and then simulate it under different target inflation rates.

## 5 Calibration

This section briefly describes our calibration procedure, but for further detail we refer the reader to AGH (2011). There are a total of 25 parameters to be calibrated. This is less than the 33 parameters in AGH (2011) because 7 of those pertained to the behavior and

TABLE 1: The calibrated parameters of the model

<u>Personal parameters</u>				
$\rho$	Rate of time preference (annual)	0.04	TMPRFY	1
$\varepsilon$	Demand parameter	7.0	DMDELS	1
$\delta$	Quit rate (per week)	0.001	BRKFRC	3
$\lambda_p$	Permanent income adjustment speed (weekly)	0.3	INCSPD	3
$\sigma$	Job search probability	0.5	SRCHPP	3
$\theta$	Frequency of innovation (weekly)	80	INFREQ	3
<u>Shop parameters</u>				
$\Delta$	Length of the contract period (in weeks)	48	CNTPRD	1
$F$	Fixed cost	3.5	FXDCST	1
$\lambda_I$	Inventory adjustment speed (weekly)	0.16	INVSPD	1
$\beta$	Wage adjustment coefficient (annual)	0.3	WAGSPD	1
$\mu$	Percentage markup over variable costs	0.13	MARKUP	1
$\phi$	Failure rate of unprofitable shops (weekly)	0.015	FAILRT	3
IS	Critical inventory/sales ratio	2.0	TRIGGR	3
$\delta_p$	Size of price cut (old price/new price)	1.0075	PDELTA	3
<u>Government policy parameters</u>				
<i>Fiscal Policy</i>				
$b^*$	Target Debt-GDP ratio	0.33	BNDINC	1
$\lambda_\tau$	Fiscal adjustment speed (annual)	0.054	FSCSPD	1
<i>Monetary Policy</i>				
$\hat{\lambda}_{\pi 0}$	Inflation autocorrelation coefficient (initial estimate)	0.29	INFCOR	1
$\hat{\lambda}_{y 0}$	Output autocorrelation coefficient (initial estimate)	0.66	GAPCOR	1
$\gamma_\pi$	Inflation coefficient in Taylor rule	1.5	INFTYR	1
$\gamma_y$	Output gap coefficient in Taylor rule	0.5	GAPTRY	1
$\pi^*$	Annual target inflation rate	0.03	PITRGY	1
$r_0^*$	Initial target real interest rate	0.035	RRTTRG	2
$\tilde{y}_0$	Initial estimate of log potential output	7.6	GAPTRG	2
$\eta_r$	Adjustment speed of evolving real rate target	0.0075	ADJRRT	3
$T_{cb}$	Number of years before central bank's learning begins	15	LRNLAG	3

regulation of banks, which are absent from the present setup.<sup>7</sup> These parameters can be categorized as shop parameters, personal parameters, and government policy parameters. They are listed in Table 1 along with their assigned values, their six-letter codes used in Figure 3, and their levels of calibration as explained in the rest of this section.

<sup>7</sup>Another parameter from the earlier paper that we have suppressed here is the setup cost of opening a shop, which we have set to zero because most entrepreneurs will not be able to finance this cost without the help of a banking sector.

TABLE 2: U.S. data vs. median outcomes in the model

Variable	Data	Model
Inflation	3.0	3.0
Real interest rate	1.8	3.5
Unemployment rate	6.1	6.2
Unemployment duration	14	9.8
Volatility of output gap	2.0 to 3.2	2.6
Volatility of inflation	1.3	0.50
Autocorrelation of gap	20 to 76	31
Autocorrelation of inflation	16	17
Exit rate	46	35
Job loss rate	0.69	0.66
Price change frequency	4.0	4.3

Our calibration took place at three different levels. At the first level, one subset of parameter values was chosen to match empirical counterparts in the U.S. data and/or to match values used in previous studies. The 14 parameters with a “1” in the fifth column of Table 1 were calibrated this way, and they take on the same values as in AGH (2011) but with one exception. The exception is the markup, which was uniformly distributed across shops in the earlier paper where the mean of this distribution was calibrated at the second level. Here, in our baseline calibration, we keep the markup fixed across shops at 13 percent, which falls within the 10 to 20 percent range of markup estimates cited by Golosov and Lucas (2007), but we relax this assumption in Section 7 below.

