Market Intelligence Gathering, Asymmetric Information, and the Instability of Money Demand*

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Abstract

The observed money demand in the U.S. had a stable negative relation with the interest rate up until the 1990s. After this period, this relation fell apart and has never been restored. We show that the central bank's ability to gather information, referred to as market intelligence, matters to generate an upward-sloping money demand curve. We calibrate the model to the U.S. data for the period from 1990 to 2019 and show that market intelligence helps to match the money demand. We also show that it is beneficial for the society, since it mitigates the inefficiency associated with asymmetric information.

JEL classification: D9, E4, E5.

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"[Federal Reserve] Staff from the Desk communicate directly with a wide range of financial market participants and other members of the public to gather information on financial market developments, a process known as market intelligence gathering," (FRBNY, 2020).

"Other risks [of market intelligence (MI)] include: being deliberately misinformed by MI contacts; being poorly informed by MI contacts; attempts by MI contacts to unduly influence decisions made by the Bank", (BOE, 2015, p. 9).

1 Introduction

The observed money demand in the U.S. had a different pattern before and after the early 1990s. Before the 1990s, there was a stable negative relation between the money demand and interest rate. This broke down in the 1990s, and became positive for high interest rates, as shown in Figure 1. Standard monetary theory predicts that consumption is decreasing in inflation due to the cost of holding money. Therefore, the transaction demand for money, which is a positive function of consumption, is also decreasing in inflation. By virtue of the Fisher equation, this implies that money demand is negatively related with interest rates.[1] In other words, standard literature on monetary theory struggles to explain the positive relation between money demand and the interest rate. Common explanations of the change in the observed money demand are the increased financial regulation, the introduction of more innovative financial products, and measurement problems associated with monetary aggregates in this period (see, e.g., Reynard, 2004, Teles and Zhou 2005, Ireland 2009, Lucas and Nicolini 2015). Our paper stands apart from this literature as we show that the central bank's ability to gather information, referred to as market intelligence, matters to generate an upward-sloping money demand curve.

The key mechanism of the model is as follows. A high inflation rate increases the buyer's incentive to misreport the true state of the economy when the actual state is low. This is because the higher the inflation rate, the smaller the buyer's surplus in the low state. To counterbalance this higher incentive to misreport, consumption in the high state must increase and stay above the low-state efficient level of consumption. This generates an upward-sloped money demand curve for high interest rates.

One challenge for central bank monetary policy is the uncertainty about the actual state of the economy. A dimension of this uncertainty is related to the fact that published commentary and research, as well as market data, are only available with lags. Even when the market data is

[1] The Fisher equation describes the relation between the nominal interest rate, the real interest rate, and inflation. Therefore, it allows us to write the money demand as a function of the inflation rate or the interest rate, and vice-versa.

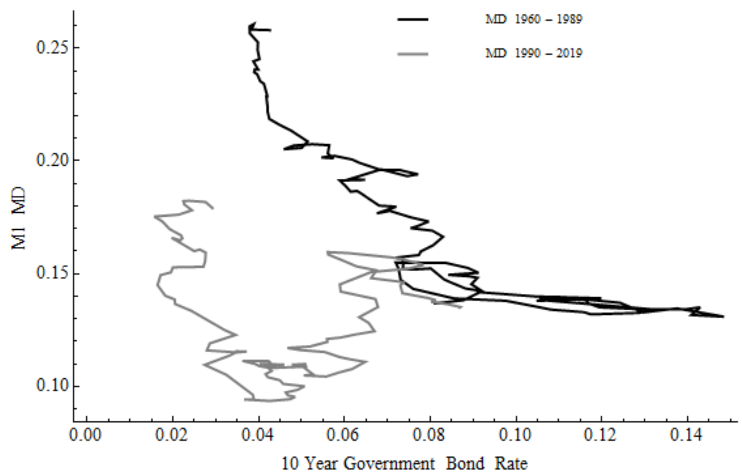

Figure 1: U.S. M1 Money Demand 1960 – 2019

immediately available, it is an imperfect measure of economic activity: it only captures transactions in the formal sector of the economy (see Restrepo-Echavarria, 2015). Central banks also face the challenge of identifying the sources of the uncertainty in the sense that a change in a given indicator, say the gross domestic product, can be the result of different shocks such as a demand shock, a supply shock, or both. Lastly, uncertainty surrounds the timing of the shock and, perhaps most importantly, its sign and magnitude.[2]

Central banks typically complement the analysis of market data with other information they collect by interacting directly with market participants. This is called data gathering or market intelligence gathering. One of the benefits of market intelligence is that it can provide immediate insights into market developments where relevant data is not yet available (e.g., BIS, 2016).[3] It is mainly gathered with contacts through bilateral conversations conducted via telephone, face-to-face meetings, or electronically (e.g., via Bloomberg or Reuters chat rooms, or emails, etc.). One of the risks is that the central bank may be "deliberately misinformed" by the contacted participants. In

[2] In this paper, we restrict our attention to demand shocks only. Therefore, the uncertainty the central bank faces in the model is only part of the whole uncertainty it faces in the real world.

[3] An example of data gathering is the *Beige Book* at the Federal Reserve. This is an "up-to-the-minute resource" for FOMC discussions. It is a report that researchers at the Federal Reserve prepare before each FOMC meeting. It contains key information gathered through contacts with industry and market participants. Market participants typically include primary dealers, central bank counterparties, and other members of the public. At the New York Fed, for example, market intelligence is gathered through "regular conversations between the Desk and members of the public, including primary dealers, other New York Fed counterparties, and a wide range of other market participants" (FRBNY, 2020). See BOE (2015) and Jeffery et al. (2017) on how market intelligence is conducted at the Bank of England.

the most serious cases, contacted participants may attempt to influence decisions made by the central bank (BOE, 2015).

In this paper, we formalize two key aspects of stabilization policy under uncertainty, i.e. asymmetric information and data gathering. Asymmetric information is formalized by assuming that private agents (e.g., households) are fully informed about the realized shocks, but the central bank is not. The idea that the central bank lacks a superior information is not new and can be found, for example, in Lorenzoni (2010). The assumption that the central bank lacks information when it comes to demand shocks is natural and reflects the fact that demand shocks hit households, not the central bank. Indeed, households and the central bank are distinct entities who have different objectives and specialize in different activities. Thus, a micro-founded approach would require that private agents have superior information than the central bank about a shock that hits the former but not the latter.[4] The data gathering process is formalized through a mechanism, designed by the central bank, that allows agents to report (or misreport) the realized shock. In equilibrium, we focus on the set of allocations that satisfy the truth-telling constraint.

Even under symmetric information, we can get an upward sloping money demand relation. This result relies on the curvature of the utility function. Indeed, Proposition 1 shows that a CARA utility function implies a monotonically decreasing consumption, and therefore a monotonically decreasing demand curve.[5] Under asymmetric information with mechanism, in contrast, it is the mechanism that drives the upward sloping money demand relation. This latter result is more general because it does not depend on the choice of the utility function. The asymmetric information case with mechanism is also more realistic than the symmetric information case. If this was not the case, the would be no role for market intelligence in the real world. The evidence shows just the opposite though. As documented in BIS (2016), and more recently in BIS (2023), market intelligence gathering has long been an important tool for central banks to inform monetary policy decisions and implementation, reserves management, and financial risk assessments.[6] The scope and size of market intelligence has expanded in the last two decades to cover new market participants, new asset classes, and new market segments. This also reflects the increased complexity of the economic and financial environment as well as the emergence of new risks such as the 2020 pandemic. One of the main results of this paper is that market intelligence gathering which is formalized in the model as state-contingent monetary

[4] There are cases that we don't study here where the central bank may actually have superior information as compared to private agents. This could be when multiple shocks, such as demand and supply shocks, hit the economy at the same time. As demand and supply shocks separately target households and firms, respectively, the central bank may be the best informed agent given its ability to collect information from both sides. We do not study this possibility in this paper but it would certainly be a direction for future research.

[5] The curvature of the cost function affects the upward sloping relation in a similar way, as shown in the quantitative analysis.

[6] See BIS (2023) for a detailed explanation of the traditional market intelligence strategy and tools.

policy is welfare improving. Furthermore, market intelligence is more beneficial when inflation is higher which is consistent with the fact that an increasing number of central banks in developing countries have used it in recent years.[7] It also suggests that market intelligence will play a much bigger role in many OECD countries in the future, if inflation stays at the current high level.

We calibrate the model to the U.S. data for the period from 1990 to 2019 and we show that the model improves the fit between the model-implied money demand and the observed one, as compared to the Lucas' specifications. The Lucas' specifications imply a monotonically decreasing money demand curve which does not replicate the observed money demand behavior for high interest rates. In contrast, our model-implied money demand, which is U-shaped, replicates the data well for both low and high interest rates.[8]

We also perform a comparative statics exercise and show that implementing a state contingent monetary policy using mechanism design matters for welfare. For example, at the calibrated inflation rate of 2.45%, the welfare benefit of mechanism design is 0.13% of the total consumption. Mechanism design does very well in mitigating the inefficiency generated by asymmetric information in the period after 1990. We find that, in the absence of mechanism design, asymmetric information reduces welfare by 0.13% of total consumption. If mechanism design is used, this welfare loss can be removed completely. For higher inflation rates, the welfare loss due to asymmetric information has a greater magnitude (e.g., 0.34% of total consumption for an annual inflation rate of 10%), which can be reduced substantially (by about 90%) by the use of mechanism design.

There are mainly two approaches in the literature that studies money demand and its instability in the data.[9] One approach is to redefine the money demand by using, or constructing, different monetary aggregates (e.g., Dutkowsky and Cynamon, 2003, Teles and Zhou, 2005, Ireland, 2009, and Lucas and Nicolini, 2015). Most of these papers are of empirical nature or do not have any microfoundations of money. This approach builds on the argument that there is a measurement problem behind the instability of the money demand.

Another approach, which is the one we follow here, is to introduce frictions in the model. These frictions affect the shape of the money demand function and thus help to explain the change in the observed money demand. In an empirical study, Reynard's (2004) finds that financial market participation increased substantially in the 1970s, and argues that this is the main determinant of the downward shift in the observed money demand and its higher interest rate elasticity in the United States. In a microfounded monetary model with full-committment, Berentsen et al. (2015)

[7] See, for example, the case of the Central Bank of Mexico (BIS, 2023).

[8] The reason we restrict our attention to the period from 1990 to 2019 is because of the increased credit market participation and financial innovation that occurred in early 1990s, which made market intelligence gathering more important than before. We show in the Appendix that market intelligence gathering did not play a significant role before 1990.

[9] Some of the first to study the money demand are Baumol (1952), Tobin (1956), Bailey (1956), and Meltzer (1963).

show that financial innovations, such as the introduction of money-market deposit accounts, help to explain the recent trend in the money demand function in the United States. In a similar framework, Berentsen et al. (2018) show that limited commitment can significantly improve the fit between the theoretical money demand curve and the data for several developed economies, compared to a model that assumes full commitment. Our model stands apart from these papers as we study the relationship between market intelligence and money demand by introducing information frictions and mechanism design which are both absent in the above mentioned works.

Our paper belongs to the new monetarist literature extensively discussed in Williamson and Wright (2010), Lagos et al. (2017), and Nosal and Rocheteau (2017). Our basic setup is that of Lagos and Wright (2005), extended to aggregate shocks and asymmetric information. In the model, asymmetric information means that the central bank is not informed about the realization of the shock, but private agents are. We take a mechanism design approach to study the central bank's problem, which is to maximize social welfare subject to the incentive-compatibility constraint that buyers truthfully report their private information. In a related paper, Draack (2018) also assumes aggregate shocks and asymmetric information. However, he models the latter as a signaling game, where the central bank gets to know the realized shock with some probability. There is no mechanism design in his paper and the demand for money is monotonic. In our model, the central bank simply does not know the shock and relies on the use of the mechanism to maximize social welfare.[10]

We are not the first to apply mechanism design to the setup of Lagos and Wright (2005).[11] Previous work has used mechanism design to study optimal trading protocols (Hu, Kennan, and Wallace, 2009), the welfare cost of inflation (Rocheteau, 2012), banking (Gu et al. 2013a), the coexistence of fiat money and higher-return assets (Hu and Rocheteau, 2013), asset bubbles (Hu and Rocheteau, 2015), decentralized efficient allocations (Bajaj et al. 2017), and credit cycles (Gu et al. 2013b, and Bethune, et al. 2018a, 2018b). Unlike these studies, we focus on the recently observed instability of the money demand curve in the U.S. and examine how effective a mechanism is in mitigating the asymmetric information problem between private agents and the central bank.

2 The environment

The basic framework is that of Lagos and Wright (2005). Time is discrete and indexed by $t = 1, 2, ..., \infty$. In each period t, two markets open and close sequentially. The first market is a decentralized market where agents can either produce or consume a special good. The second market is a

[10] In two related papers, Berentsen and Waller (2011) and Boel and Waller (2019) study stabilization policy, but assume perfect information and no mechanism design.

[11] Applications of mechanism design to monetary theory include Kocherlakota (1998), Kocherlakota and Wallace (1998), Cavalcanti and Nosal (2011), and Cavalcanti and Wallace (1999). A literature review is provided by Wallace (2010).

frictionless, centralized market where agents can produce and consume a general good. We refer to these markets as the goods market and the settlement market, respectively. All goods are perishable and perfectly divisible.

The economy is populated by a continuum of infinitely lived agents with measure one. At the beginning of each period an agent is subject to two sequential shocks. The first shock is an idiosyncratic shock that determines whether an agent will be a producer or a consumer in the goods market. With probability n the agent can produce but not consume the special good, while with probability $1-n$ the agent can consume but not produce the special good. We refer to consumers as buyers and to producers as sellers. The second shock is an aggregate shock that affects an agent's desire to consume in the goods market, which is denoted by $\varepsilon > 0$. The desire to consume is low, $\varepsilon = \varepsilon_l$, with probability π_l, and it is high $\varepsilon = \varepsilon_h > \varepsilon_l$, with probability $\pi_h = 1 - \pi_l$. The subscripts l and h stand for low state and high state, respectively.

A buyer enjoys utility $\varepsilon u(q)$ from consuming q units of the special good. The function $u(q)$ is twice continuously differentiable, with $u'(q) > 0$, $u''(q) < 0$, $u'(0) = u(\infty) = \infty$, and $u(0) = u'(\infty) = 0$. A seller suffers a disutility $c(q)$ from producing q units of the special good. We assume a linear cost function in the goods market, $c(q) = q$.[12] There is a general good that can be produced and consumed by all agents in the settlement market. Agents enjoy utility $U(x)$ from consuming x units of the general good, where $U'(x), -U''(x) > 0$, $U'(0) = \infty$, and $U'(\infty) = 0$. They produce the general good with a linear technology, such that x units of the general good are produced with h units of labor, which generates a disutility h. This assumption eliminates the wealth effect, which makes the end-of-period distribution of money holdings degenerate. Agents discount between, but not within, periods at the discount factor $\beta \in (0,1)$.

There is an intrinsically useless object called fiat money in the economy. Money is perfectly storable and divisible. Agents are anonymous in the goods market, thus a medium of exchange is needed for transactions in this market. Since goods are not storable, money is the only object serving this role.

There exists a central bank that controls the money supply. The central bank has long-term and a short-term goals. The long-term goal is aimed at controlling the inflation rate, while the short-term goal is to maximize social welfare. Long term here means *between* periods and short term means *within* a period.

In what follows we focus on symmetric steady-state equilibria where real variables are constant over time. The law of motion of the real money supply between two consecutive periods is

$$\phi_t M_t = \phi_{t+1} M_{t+1},$$

[12] In the quantitative section, we consider also the case of a nonlinear cost function.

where $\gamma = \phi_t/\phi_{t+1} = M_{t+1}/M_t$ denotes the gross growth rate of money supply, the central bank's long-term goal. This goal is achieved through a non–state-contingent money transfer, as is standard. New money is injected ($\gamma > 1$) or withdrawn ($\gamma < 1$) through a lump-sum transfer, $T_t = \phi_t \tau M_t$, to all agents in the settlement market, where τ is the per-unit money transfer and $\gamma = 1 + \tau$.

The short-term goal is achieved through a state-contingent money transfer. Specifically, at the beginning of each period, a benevolent central bank announces a state-contingent money transfer and commits to it. After the aggregate state is realized, but before the goods transactions take place, the central bank injects $\mathcal{T}_{tj} = \phi_t \tau_j M_t$, where $j = l, h$. The transfer, $\mathcal{T}_{tj}$, is undone in the same-period settlement market by injecting $-\mathcal{T}_{tj}$. Therefore, the money transfer between two consecutive periods is non–state-dependent and equal to T_t.

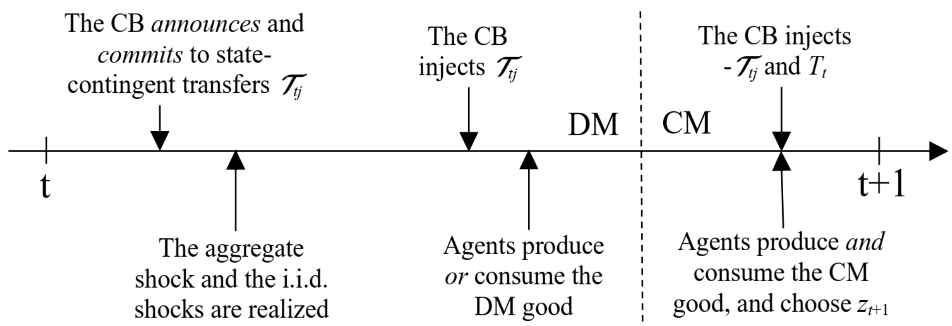

Figure 2: Timing of events

Figure 2 describes the timing of events. At the beginning of each period, a benevolent central bank *announces* and *commits* to a state-contingent money transfer, $\mathcal{T}_{tj}$. Then the aggregate and idiosyncratic shocks are realized. After the shocks are realized, the central bank implements the state-contingent policy, by injecting $\mathcal{T}_{tj}$. Subsequently, buyers consume and sellers produce the decentralized market good. In the centralized market, the central bank injects $-\mathcal{T}_{tj}$ and T_t, while agents produce, consume and decide how much money to carry into the next period.[13]

3 The agent's problem

We characterize the agents' decisions in a representative period and work backwards, from the settlement market to the goods market. To facilitate notation, we omit the state index j in the value functions and introduce it at the end. We also omit the time subscript t and rewrite $t-1$ and $t+1$ by -1 and $+1$, respectively.

[13] In standard time-inconsistency models, the social planner –in our case the central bank– announces and commits at time $t = 0$. This is equivalent to our assumption that both the announcement and commitment are at the beginning of each period because we focus on steady state and each period is the same. The crucial assumption here is that the announcement and commitment take place *before* the aggregate shock is realized.

Real balances $z = \phi m$ are expressed in terms of the centralized market good and they are time invariant in stationary equilibrium. Let $V_2(z)$ denote the value function of an agent entering the settlement market with z units of real balances. Then the agent's problem in the settlement market is

$$V_2(z) = \max_{x,h,z_{+1}} \left[U(x) - h + \beta V_1(z_{+1}) \right]$$

subject to

$$x + \gamma z_{+1} = h + z - \mathcal{T} + T.$$

Agents in the settlement market maximize their lifetime utility by choosing consumption of the general good, x, hours of work, h, and real balances to bring into the next period, z_{+1}, subject to the budget constraint. Eliminating h from $V_2(z)$ using the constraint, the above problem reduces to

$$V_2(z) = z - \mathcal{T} + T + \max_{x,z_{+1}} \left[U(x) - x - \gamma z_{+1} + \beta V_1(z_{+1}) \right].$$

The first-order conditions for this problem are $U'(x) = 1$ and $\gamma/\beta = V_1'(z_{+1})$. Due to the quasi-linearity in consumption, the choice of z_{+1} is independent of z. Therefore, the amount of money an agent brings into the next period z_{+1} is degenerate, a well known result. The envelope condition in the settlement market is

$$V_2'(z) = 1. \tag{1}$$

In the goods market, there are two types of agents: buyers and sellers. Buyers can only consume the special good, while sellers can only produce the special good. We assume the terms of trade in the goods market are determined by competitive pricing.