At the second level, the values of other parameters were chosen to be internally consistent with the central tendency of simulation outcomes. The two parameters with a “2” in the fifth column of Table 1 were calibrated this way, namely the initial values of the government targets for log potential output and the real interest rate. We used an adaptive procedure to select each value so that it would equal the median outcome of the targeted variable across simulations.

The remaining 9 parameters, indicated with a “3” in the fifth column of Table 1, were calibrated at the third level. The values of these parameters, for which we could find no convenient empirical counterparts, were chosen so as to make median outcomes across simulations (loosely) match certain properties of the U.S. data. More specifically, we ran 10,000 simulations of 60 years. Each 60-year simulation began near the no-shock equilibrium and continued for 20 years before we started calculating the average value of each outcome variable across the remaining 40 years of that simulation. This was done to eliminate transient effects due to initial conditions. For each variable, we then computed

the median of these cross-year averages across all simulations.<sup>8</sup> The 11 outcome variables to which we calibrated these parameters are listed in Table 2, along with their data values and their median values in our fully calibrated model. All numbers are expressed in percentage points, except for unemployment duration, which is expressed in weeks, and price change frequency, which is expressed in numbers per year.

## 6 Main results

In order to assess the effect of higher inflation on macro performance, we simulated the model while varying the central bank’s target rate of inflation. Specifically, we conducted an experiment in which, for each integer-valued inflation target from 0 to 10, we ran 10,000 60-year simulations of the model economy. For each set of simulations (or “runs”), we recorded the cross-run median of the 40-year average value of each of 5 different macroeconomic indicators: the log output gap, the unemployment rate, the annual inflation rate, the volatility of output, and the volatility of inflation.<sup>9</sup>

The results of this experiment are reported in Figure 1. The most salient finding is a monotonic deterioration in performance of all 5 indicators for target inflation rates between 3 and 10 percent per year. Over this range, the median output gap increased by over 5 percent while median unemployment rose by over 6 percentage points. Median output volatility nearly doubled while median inflation volatility rose by about 40 percent. In addition, over the whole range, the median inflation rate rose approximately point for point with the inflation target, indicating that the central bank does typically hit its long-run target in the model.

During some simulations, our model economy crashed, in the sense that the log output gap became infinite in finite time. Further, we observed that the incidence of these crashed runs increased monotonically with the target inflation rate. Specifically, while we did not observe any crashes for low inflation targets, the fraction of crashed runs increased from 0.07 percent at the 5 percent target to 17.7 percent at the 10 percent target. Given that we omitted crashed runs from the sample when calculating the cross-run medians, the adverse effect of inflation on economic performance in our model is presumably higher than what is reported in Figure 1.

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<sup>8</sup>Because the absence of banks by itself tends to make the economy operate further from capacity, we could not use the same values of these 9 level-3 parameters as in AGH (2011).

<sup>9</sup>The output gap is defined as the ratio of capacity to actual GDP. For each run, the volatilities of output and inflation are measured as the standard deviations of the annual time series of log GDP and year-to-year percentage inflation respectively.

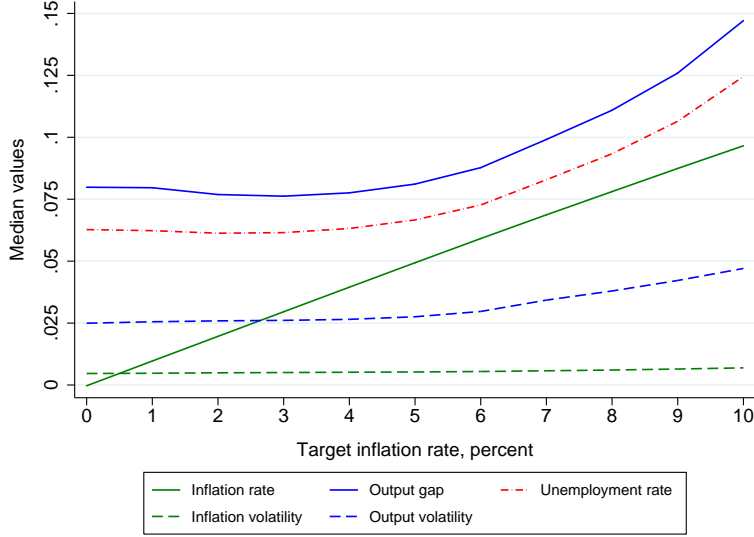


FIGURE 1: Inflation and macroeconomic performance

For low rates of target inflation, that is, between 0 and 3 percent, the results shown in Figure 1 indicate little or no deterioration as inflation rises. Indeed, it seems that the economy performs slightly better at 3 percent inflation than at zero inflation, at least in terms of output and unemployment, although both measures of volatility are virtually constant over this range. Exactly why there is this small beneficial effect of inflation at very low rates is not something we have managed to answer. There is apparently more going on than the zero lower bound on nominal interest rates since, when we suppress that lower bound by allowing the nominal interest rate to become negative, we get almost identical results in terms of our macro indicators between 0 and 3 percent target inflation.<sup>10</sup>

The deterioration in performance when target inflation rises above 3 percent is significant not just economically but also statistically. The left panel of Figure 2 shows, for each inflation rate, the 95 percent confidence intervals for the output gap and the unemployment rate based on our simulation sample. The confidence interval bands are narrow, and their bounds are rising monotonically for inflation rate targets between 3 and 10 percent. Similar results were found for all our other macro indicators. Thus, it seems certain that the monotonic deterioration we have found is indeed implied by the model and is not just a result of sampling error from too small a number of simulations.

Given that there was indeed considerable variation in outcomes across runs even when all parameters were held constant, there exists a significant chance that an increase in target

<sup>10</sup>Of course, negative nominal interest rates are not consistent with our assumption that the cash-in-advance constraint is binding on households, but we retained that assumption in any event just to see what difference it made when the central bank was freed from the zero lower bound constraint.