Let $V_1^s(z)$ be the value function of a seller entering the goods market with z units of real balances. Then, the seller's problem in this market is to choose the quantity of the special good to be produced, q_s, such that

$$V_1^s(z) = \max_{q_s} -q_s + V_2(z + \phi p q_s + \mathcal{T}).$$

The first-order condition for this problem is $1/\phi p = V_2'(z)$, which can be rewritten as

$$1 = p\phi, \tag{2}$$

by (1). The envelope condition is

$$\frac{\partial V_1^s(z)}{\partial z} = 1. \tag{3}$$

Let $V_1^b(z)$ be the value function of a buyer entering the goods market with z units of real balances.

Then the buyer's problem in the goods market is

$$V_1^b(z) = \max_{q_b} \varepsilon u(q_b) + V_2(z - \phi p q_b + \mathcal{T})$$

subject to the constraint $z - \phi p q_b + \mathcal{T} \geq 0$. Buyers in the goods market decide how much to consume, q_b, taking the prices p and ϕ as given, subject to the constraint that they cannot spend more real balances than what they have. Let λ be the Lagrange multiplier for this constraint. Then, using (1) and (2), the first-order condition for the buyer can be rewritten as

$$\varepsilon u'(q_b) = 1 + \lambda. \tag{4}$$

The solution to this is $q_b = q^*$, where q^* satisfies $\varepsilon u'(q^*) = 1$, if the buyer doesn't spend all the money in the goods market, and so consumption is efficient. If the buyer is cash constrained in the goods market, the solution is $q_b < q^*$ and consumption is inefficient. The envelope condition is

$$\frac{\partial V_1^b(z)}{\partial z} = 1 + \lambda. \tag{5}$$

The clearing condition in the goods market implies that in each state, aggregate consumption and aggregate production are the same, i.e.,

$$(1 - n) q_b = n q_s.$$

To simplify notation, we rewrite q_b as q and express q_s in terms of q, so $q_s = \frac{1-n}{n} q$.

The value functions in the goods market are state-dependent. Therefore, the beginning-of-period value function of a representative agent is

$$V_1(z) = \pi_h \left[(1 - n) V_{1h}^b(z) + n V_{1h}^s(z) \right] + (1 - \pi_h) \left[(1 - n) V_{1l}^b(z) + n V_{1l}^s(z) \right]. \tag{6}$$

The first part on the right-hand side of (6) is the agent's expected utility in state h while the second part is the agent's expected utility in state l. The marginal value of money at the beginning of the period is

$$V_1'(z) = \pi_h \left[(1 - n) \frac{\partial V_{1h}^b(z)}{\partial z} + n \frac{\partial V_{1h}^s(z)}{\partial z} \right] + (1 - \pi_h) \left[(1 - n) \frac{\partial V_{1l}^b(z)}{\partial z} + n \frac{\partial V_{1l}^s(z)}{\partial z} \right].$$

Using (3), (4), and (5), $V_1'(z)$ can be rewritten as,

$$V_1'(z) = (1 - n) \left\{ \pi_h \left[\varepsilon_h u'(q_h) - 1 \right] + (1 - \pi_h) \left[\varepsilon_l u'(q_l) - 1 \right] \right\} + 1.$$

We can use (2)–(5), and the first-order condition for the settlement market to obtain,

$$\frac{\gamma}{\beta} - 1 = (1-n)\left\{\pi_h\left[\varepsilon_h u'(q_h) - 1\right] + (1-\pi_h)\left[\varepsilon_l u'(q_l) - 1\right]\right\}. \tag{7}$$

The left-hand side of (7) is the marginal cost of holding money; the right-hand side is the marginal benefit. At the Friedman rule (i.e., $\gamma \to \beta$), consumption is efficient in both states. That is, $\varepsilon_h u'(q_h^*) = 1$ in state h, and $\varepsilon_l u'(q_l^*) = 1$ in state l. There is no cost of holding money, so agents can perfectly insure against any shock by bringing enough money into the next period.

4 The central bank's problem

At the beginning of each period, before the aggregate shock is realized, a benevolent central bank announces and commits to a state-contingent policy that maximizes expected social welfare –the short-term goal– taking as given the agent's decision problem. After the realization of the shock, the central bank implements the announced policy using state-contingent money transfers. Then, agents produce or consume in the decentralized market.

We study two versions of the model. One version where both the central bank and the agents are equally informed about the state of the economy –i.e. they can both observe the aggregate shock once it is realized– and another version where the central bank cannot observe the shock, but agents can. We refer to them as the symmetric information model and the asymmetric information model, respectively. We first analyze the symmetric information model.

In the symmetric information model, the central bank's announces state-contingent quantities q_l and q_h (or money transfers), and commits to them, before the realization of the shock. Therefore, its problem is to maximize the expected social welfare:

$$\max_{q_l, q_h} (1-n)\left\{\pi_h\left[\varepsilon_h u(q_h) - q_h\right] + (1-\pi_h)\left[\varepsilon_l u(q_l) - q_l\right]\right\} + U(x) - x \tag{8}$$

subject to

$$\frac{\gamma - n\beta}{\beta} = (1-n)\left[\pi_h \varepsilon_h u'(q_h) + (1-\pi_h)\varepsilon_l u'(q_l)\right], \tag{9}$$

$$q_h \leq q_h^*, \tag{10}$$

$$q_l \leq q_l^*. \tag{11}$$

The first constraint comes from (7) and means that the central bank takes the agent's decision as given when maximizing the social welfare. The other constraints, (10) and (11), are the individual rationality constraints of a buyer in state h and state l, respectively. They mean that it is never optimal for the buyer to consume more than the efficient quantity. The buyer's participation constraints, i.e., $\varepsilon_h u(q_h) - q_h \geq 0$ and $\varepsilon_l u(q_l) - q_l \geq 0$, are always satisfied when (10), respectively (11), are satisfied. If $\gamma > \beta$, both (10) and (11) are non-binding, and the first-order conditions are

$$\begin{aligned} \varepsilon_l u'(q_l) - 1 + \tilde{\lambda}\varepsilon_l u''(q_l) &= 0, \\ \varepsilon_h u'(q_h) - 1 + \tilde{\lambda}\varepsilon_h u''(q_h) &= 0. \end{aligned}$$

Combining these yields

$$\frac{\varepsilon_h u'(q_h) - 1}{\varepsilon_h u''(q_h)} = \frac{\varepsilon_l u'(q_l) - 1}{\varepsilon_l u''(q_l)}. \tag{12}$$

The solution of the central bank problem is a pair $\{q_l, q_h\}$ satisfying (9) and (12). If $\gamma = \beta$, consumption is efficient and both (10) and (11) bind.

Equation (12) displays the second derivative as well as the first derivative of the utility function. Therefore the agents' risk aversion matters in the symmetric information economy. For a CRRA utility function, which is commonly used for calibration, the curvature of the utility function can play an important role, in such a way that for high inflation rates, consumption in the high state is increasing in the inflation rate, while the low-state consumption is decreasing in the inflation rate. This dynamics may not hold for other specifications such as, for example, CARA utility functions. For CARA utility functions, both the low-state and high-state consumption are decreasing with inflation for *any* inflation rate.

The following Proposition 1 formalizes this result. All proofs are in the appendix.

Proposition 1 *Assume a CARA utility function. Then, if there is symmetric information,* $\frac{dq_h}{d\gamma} < 0$ *and* $\frac{dq_l}{d\gamma} < 0$ *for any* $\gamma > \beta$*. Assume a CRRA utility function. Then, if there is symmetric information, there exists a* $\hat{\gamma}$ *such that* $\frac{dq_h}{d\gamma} < 0$, $\frac{dq_l}{d\gamma} < 0$ *if* $\beta < \gamma < \hat{\gamma}$*; and* $\frac{dq_h}{d\gamma} > 0$, $\frac{dq_l}{d\gamma} < 0$ *if* $\gamma > \hat{\gamma}$.

To summarize, risk aversion plays an important role in shaping consumption, and thus money demand, when the central bank is informed. Throughout the paper, we assume a CRRA specification for the utility function which is a standard practice in the literature. While this choice allows us to make comparisons with other studies, we show later that it is not crucial to obtain an upward sloped money demand when the central bank is *uninformed* but uses the mechanism.

4.1 Asymmetric information

We now consider a more realistic version of the model, where the state of the economy is known by private agents but not by the central bank. We refer to this as the asymmetric information model. Within this framework, we are going to study two subcases: one where the uninformed central bank uses a mechanism to characterize the set of incentive-feasible allocations and the other one where it does not. We devote this section to the former whereas the latter is analysed in the next section.

In the asymmetric information model with the mechanism, the central bank proposes the allocation set $\{q_l, q_h\}$ to each buyer. If a buyer chooses the consumption quantity "q_l", the central bank transfers $\mathcal{T}_l$ to the buyer; if the buyer chooses "q_h", the central bank transfers $\mathcal{T}_h$. The transfers $\{\mathcal{T}_l, \mathcal{T}_h\}$ have the purpose of implementing the proposed allocation set $\{q_l, q_h\}$. An agent truthfully reports whether q_l was chosen in state l or q_h in state h; the agent misreports if q_l was chosen in state h or q_h in state l.