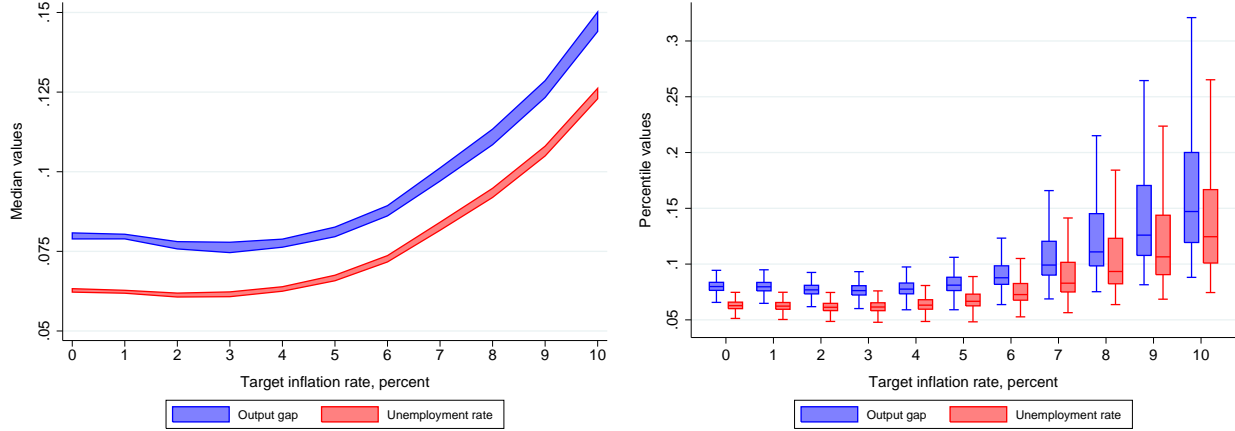


FIGURE 2: Statistical significance of the main results

inflation might not cause a deterioration in macro performance. This is indicated by the box-and-whisker plots on the right panel of Figure 2. For each inflation target, and for both the average output gap and the average unemployment rate, the plots show the interquartile range, the median, and the 5th and 95th percentiles of the cross-run distributions. As is apparent from the diagram, although there is considerable overlap of the interquartile ranges between contiguous inflation targets, we still observe a monotonic upward shift of the distribution of possible outcomes as target inflation rises above 3 percent.

To check the robustness of our main findings to variations in parameter values, we conducted a sensitivity analysis. We did this one parameter at a time and for all the 25 parameters of the model, except for the target inflation rate. Specifically, for each of these 24 parameters, we redid our experiment assuming that the parameter value was first 25 percent higher than in the baseline calibration and then 25 percent lower. In the case of 5 parameters, the model crashed more than 90 percent of the time at one of these extremes when the inflation target was 10 percent, so we reduced the variation to plus or minus 10 percent. In one of those cases, namely the fixed cost, there was still more than a 90 percent incidence of crashes, so we reduced the variation to plus or minus 5 percent. Our confidence in our results was increased when we found, without exception, that the monotonic increase in the output gap, unemployment, and output volatility, as the inflation target increases from 3 to 10 percent, survived the variations in the parameter values. The same was largely true of the monotonic increase in inflation volatility.<sup>11</sup>

<sup>11</sup>There were two very minor exceptions to the robustness of the monotonic effect of target inflation above 3 percent on inflation volatility. First, with the demand parameter at 25 percent above its baseline value, an increase in the inflation target from 4 to 5 percent reduced median inflation volatility by 1/50-th of a basis point. Second, with the wage adjustment coefficient at 25 percent below baseline, median inflation volatility

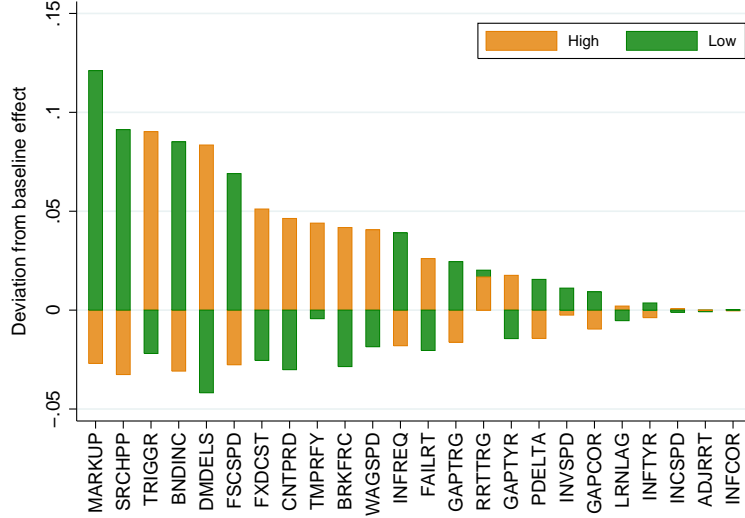


FIGURE 3: Sensitivity of the main results to baseline parameter values

This sensitivity analysis also helped us to understand which of the parameters in the model are most critical for our main results. Figure 3 shows how sensitive the effect of trend inflation on the output gap is to parameter variations. We measure this effect as the difference between the cross-run median output gaps observed under the 3 and 10 percent inflation targets. For each parameter and for each of its high and low values, the figure thus plots the difference between the effect observed under this value and that observed under the baseline calibration. This analysis shows that, of all the parameters in the model, the most critical one appears to be the markup even though we are only considering variations of plus or minus 10 percent for this parameter. This finding will be used in section 7 below where we address the Lucas critique.