We restrict a buyer's consumption in the goods market to be either q_l or q_h. We require the central bank to have some monitoring power. One way to do this is to assume that monetary transactions—but not goods transactions—in the goods market are perfectly monitored by the central bank. Such an assumption is natural if we think of the central bank as an intermediary in payments.[14] Another way is to assume that money can be counterfeited by buyers (Lester et al., 2012) and the central bank is the only institution capable of detecting counterfeits. Then, a seller who wants to check the genuineness of money needs to hire the central bank. Monitoring financial transactions, but not good transactions, makes sure money is essential but trade credit is not possible, due to lack of commitment.[15]

In general, if a third party is needed for transaction payments —and this role can be taken by the central bank— the third party can observe the monetary transfers. Since the central bank knows each agent's money holdings before the goods transactions occur, it can implement the proposed allocation by simply refusing to execute, or authenticate, a transaction if the buyer does not spend all the money. This means that a buyer who misreports in the low state, by selecting q_h, cannot spend less money than what the buyer has. That buyer receives $\mathcal{T}_h$ and has to spend it all, and purchase q_h, in order for the transaction to be executed.[16]

We study allocations that maximize expected social welfare subject to incentive-compatibility constraints. The incentive constraints require that buyers truthfully report the actual state of the economy.

[14] This is the case for electronic payments where a third party, typically a financial intermediary, is needed for the transaction. The financial intermediary can see how much we spend with our debit card, credit card, or bank account. However, it may not know the quantity and quality of the goods and services we are buying. We recognize that the financial intermediary is typically a bank, not the central bank. We also claim that the central bank may own, or supervise, financial intermediaries, and thus have access to this information.

[15] See Rocheteau and Nosal (2017, Chapter 2) Sanches and Williamson (2010), Gu et al. (2013b) for models of credit economies where money is not essential.

[16] This is consistent with the assumption that agents' actions are voluntary. Agents are not forced to spend all their money in a good transactions. They can always offer less money that what they have, in which case the central bank will refuse to authenticate the transaction and the outcome will be autarky with zero payoff. As a result, no deviation from either q_l or q_h is profitable.

The central bank's problem in this environment is

$$\max_{q_l, q_h} (1-n)\{\pi_h [\varepsilon_h u(q_h) - q_h] + (1-\pi_h)[\varepsilon_l u(q_l) - q_l]\} + U(x) - x \tag{13}$$

subject to (9), and

$$\begin{aligned} \varepsilon_l u(q_l) - q_l &\geq 0, & (14)\\ \varepsilon_h u(q_h) - q_h &\geq 0, & (15)\\ \varepsilon_l u(q_l) - q_l &\geq \varepsilon_l u(q_h) - q_h, & (16)\\ \varepsilon_h u(q_h) - q_h &\geq \varepsilon_h u(q_l) - q_l. & (17) \end{aligned}$$

The constraints (14) and (15) are the buyer's participation constraints in state l and state h, respectively. The constraints (16) and (17) are the incentive-compatibility constraints. Among all the allocations, they select those that are compatible with truth-telling. The constraint (16) means that a buyer in state l will be weakly better off by consuming q_l instead of consuming q_h. Similarly, the constraint (17) means that a buyer in state h is weakly better off by consuming q_h rather than consuming q_l.

It is evident that a buyer never misreports in the high state, i.e., (17) is never binding. However, the buyers may or may not misreport in the low state.

Lemma 2 *A type-I equilibrium is a time-invariant path $\{q_l, q_h\}$ satisfying (9) and*

$$\frac{\varepsilon_h u'(q_h) - 1}{\varepsilon_h u''(q_h)} = \frac{\varepsilon_l u'(q_l) - 1}{\varepsilon_l u''(q_l)}. \tag{18}$$

In a type-I equilibrium, buyers in the low state will always be better off by reporting the true state and the central bank problem with the mechanism reduces to that with symmetric information. Therefore, the set of incentive feasible allocations with the mechanism is identical to that with symmetric information.

Lemma 3 *A type-II equilibrium is a time-invariant path $\{q_l, q_h\}$ satisfying (9) and*

$$\varepsilon_l u(q_h) - q_h = \varepsilon_l u(q_l) - q_l. \tag{19}$$

In a type-II equilibrium, the binding truth-telling constraint implies $q_h \geq q_l^*$ when $q_l < q_l^*$.[17] This induces the buyers to report the true state of the economy. To see this, suppose $q_l < q_l^*$. Then, in

[17] A more detailed analysis of consumption dynamics, and why risk aversion does not matter, in the type-II equilibrium is in the Appendix.

order for the buyer to truthfully report in state l, lying must yield a lower surplus which can only happen if $q_h \geq q_l^*$. Indeed, a buyer who misreports in state l has to consume q_h. However, the surplus from consuming q_h is lower than that from consuming q_l only if $q_h > q_l^*$. The higher the q_h the smaller the surplus from misreporting, when $q_h > q_l^*$.

Proposition 4 *There exists a cutoff value $\tilde{\gamma}$ such that the asymmetric information equilibrium under state-contingent monetary policy is characterized by Lemma 2 if $\gamma < \tilde{\gamma}$ and by Lemma 3 if $\gamma > \tilde{\gamma}$. If $\gamma = \tilde{\gamma}$ then the two equilibria are identical.*

For low inflation rates, the cost of holding money is low. Hence, the central bank provides agents with higher transfers (in real terms), which allow them to consume more in both states. This means that a buyer's surplus from consumption is high and close to the efficient one, both in the low state and the high state, when γ is low and close to β. In this case, buyers in the low state have no incentive to misreport (type-I equilibrium). As γ increases, however, a buyer's surplus from consumption reduces because the central bank transfers less money in real terms. For $\gamma > \tilde{\gamma}$, inflation reduces buyers surplus in the low state so much that the truth-telling constraint must bind to induce them to truthfully report. The binding truth-telling constraint forces consumption in the high state to be above the low-state efficient level of consumption, thus making misreporting unprofitable in the low state.

4.2 Discussion

To discuss the above results, the left diagram in Figure 3 displays the consumption in the goods market as a function of the inflation rate, in the low state and high state, for the symmetric information model (dashed line) and the asymmetric information model with the mechanism (gray line). The first thing to note is that the two models achieve the same allocation for sufficiently low inflation (i.e., $\gamma < \tilde{\gamma}$). This is because agents have no incentive to misreport in the low state for low inflation rates. Although the central bank cannot observe the shock, the mechanism reveals the actual state of the economy. For low inflation, the symmetric information model is equivalent to the asymmetric information model with the mechanism.

In contrast, for sufficiently high inflation (i.e., $\gamma > \tilde{\gamma}$), the two models yield different allocations. There are some similarities in the consumption behavior though. As shown in the diagram, consumption in the low state is decreasing in inflation, while consumption in the high state is increasing, for high inflation. This common pattern in the high state is counterintuitive at first, and it relies on different assumptions in the two models.[18] In the asymmetric information model with the mechanism,

[18] In traditional monetary models, we should expect a decrease in consumption as inflation increases. This is because inflation acts as a tax on consumption.

consumption in the high state is increasing in inflation because of the truth-telling constraint (16) which is binding for high inflation. Therefore, the mechanism is what makes consumption upward sloping. Consumption in the high state must be larger —in the low state it must be smaller— as inflation gets higher in order to induce a buyer to truthfully report in the low state. The higher the inflation rate, the smaller the buyer's surplus in the low state, therefore the stronger the buyer's incentive to misreport. To counterbalance this higher incentive to misreport, consumption in the high state must increase and be above the low-state efficient level of consumption. In the symmetric information model, it is the assumption regarding risk aversion that makes consumption in the high state increasing in inflation, as shown by Proposition 1. For the CRRA utility function, the coefficient of absolute risk aversion, $-u''(q)/u'(q)$, is decreasing in q. By (12), this means that consumption in the two states does not behave similarly as inflation increases: for high inflation, (12) implies that consumption in the low state is decreasing in inflation while consumption in the high state is increasing in inflation. In other words, the choice of the utility function matters to have an upward-sloped consumption in the high state when the central bank is informed, but it does not when the central bank is uninformed and uses a mechanism.

The right diagram in Figure 3 shows that both models predict an upward-sloping theoretical money demand for high inflation rates. This matters for the calibration, as it enables us to fit the observed money demand well, as we will show in the quantitative section.

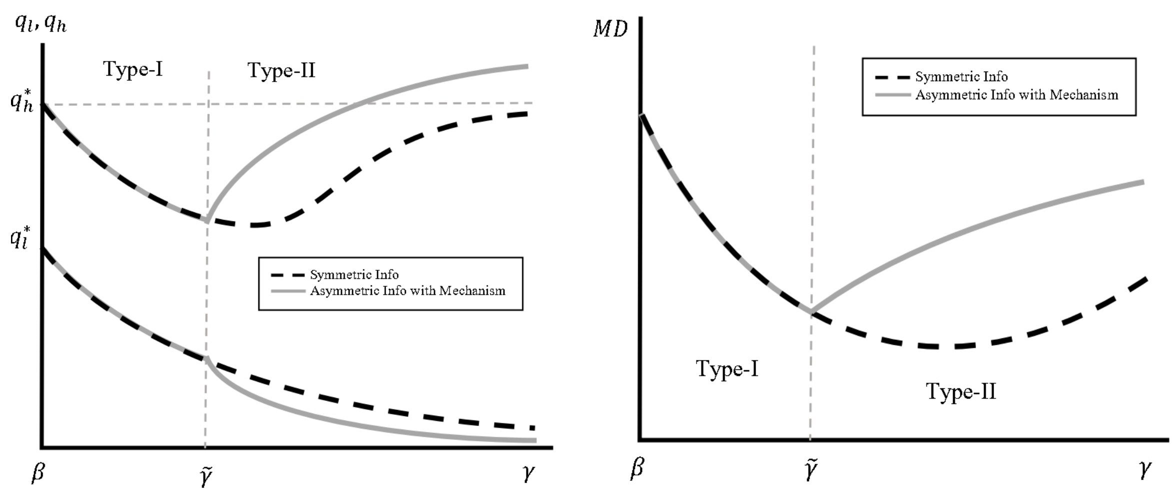

Figure 3: Consumption and Money Demand

Figure 4 displays the welfare level in the case of symmetric information (dashed line) and asymmetric information with mechanism (gray line). For low inflation, welfare is clearly the same in the two cases because the allocation is the same. For high inflation, the symmetric information model attains a higher welfare than the asymmetric information model with the mechanism.