Our interpretation of the deterioration of macro performance when trend inflation rises above 3 percent focuses on the costs of maintaining the trading facilities that are necessary for economic transactions. Specifically, given that price changes are not perfectly coordinated across shops, an increase in inflation should create an artificial increase in the dispersion of relative prices, that is, an increase unrelated to tastes for consuming and technology for producing the wares of different sellers. This will clearly add to the volatility and unpredictability of demand faced by any seller, making it more likely that some sellers will be at risk of failure because of an inability to cover their fixed overhead costs. The result should be a reduction in the number of shops, an increase in the number of potential

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fell by 1/10-th of a basis point for an increase in target inflation from 4 to 5 percent, and by 2/25-ths of a basis point for an increase in target inflation from 5 to 6 percent.

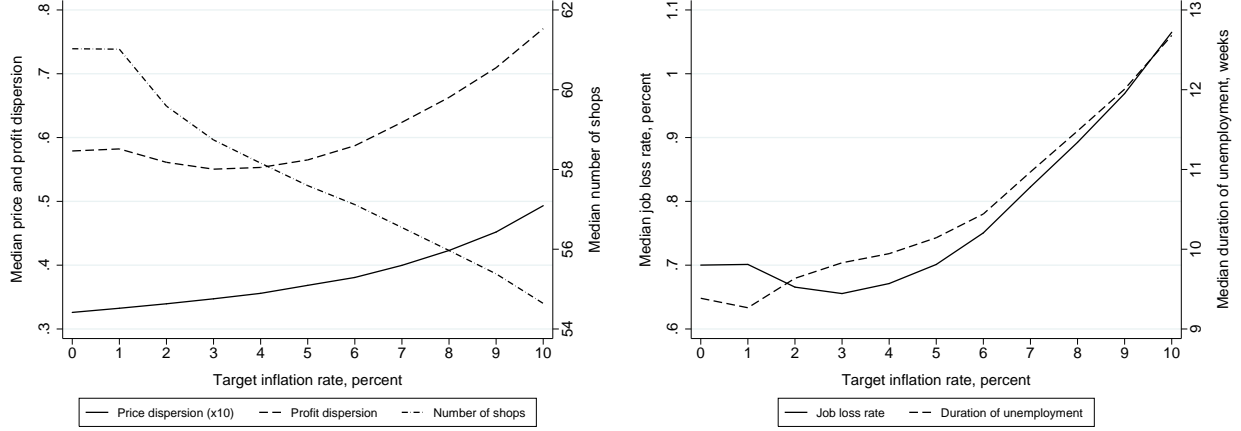


FIGURE 4: Identifying the mechanism behind the main results

transactions that go unconsummated for lack of a trading facility, and, hence, a fall in the level of economic activity and a rise in the rate of unemployment.

This interpretation is consistent with the facts shown in Figure 4. Specifically, the left panel of the figure shows that, as the inflation target rises from 3 to 10 percent, there is indeed a monotonic increase in both sales-weighted price and profit dispersion across sellers. This panel also shows that the annual average number of shops in the median run declines monotonically over this range. While this decline is only on the order of 10 percent, it is economically significant in an economy that needs at least 50 shops to function at peak efficiency and has only a 20 percent margin of redundant shops (60 shops in total) when target inflation is at 3 percent. The right panel of Figure 4 shows that, with target inflation increasing from 3 to 10 percent, both the job loss rate and the duration of unemployment increase substantially and monotonically, which is what one would expect if the main effect of increased inflation was working through a higher incidence of business failures and a smaller number of shops offering employment.

We sought further corroboration of our interpretation by running a number of related experiments. First, we suppressed the source of price variability by forcing all wages and prices to be reset every week. As shown in the left panel of Figure 5, this did not eliminate unemployment or the output gap, which are still non zero because of other frictions in the model, but it did cause both indicators to be virtually independent of inflation, suggesting that our main results are indeed attributable to the effects of uncoordinated price changes. Next, we suppressed all turnover in firms, thereby eliminating job loss as a result of shop failures. There was still a monotonic increase in unemployment and the output gap for trend inflation rates higher than 3 percent, but, as shown in the right panel of Figure 5, the increase in each case was much smaller in magnitude than in our main experiment, suggesting that

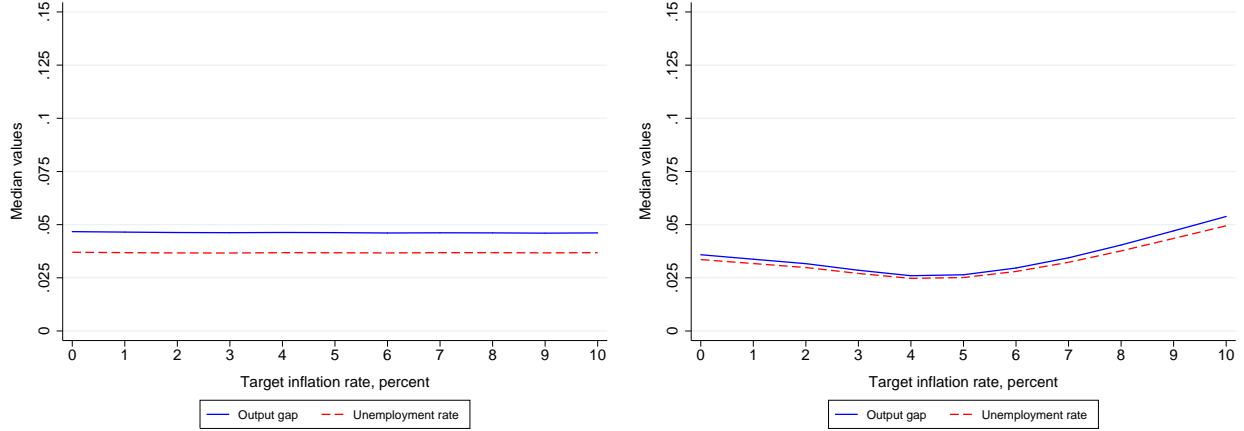


FIGURE 5: Breakdown of the main results under price flexibility and no turnover

much of the deterioration in the main experiment did indeed come from people losing their jobs when shops failed. Finally, we combined the two previous experiments by suppressing price variability and turnover simultaneously. As a result, both the unemployment rate and the output gap fell to about 1 percent for all rates of inflation, suggesting that these two factors taken together are at the root of our main results.

## 7 Lucas critique

Our approach thus far leaves us open to the Lucas critique, namely that our predicted effects of a change in the policy environment may be undone by endogenous changes in behavior due to individual or social learning on the one hand and Darwinian selection on the other. In this section, we discuss how one might address such a critique in an agent-based framework, and we illustrate our strategy with respect to the behavioral parameter identified by our sensitivity analysis as being the most critical for our main results – the markup.

In particular, our analysis thus far begs the question of whether an increase in the trend rate of inflation, which affects the economy by putting more firms at risk of failure, might not naturally induce shops to set a larger markup, thereby delivering them more profits in any given situation and, hence, alleviating the increased failure risk. We address this concern here by modifying our model such that each shop now picks its own markup at birth by drawing from a uniform distribution that changes with the target inflation rate, rather than entering with an identical policy-invariant markup coefficient. This variant of our model essentially permits the economy-wide average markup to respond endogenously to changes