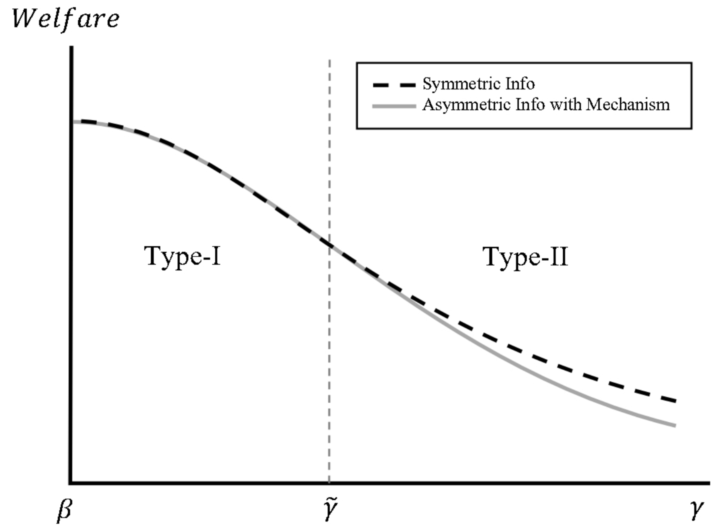

Figure 4: Welfare Comparison

This is because the central bank problem in the latter case has one additional constraint than in the former case –that is the constraint (16)– which is binding for high inflation. This shrinks the set of incentive feasible allocations that can be implemented in the asymmetric information economy with mechanism, as compared to that with symmetric information, and therefore welfare.

5 Optimal policy

Does the mechanism matter for the allocation and welfare? Does it matter for explaining the money demand behavior after the 1990s? Should the central bank adopt a state-contingent monetary policy, via the mechanism, or simply ignore such a mechanism and stick to a non–state-contingent policy? To answer these questions, we now study a version of the model where the central bank does not implement the mechanism, and compare it with that with the mechanism.

The model we present here is exactly the same as that in the previous section, except that there is no mechanism in place; agents are not required to report to the uninformed central bank. In such an environment, the central bank's problem is

$$\max_{q_l, q_h} (1-n)\left\{\pi_h\left[\varepsilon_h u\left(q_h\right)-q_h\right]+\left(1-\pi_h\right)\left[\varepsilon_l u\left(q_l\right)-q_l\right]\right\}+U(x)-x$$

subject to (9), (14), (15) and

$$0=\left(q_l^*-q_l\right)\left(q_h-q_l\right). \tag{20}$$

One can immediately see that the truth-telling constraints are no longer in the problem. Without the mechanism in place, the actual state of the economy is now unknown to the central bank.

Consequently, the central bank's monetary policy is non–state-contingent; i.e. the beginning-of-period money injection is the same across states. It is still possible, however, that consumption is different in the two states. This is the case if the central bank's non–state-contingent money injection is sufficiently large (in real terms).

The fact that consumption may depend or not on the state of the economy is captured by the second constraint in the central bank's maximization problem, $0 = (q_l^* - q_l)(q_h - q_l)$. This constraint admits two solutions: $q_l^* = q_l$ and $q_h = q_l$. For low inflation, a buyer holds sufficient real money balances to consume the efficient quantity of goods in the low state; in the high state, however, they are unconstrained and consume the efficient quantity, if $\gamma = \beta$, or they are cash constrained and consume the inefficient quantity, if $\gamma > \beta$. We label this case as type-A equilibrium. For sufficiently high inflation, buyers in the low state are also cash constrained, which means consumption is the same in both states. We label this case as type-B equilibrium. We formalize this as follows.

The solution to the central bank's problem in the asymmetric information model without the mechanism is a pair $\{q_h, q_l\}$ satisfying

$$\frac{\gamma - n\beta}{\beta(1-n)} = \pi_h \varepsilon_h u'(q_h) + (1 - \pi_h), \tag{21}$$

$$q_l^* = q_l, \tag{22}$$

in the type-A region, and a pair $\{q_h, q_l\}$ satisfying

$$\frac{\gamma - n\beta}{\beta(1-n)} = [\pi_h \varepsilon_h + (1 - \pi_h)\varepsilon_l] u'(q_l), \tag{23}$$

$$q_h = q_l, \tag{24}$$

in the type-B region.

Figure 5 display consumption quantities in the three equilibria formalized above (black lines). At the Friedman rule ($\gamma = \beta$), consumption is efficient in both states ($q_l = q_l^* < q_h = q_h^*$). In the type-A equilibrium ($\beta < \gamma < \bar{\gamma}$), consumption is efficient in the low state but it is inefficient in the high state ($q_l = q_l^* < q_h < q_h^*$). In the type-B equilibrium ($\gamma > \bar{\gamma}$), consumption is inefficient in both states ($q_l = q_h < q_l^* < q_h^*$). In this last case, consumption must also be the same in both states. The cut-off inflation rate that separates the type-A and type-B regions satisfies:

$$\frac{\bar{\gamma} - n\beta}{\beta(1-n)} = \pi_h \frac{\varepsilon_h}{\varepsilon_l} + 1 - \pi_h. \tag{25}$$

As displayed in Figures 5, consumption variability across states is higher in the economy with mechanism (gray lines) than it is in the economy without it (black lines). This is in sharp contrast with standard consumption smoothing theory and has the following rationale. If there is a mechanism in place that can be used to infer the state of the economy, the central bank allows buyers to consume more in the high state and less in the low state, as compared to the case where no mechanism exists. This improves welfare because agents have a desire to consume more in the high state and less in the low state.

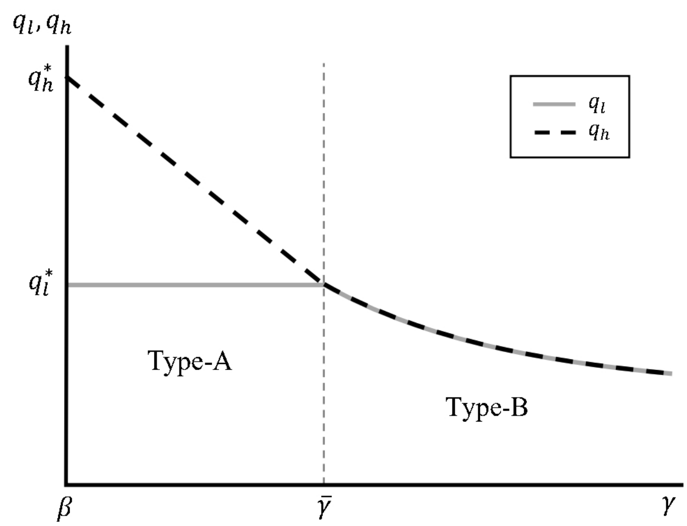

Figure 5: Goods Market Consumption

The welfare improving role of the mechanism is formalized in the following Proposition.

Proposition 5 *For any $\gamma > \beta$, a state-contingent monetary policy via the mechanism described by the problem (13) subject to (9) and (14)-(17) is welfare improving.*

The idea behind Proposition (5) is that any allocation that is implemented in the economy without the mechanism would still be feasible, but it is never implemented, in the economy with the mechanism. Hence, the chosen allocation in the latter must be better than that in the former. As a result, the mechanism is welfare improving.

To summarize, the central bank is completely uninformed about the state of the economy in the asymmetric information model without the mechanism. Hence, its short-term goal, which relies on state-contingent money transfers, cannot be achieved. For low inflation, the cost of holding money is low, so agents have enough money to buy the efficient quantity of goods in the low state, but not in the high state. As inflation increases, agents economize on money holdings. Above a given threshold, $\bar{\gamma}$, agents economize so much on money holdings that they are cash constrained in both states. Adding the mechanism to this economy improves the allocation, as thus welfare, as it allows the central bank to infer the actual state of the economy and implement state-contingent allocations across states. Consumption is more valued by agents in the high state than in the low state, thus consumption (or money transfer) should be higher in the former than in the latter to be welfare improving.

6 Comparative Statics

In this section we perform some comparative statics analysis, both analytically and numerically. More specifically, we analyse how welfare and the cut off inflation rate depend by π_h and n. We derive analytical results for the symmetric information case and the asymmetric information case without mechanism. For the asymmetric information case with mechanism we solve the model numerically.

In all cases, we find that the expected welfare is increasing in π_h and decreasing in n. This is because a higher probability of the high state occurring translates into higher expected consumption, and therefore higher expected surplus and welfare. Similarly, a larger fraction of buyers (i.e. a smaller n) has a positive effect on the expected welfare because buyers take all the surplus from trade.

These results can be summarized by the following Proposition.

Proposition 6 *In equilibrium,*
(i) $\frac{\partial W}{\partial \pi_h} > 0$ *and* $\frac{\partial W}{\partial n} < 0$ *in the symmetric information case with a CARA utility function, and;*
(ii) $\frac{\partial W}{\partial \pi_h} > 0$ *and* $\frac{\partial W}{\partial n} < 0$ *in the asymmetric information case without mechanism*

We solve the asymmetric information case numerically and results are consistent with those in Proposition 6, as displayed in Figure 6.

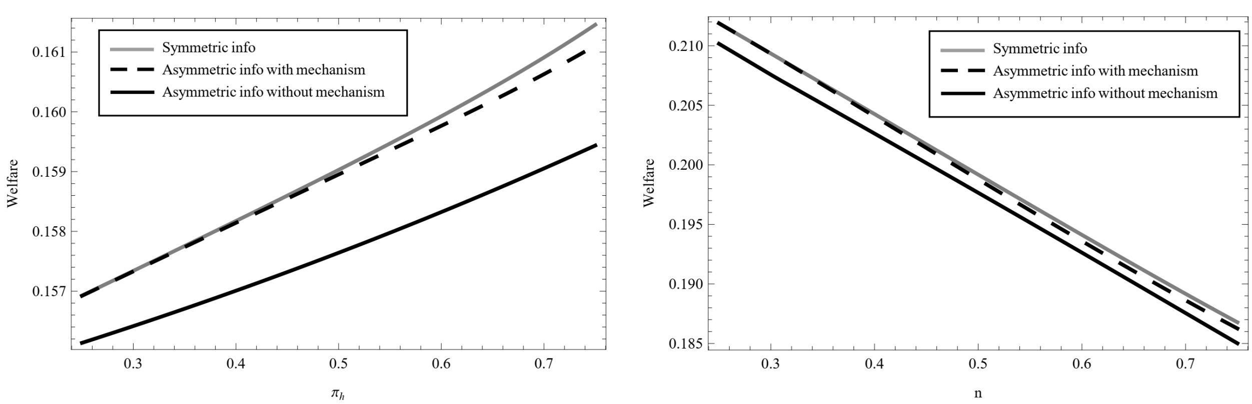

Figure 6: Effects of π_h and n on welfare

Figure 6 also shows that there are cutoff values $\tilde{\pi}_h$ and $\tilde{n}$ (not reported in the Figure) such that the economy is in the type-I equilibrium for π_h and n below the cutoff values. In this region, we know the allocation is the same in the symmetric information case and the asymmetric information case with mechanism, which is where the dashed line and gray line overlap. For values of π_h and n sufficiently close to 1, the economy is in the type-II region, where the symmetric information case (gray line) attains a better allocation than the asymmetric information case with mechanism (dashed line).