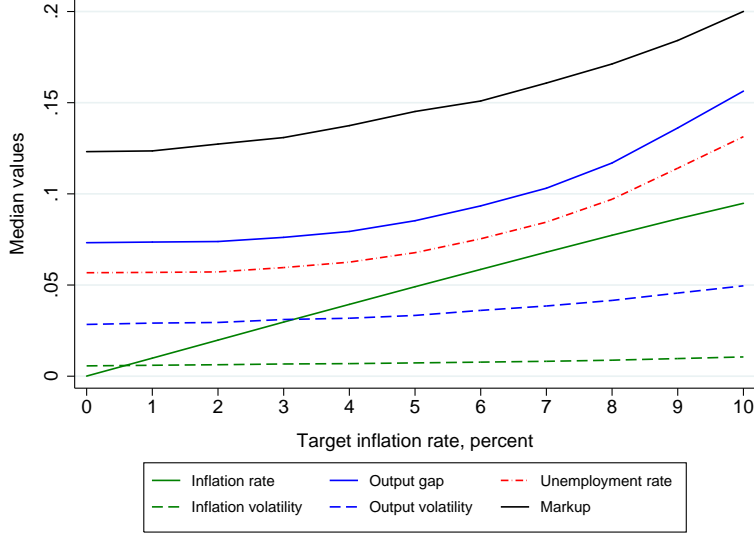


FIGURE 6: The main results under endogenous markups

in the policy environment through the evolutionary selection mechanism that is implicit in the exit process.

However, in pursuing this strategy, we are left with the difficult task of choosing, for each target inflation rate in our main experiment, the mean of the distribution from which markups are drawn. We decided to let these policy environment-specific means be determined by internal consistency. Specifically, for each target inflation rate, we used an adaptive procedure to select an “equilibrium” value for the mean of this distribution, such that, when new entrants draw from this distribution, the “median markup” (that is, the cross-run median of the 40-year average of the economy-wide average markup) ends up being equal to that value. Having thus determined the means of the policy environment-specific distribution from which markups are drawn, we then reconducted our main experiment using this alternative version of our model.

The results of our exercise are shown in Figure 6. As is evident from the figure, surviving markups do indeed respond to changes in the policy environment, being systematically higher on average the higher the target inflation rate. Specifically, the “median markup” rises monotonically from 13 to 20 percent as the target inflation rate increases from 3 to 10 percent. Interestingly, however, as shown in the figure, allowing for this endogenous response of markups does not seem to mitigate the deleterious effects of inflation uncovered by our baseline analysis under fixed markups. For instance, with endogenous markups, as the target inflation rate rises from 3 to 10 percent, the median output gap increases by 7.2 percent while median unemployment rises by 7.7 percentage points. We conclude that, at least with respect

to endogenous variations in markups, our estimates of the macroeconomic costs of inflation are less vulnerable to the Lucas critique than one might think.

## 8 Cross-country regressions

As already discussed, existing empirical studies have generally failed to uncover a systematic relationship between long-run inflation and the level or growth of GDP at the country level. In attempting to address the discrepancy between this finding and our numerical results, we proceeded to quantify the likelihood that, under the null hypothesis that our baseline calibrated model were the true data generating process, a cross-country regression of GDP on the observed rate of inflation would yield a statistically insignificant effect.

To accomplish this task, we needed to generate a large number of artificial cross-country samples using our model. We did this by focusing on a sample of 63 countries, and for each country in this sample, we set the target rate of inflation in our baseline calibrated model equal to the country's actual trend inflation rate during the 1960-2009 time period before simulating the model 5000 times over.<sup>12</sup> For each country, this yielded 5000 artificial histories of the 40-year average values of the log output gap and the annual inflation rate, thereby allowing us to construct just as many artificial cross-country samples of these two variables. For each artificial cross-country sample, we then ran a regression of the log output gap on the annual inflation rate and recorded the  $t$ -statistic associated with the relevant slope coefficient. The left panel of Figure 7 depicts the histogram of these  $t$ -statistics across 5000 artificial cross-country regressions along with a kernel density estimate of the distribution. Our analysis of this distribution suggests that, in a world described fully by our baseline calibrated model, the likelihood that one would find a statistically insignificant result from running a cross-country regression of GDP on inflation is about 15 percent.

While this likelihood may not seem large, it is certainly significant considering the fact that a cross-country regression in a world described by our model will not be plagued by the same set of endogeneity issues afflicting such regressions in real life. We therefore sought to find an explanation for why, in some states of our model world, a cross-country regression would fail to detect a significant effect of inflation on output. In the course of our investigations, we decided to look at the relationship between the 40-year average values of

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<sup>12</sup>Our sample of 63 countries is based on that used by Levine and Zervos (1993) in their influential paper that finds no relationship between inflation and GDP growth. To be consistent with the range of inflation targets used in our main experiment, we excluded those countries with historical trend inflation rates above 10 percent. We also updated the Levine-Zervos analysis with data for the 1960-2009 time horizon and verified that their baseline cross-country regression of GDP growth on inflation continues to find no statistically significant relationship.

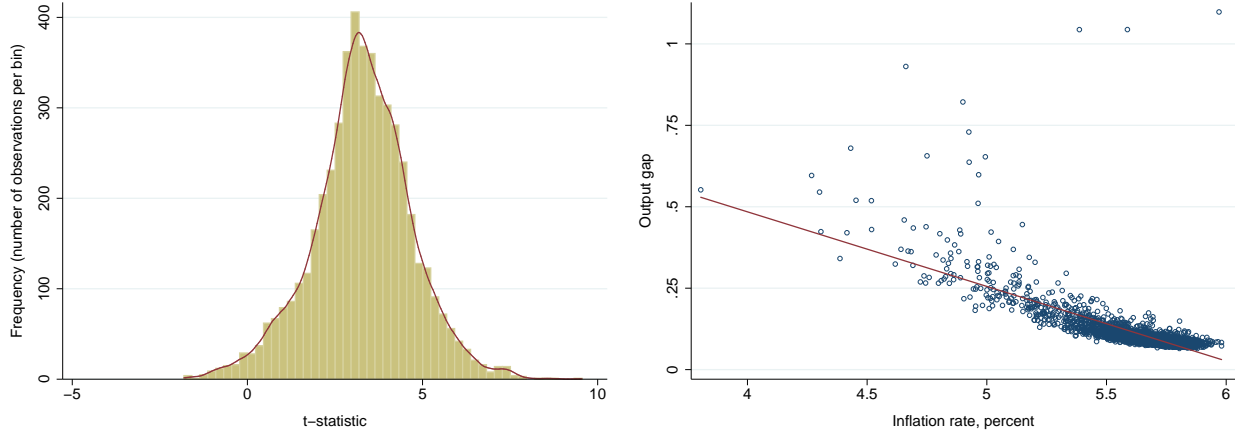


FIGURE 7: Cross-country regression results

the annual inflation rate and the log output gap across country-specific artificial histories, that is, across simulations with the same target inflation rate. For any target inflation rate, what we found was a systematic Phillips-type relationship like the one shown in the right panel of Figure 7 for the country with the median trend inflation rate in our 63-country sample. We hypothesize that this negative Phillips-type relationship between the output gap and actual inflation might be responsible for partially masking the positive causal effect of trend inflation on the output gap in our model.

## 9 Conclusion

In this paper, we use an ACE model to show how inflation can disrupt the mechanism of exchange in a decentralized market economy and, thus, have an adverse effect on macroeconomic performance. The effect works through the increased dispersion of relative prices caused by staggered price setting, which ultimately raises the incidence of failures amongst the specialist trading enterprises crucial for creating and organizing the network of markets that coordinate economic activities.

We find that the trend rate of inflation has a substantial deleterious effect when it rises above 3 percent. Our analysis, however, provides no support for the notion that inflation targets below 3 percent can yield any gains in output or employment. Our main finding remains qualitatively robust to changes in parameter values and to modifications made to our model to partly address the Lucas critique. Finally, we contribute a novel explanation for why it may be difficult to detect a significant negative effect of trend inflation on output in a cross-country context.

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