The following Proposition characterizes the effects of π_h and n on $\bar{\gamma}$.

Proposition 7 *In equilibrium,* $\frac{\partial \bar{\gamma}}{\partial \pi_h} > 0$ *and* $\frac{\partial \bar{\gamma}}{\partial n} < 0$.

Numerical solutions show that $\tilde{\gamma}$ is decreasing in both π_h and n, for a wide range of parameters. Figure 7 displays the different patterns for $\tilde{\gamma}$ and $\bar{\gamma}$ as a function of π_h and n.

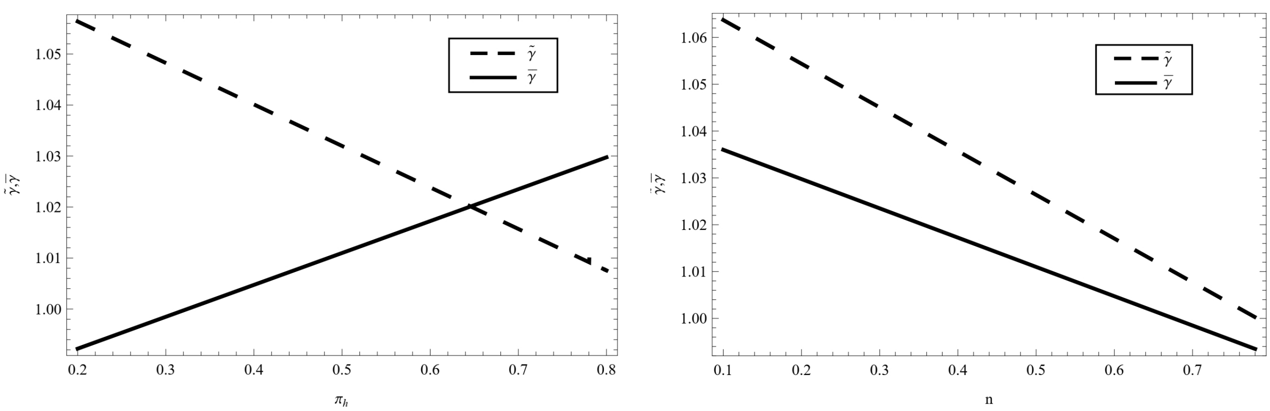

Figure 7: Effects of π_h and n on $\tilde{\gamma}$ and $\bar{\gamma}$

In other words, for a given inflation rate, the chances that the economy is in the type-II region are higher when π_h and n are large, because larger π_h and n are associated to a smaller $\tilde{\gamma}$. Similarly, the type-B equilibrium is more likely to occur for large values of n. However, a larger π_h increases $\bar{\gamma}$ which reduces the chances of a type-B equilibrium occurring in the symmetric information case without mechanism.

7 Quantitative Analysis

We can now compare the asymmetric information models, with and without the mechanism, and address some of the key questions highlighted above. We calibrate the three models to the U.S. economy, for the period starting 1990, and compare the best fit calibration. We compute the welfare cost of inflation for the three models and show that the mechanism explains the observed behavior since the 1990s of the U.S. money demand reasonably well.

7.1 Calibration

We calibrate the three models and compare them with the fits of the two empirical methods proposed by Lucas (2000). Lucas considers two functional forms for the money demand: the log-log and semi-log specifications. The log-log money demand is defined as $\mathcal{MD}(i) = Ai^{-\alpha}$, where i is the nominal interest rate, and A and α are parameters; the semi-log money demand is defined as $\mathcal{MD}(i) = Ae^{-\alpha i}$. For both functions, we estimate the parameters A and α using nonlinear least squares.[19]

The calibration of our three models is more sophisticated. We assume a period length of one year, and therefore we annualize all data accordingly. The functional forms used in the calibration are $u(q) = Aq^{1-\alpha}/(1-\alpha)$, $U(x) = x^{1-\alpha}/(1-\alpha)$, and $c(q) = q$.

Compared to previous studies, our models have three additional parameters to be identified: the demand shocks in the two states, ε_l and ε_h, and the probability of the economy being in the high state, π_h. For calibration purposes, we focus on symmetric shocks with expected value equal to 1, and therefore $\varepsilon_l = 1-\Delta_\varepsilon$, $\varepsilon_h = 1+\Delta_\varepsilon$, $\pi_h = 0.5$. This reduces the number of parameters to calibrate from three (namely, $\varepsilon_l, \varepsilon_h, \pi_h$) to one (namely Δ_ε). We can interpret Δ_ε as the percentage change of an agent's desire for consumption with respect to the steady state consumption.[20]

The parameters to be identified are the following: (i) the preference parameters β, A, Δ_ε, and α; and (ii) the technology parameter n. We identify these parameters using quarterly U.S. data, from 1990 to 2019.[21] The preference parameter $\beta = (1+r)^{-1} = 0.9797$ is chosen such that the real interest rate in the model, r, replicates the empirical one, which is measured as the difference between the average annual yield on government bonds with a maturity of 10 years and the average annual change in the consumer price index.[22] In search-based monetary models, the measure of sellers n is often set to 0.5 in the calibration in order to maximize the number of matches. To be consistent with these studies, we do the same here. Table 1 shows the targets that are matched directly with the moments in the data.

[19] See Craig and Rocheteau (2008) for an application and a detailed explication of this method.

[20] In an earlier version of the model, we relax $\pi_h = 0.5$ but keep the assumption of symmetric shocks, and we show that the main results are not affected qualitatively.

[21] A detailed data source is provided in the Appendix. All data used in this paper was obtained from the FRED database, which is maintained by the Federal Reserve Bank of St. Louis. Our main analysis focuses on the period from 1990 because this is when financial innovation and increased financial market participation occurred. In the Appendix, we calibrate and discuss the calibration results also for the periods from 1960 to 1989 and from 1960 to 2019.

[22] Some studies use the yield on corporate bonds with a remaining maturity of 20 years instead (e.g., Aruoba et al. 2011). Here, we use the 10-year government bonds because this measure is widely available across countries and thus can be useful for future comparison.

Table 1: Calibration targets from 1990 to 2019.[a]

Target description	Target value
Average real interest rate r	0.021
Average 10-year government bond yield	0.046
Average inflation rate	0.024
Average velocity of money	7.87

[a] Table 1 reports the calibration targets and the target values. We can match these targets exactly.

The remaining parameters A, Δ_ε, and α are identified as follows. The parameter Δ_ε is chosen to match the empirical elasticity of money demand with respect to the interest rate. The parameters A and α are jointly chosen by minimizing the sum of squared differences between the model-implied and the observed money demand.[23] The model-implied money demand comes from the Quantity Theory equation, and is given by the inverse of the velocity of money

$$MD = \frac{\pi_h q_h + (1-\pi_h)\, q_l}{x + (1-n)\left[\pi_h q_h + (1-\pi_h)\, q_l\right]}.$$

The calibration results of our models in the cases of symmetric information, asymmetric information with the mechanism, and asymmetric information without the mechanism, are reported in Table 2. Table 2 also reports the estimates of the Lucas' methodology.

Table 2: Calibration from 1990 to 2019.[a]

Methodology	A	α	Δ_ε	$\widetilde{\gamma}$	Δ	Σ sq. diff.
Symmetric Info.	0.894	0.09	0.003	-	0.0027	0.0428
Asymm. Info. with Mechanism	0.77	0.152	0.059	1.0246	0.0067	0.0499
Asymm. Info. without the Mechanism	0.398	0.515	0.131	1.0554	0.0041	0.0694
Log-Log	0.079	0.16	-	-	0.0019	0.0647
Semi-Log	0.146	2.38	-	-	0.0121	0.0706

[a] Table 2 presents the calibrated values for the key parameters A, α, and Δ_ε. It also shows the values of the critical gross rate of growth of money supply, $\widetilde{\gamma}$, and the welfare cost of inflation, Δ. The last column displays the sum of squared differences between the model-implied money demand and the observed money demand.

The asymmetric information model with the mechanism has the second best fit, with a sum of squared differences between the model-implied and the observed money demand equal to 0.0499. The

[23] An alternative way to go is to choose A to match the empirical velocity of money, and jointly choose Δ_ε and α to minimize the sum of squared differences between the model-implied and the observed money demand. This alternative calibration does not affect the results.

The assumption of price taking, as opposed to Nash bargaining, simplifies our calibration as there is one less parameter to identify, the bargaining weight.

best fit calibration is provided by the symmetric information model, with a sum of squared differences equal to 0.0428.

The preference shock parameter, Δ_ε, is 5.9% in the case of the asymmetric information model with mechanism design, and 0.3% in the case of the symmetric information model. The values of the other parameters, A and α, are in line with previous studies. In all cases, eliminating 10% inflation is worth less than 1% which is in line with the literature. The welfare cost of inflation is higher in the asymmetric information cases, with mechanism (0.67%) and without mechanism (0.41%), than it is for the symmetric information case (0.27%).[24]

The asymmetric information model without the mechanism is the worst in fitting the data, with a sum of squared differences of 0.0694. The Lucas' Log-Log and Semi-Log specifications do not perform much better than that, with a sum of squared differences equal to 0.0647 and 0.0706, respectively. The best fit calibration of these models is shown in the right panel of Figure 8.

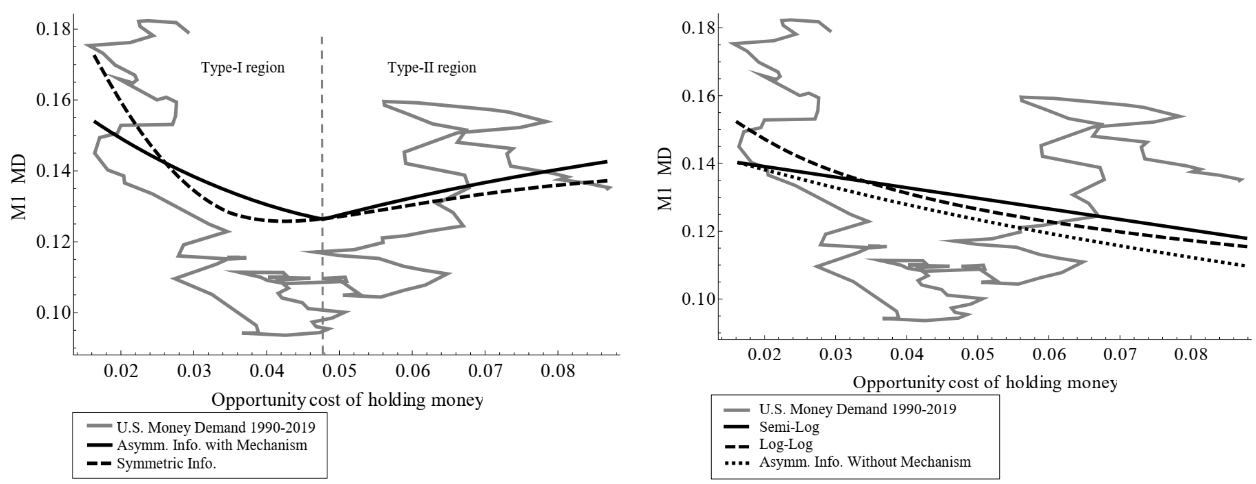

Figure 8: Best Fit Calibration

The left panel of Figure 8 displays the best fit calibration for the symmetric information model and the asymmetric information model with the mechanism. Both models feature a U-shaped model-implied money demand that is downward sloping for low inflation rates and upward sloping for high inflation. This pattern replicates the observed money demand behavior and is the reason why these models perform better in fitting the data. In contrast, the model-implied money demand behaves differently for the other three models. The right panel of Figure 8 shows that it is monotonically decreasing in the inflation rate for all of them.

[24] We compute the welfare cost of inflation Δ as the percentage of the special good consumption an agent is willing to give up to be at an inflation rate of 3% instead of an inflation rate of 13% (Craig and Rocheteau, 2008).

7.2 Welfare benefit of mechanism design

Is the mechanism beneficial for the society? Does it help to mitigate the inefficiency generated by asymmetric information? To answer these and other questions we compute the welfare benefit of the mechanism. We measure it as the percentage of consumption an agent is willing to give up to be in the asymmetric information economy with the mechanism instead of the asymmetric information economy without the mechanism. This analysis is purely static and the parameters to be used in the calculation are those calibrated to the asymmetric information model with the mechanism—our baseline model. Holding these parameters constant, we then compute the welfare benefit of the mechanism as described above.

We also compute the welfare cost of asymmetric information as the percentage of consumption an agent is willing to give up to be in the symmetric information economy instead of the asymmetric information economy without the mechanism. The sum of the welfare benefit of the mechanism and the welfare cost of asymmetric information gives us the combined effect of the mechanism and asymmetric information on welfare.

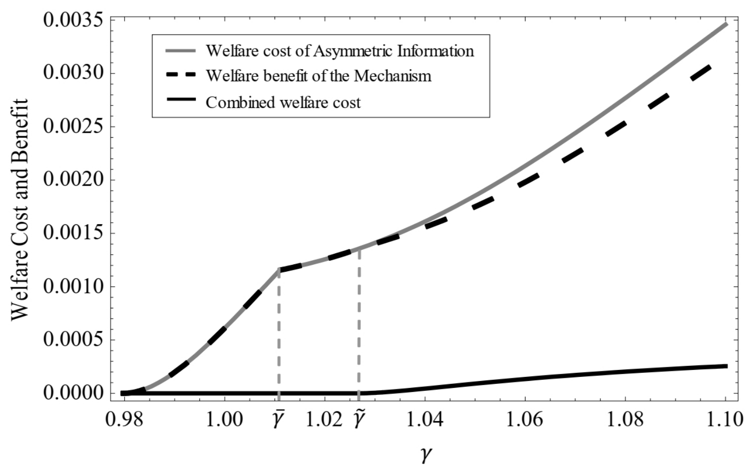

Figure 9: Welfare Cost of Asymmetric Information

Figure 9 displays the welfare benefit of mechanism design (dashed line) and the welfare cost of asymmetric information (gray line) as a function of γ. It also displays the combined effect (black line) as the sum of the two. Firstly, it is immediate to see that both measures are positive and increasing as inflation grows. Thus, having a mechanism in place is generally beneficial for the society, but it is more beneficial in economies with a higher inflation than in those with low inflation. At the same time, the asymmetric information problem is more severe in economies with higher inflation. Secondly, for a sufficiently low inflation (i.e. $\gamma \leq \tilde{\gamma} = 1.0246$), the combined welfare effect of asymmetric information and mechanism design (dark line) is zero. In other words, the mechanism eliminates the asymmetric information problem completely for low inflation. This is because the baseline model (i.e. the model with the mechanism) collapses to the symmetric information model, by definition, if inflation is low enough. The dashed and gray lines have a kink at $\gamma = \bar{\gamma} = 1.011$ simply because the model with asymmetric information without the mechanism is used to compute the welfare effect in both cases. As the two lines overlap, the kink does not affect the combined effect in this calibration. Thirdly, for sufficiently high inflation (i.e. $\gamma > \tilde{\gamma} = 1.0246$), the welfare cost of asymmetric information dominates the welfare benefit of the mechanism. In this case, the mechanism reduces the asymmetric information problem, but does not eliminate it completely.

At the calibrated inflation rate of 2.4% for the U.S. –not reported in the Figure– the composite welfare cost is zero (as $\gamma \leq 1.0246$) and the welfare benefit of having the mechanism is 0.13% in terms of GDP consumption. Thus, for the U.S., the mechanism eliminates the asymmetric information problem. For comparison, at an hypothetical inflation rate of 10%, the composite welfare cost would be 0.025%, but the welfare benefit of having the mechanism would be 0.3% in terms of GDP consumption. In this case, the mechanism would not eliminate the asymmetric information problem, but it would reduce it by more than 90%. This may suggest that having the mechanism is more beneficial when inflation is high.

7.3 Nonlinear cost function

We now check for robustness using a nonlinear cost function, $c(q) = q^{\psi}$ with $\psi > 1$. We assume two values for the coefficient ψ: 1.05 and 1.1. The calibration results are reported in Table 3.

Table 3: Calibration from 1990 to 2019 (Nonlinear cost).[a]

Model	ψ	A	α	Δ_ε	γ	$\widetilde{\gamma}, \bar{\gamma}$	Δ	Σ sq. diff.
Symmetric Info.								
	1.05	0.889	0.04	0.01	1.0245	-	0.0011	0.0479
	1.1	0.853	0.01	0.02	1.0245	-	0.0002	0.0521
Asymm. Info. with Mechanism								
	1.05	0.762	0.11	0.06	1.0245	1.0254	0.0061	0.0518
	1.1	0.749	0.07	0.06	1.0245	1.0247	0.0025	0.0525
Asymm. Info. without Mechanism								
	1.05	0.395	0.46	0.14	1.0245	1.0595	0.0037	0.0712
	1.1	0.395	0.41	0.14	1.0245	1.0595	0.0034	0.0712

[a] Table 3 presents the calibrated values for the key parameters A, α, and Δ_ε; the cut-off gross rate of growth of money supply, $\overline{\gamma}$ and $\widetilde{\gamma}$; the welfare cost if inflation Δ; and the sum of square differences. Different values of the cost function parameter ψ are considered.

Assuming a convex cost function has different implications for the three models. A more convex cost function (i.e. a higher ψ) flattens the money demand curve for the cases of symmetric information and the asymmetric information with mechanism, as shown in Figure 10. This makes it harder to match the empirical money demand and worsens the model fit in both cases. However, the effect of ψ on the model fit is much larger in the former case than in the latter case. In other words, the curvature of the cost function plays a much bigger role in the symmetric information case than in the asymmetric information case with mechanism.

A more convex cost function also reduces the welfare cost of inflation substantially for higher values of ψ. For example, when ψ increases from 1.05 to 1.1, the welfare cost of inflation drops by more than 80% (from 0.0011 to 0.0002) in the symmetric information case and almost by 60% (from 0.0061 to 0.0025) in the asymmetric information with mechanism case.

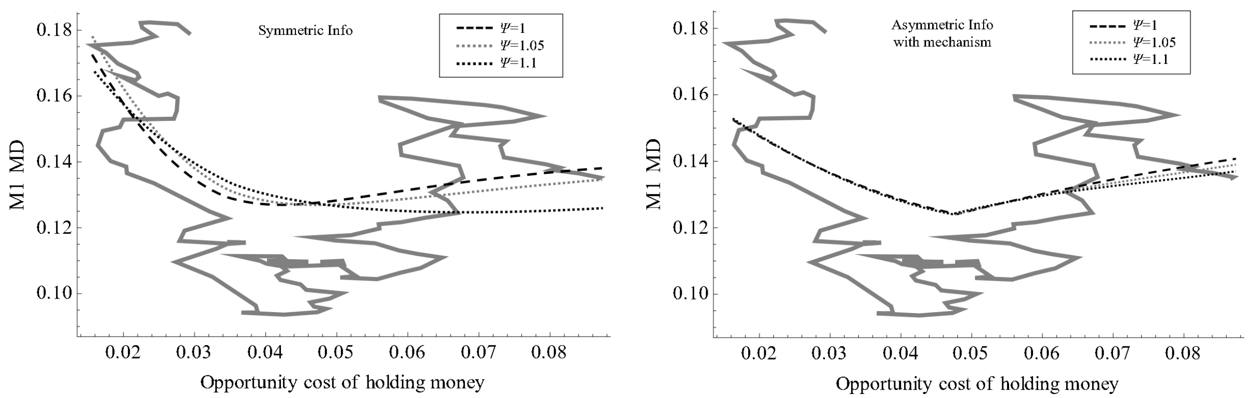

Figure 10: Best Fit Calibration with nonlinear cost function

These results are consistent with previous studies, such as Berentsen et al (2011), that show that a more convex cost function magnifies the response of u to γ, but makes the money demand less responsive to γ. The same cannot be said for the asymmetric information case without mechanism where a higher ψ reduces α, without affecting either A or Δ_ε. In this case, an increase in ψ leads to a one-to-one decrease of α with no effects on the calibrated money demand, and so the model fit. The welfare cost of inflation decreases as ψ increases, but only by a small amount, in the case of asymmetric information without mechanism, compared to the other two cases.

7.4 Discussion

The calibration results in Table 2 show that the baseline model and the symmetric information model perform very well in fitting the U.S. money demand data. The reason for this lies in the U-shaped implied money demand, as clearly shown in the left diagram of Figure 8. The calibration also shows that the other three models, i.e., the asymmetric information model without the mechanism and the two Lucas's specifications, perform quite poorly. These models generate a monotonically decreasing money demand, as shown in the right diagram of Figure 8.

The calibration results in Table 2 also unveil the role of the mechanism in fitting the data. This can be seen by comparing the best fit calibrations of the asymmetric information model with and without the mechanism—where these two models differ only in terms of the use of the mechanism. The former performs significantly better that the latter in fitting the data. Thus, the mechanism is the driving force in getting an upward-sloping money demand curve in the asymmetric information case with the mechanism, whereas risk aversion (or the curvature of the utility and cost functions) matters in the symmetric information case. Figure 10 provides further evidence of this as it shows that a nonlinear cost function flattens the model-implied money demand curve much more in the symmetric information case than in the asymmetric information case with mechanism.

As discussed earlier, the mechanism is successful in mitigating the inefficiency caused by asymmetric information. In fact, both the baseline model, where both asymmetric information and mechanism design coexist, and the symmetric information model, where both are absent, perform very similarly in fitting the observed money demand. This can also be seen in Figure 9 where the welfare cost of asymmetric information (gray line) is above, but very close, to the welfare benefit of the mechanism (dashed line). This pattern is reflected in the composite effect of the two (black line) being null or very small.

Therefore, the mechanism plays a crucial role in mitigating the inefficiency caused by the central bank's lack of information about the state of the economy, and it provides a rationale for the upward-sloping observed money demand curve. Of course, we do not claim that the mechanism is the only determinant of the observed money demand behavior after the 1990s. We only argue that the mechanism, in the form of market intelligence, could have, together with other factors studied in the literature – e.g. financial innovation, increased financial market participation, and limited commitment– explained part of the behavior of the money demand. Our paper complements this literature.

8 Conclusion

The empirical relationship between money demand and interest rates in the U.S. began to change in the 1990s. In this paper, we investigate the role of asymmetric information and mechanism design in explaining the change in the money demand behavior. We construct a microfounded monetary model in which private agents are informed about the actual state of the economy while the central bank is not. To overcome the asymmetric information problem, we assume the central bank uses a mechanism to gather private information from market participants, which captures some important aspects of the market intelligence procedure recently adopted by many central banks. We find that market intelligence gathering does very well in mitigating the inefficiency generated by asymmetric information and, compared to previous studies, improves the fit between the model-implied money demand and the observed one for the U.S. after the 1990s. The model also features an upward-sloping theoretical money demand. The reason behind this result is the binding truth-telling constraints of a buyer in the low state. For high inflation, a further increase in the inflation rate must increase high-state consumption in order for the buyer to truthfully report in the low state. This increases the expected consumption as well as the expected money demand. Previous models struggle to generate an upward-sloping money demand for high inflation rates.

Appendix

9 Appendix I: Robustness

9.1 Different time periods

We now test the performance of the models for the period before financial innovation, from 1960 to 1989, as well as for the entire period that goes from 1960 to 2019. As in the benchmark calibration, we use quarterly data and choose $\beta = (1+r)^{-1}$ so that the model replicates the real interest rate in the data, measured as the difference between the average annual rate on government bonds with a maturity of 10 years and the average annual inflation rate. To be consistent, we set $n = 0.5$ and limit our attention to symmetric shocks where $\varepsilon_l = 1 - \Delta_\varepsilon$, $\varepsilon_h = 1 + \Delta_\varepsilon$, and $\pi_h = 0.5$. The parameter A is chosen such that the velocity of money in the model matches the average velocity of money in the data. The remaining parameters, Δ_ε and α, are chosen by minimizing the sum of squared differences between the model-implied and the observed money demand.

Table A.1 shows the targets that are matched directly for these two periods.

Table A.1: Calibration targets.[a]

	Target value	
Target description	1960–1989	1960–2019
Average real interest rate r	0.026	0.024
Average 10 years government bond yield	0.076	0.061
Average inflation rate	0.050	0.038
Average velocity of money	5.881	6.844

[a] Table A.1 is the Table 2 counterpart for the period from 1960 to 1989 and the period from 1960 to 2019.

The calibration results for the period from 1960 to 1989 are reported in Table A.2. For this period, the best fit is provided by the log-log specification with a sum of squared differences of 0.0151. The second best fit is given by the asymmetric information model without the mechanism with a sum of squared differences of 0.0191. The best fit we can get with the baseline model is 0.1082 which is far worse than all other models. The symmetric information model has a sum of squared differences equal to 0.0291. The calibrated consumption volatility for this model is 1% which is much lower than the value of 22% we get for the asymmetric information model without the mechanism.

TABLE A.2: CALIBRATION FROM 1960 TO 1989.[a]

	A	α	Δ_ε	$\widetilde{\gamma}$	Δ	Σ sq. diff.
Symmetric Information	0794	0.22	0.01	-	0.0089	0.0291
Mechanism Design	0.582	0.37	0.15	1.103	0.0045	0.1082
No-Mechanism Design	0.769	0.24	0.22	1.113	0.0184	0.0191
Log-Log	0.041	0.55	-	-	0.0097	0.0150
Semi-Log	0.315	7.84	-	-	0.0173	0.0263

[a]Table A.2 is Table 3's counterpart for the period from 1960 to 1989. For a description of the reported variables, we refer to Table 3.

Table A.3 reports the calibration results for the entire period from 1960 to 2019. In this period, the log-log and semi-log specifications provide a slightly better fit than our three models. Compared to the other periods, however, none of the models perform well in fitting the data in this period with all the sum of squared differences being above 0.37.

TABLE A.3: CALIBRATION FROM 1960 TO 2019.[a]

	A	α	Δ_ε	$\widetilde{\gamma}$	Δ	Σ sq. diff.
Symmetric Information	0.638	0.26	0.15	-	0.0027	0.3927
Mechanism Design	0.638	0.26	0.15	2.461	0.0026	0.3927
No-Mechanism Design	0.227	0.87	0.22	1.115	0.0044	0.3946
Log-Log	0.126	0.07	-	-	0.0011	0.3789
Semi-Log	0.171	1.57	-	-	0.0151	0.3751

[a]Table A.3 is Table 3's counterpart for the period from 1960 to 2019. For a description of the reported variables, we refer to Table 3.

The sum of squared differences of the semi-log and log-log models are 0.3751 and 0.3789, respectively; those of the symmetric information model and asymmetric information model without the mechanism are 0.3927 and 0.3946, respectively. It is worth mentioning that the asymmetric information model with the mechanism and the symmetric information model have the same calibrated parameters for the period 1960 to 2019. This is because the type-I region—where the two models yield the same allocation—is the relevant one for the calibration.

9.1.1 Discussion

None of the models perform very well in the broader period from 1960 to 2019. This is because of the well documented structural change occurring in the observed money demand in the early 1990s. In this period, the observed money demand curve shifted downwards and flattened. This structural change was mainly driven by financial innovation and increased market participation which are not modelled in our paper.

In contrast, all the models, except the asymmetric information model with the mechanism, perform very well in the period from 1960 to 1989. The baseline model does not do well in this period for two reasons. One reason is that it predicts an upward-sloping money demand curve for high interest rates; in contrast, the observed money demand curve was very stable, and monotonically decreasing in the interest rate. Another reason is that the model does not do well in replicating the high elasticity of money demand that characterizes this period. For these two reasons, the fitted money demand is lower than the observed-money demand for low inflation rates, and it is higher for high inflation rates. It is no surprise that the asymmetric information model without the mechanism perform very well in this period. In fact, it predicts a monotonically decreasing money demand which is what we observe in the data. This model is best suited to explain the observed money demand before the 1990s.

Following the above results, market intelligence does not help to explain the money demand behavior before 1990s. Among the models we consider, this behavior is much better described by an asymmetrically informed central bank who does not use market intelligence. One reason for this is that the markets were calm and stable in this period, and so market intelligence was not needed.

10 Appendix II: Consumption dynamics in the type-II equilibrium

Figure A1 plots the consumed quantities in the type-II equilibrium, as a function of γ, in the low state (dashed gray) and in the high state (dashed dark). It also plots consumed quantities in the type-I equilibrium, in the low state (gray line) and the high state (dark line). Equation (19) has two solutions, a solution where $q_h = q_l$ and a solution where $q_h > q_l$. The solution $q_l = q_h$ is not an equilibrium because the central bank can use the mechanism to infer the state of the economy and implement a state-contingent consumption allocation. The region of interest is therefore $\gamma > \breve{\gamma}$ where $q_h > q_l$. It is evident from Figure A1 that $\tilde{\gamma} > \breve{\gamma}$. To see this, observe that consumption is state-contingent in the type-I equilibrium and it is equal to consumption in the type-II equilibrium at $\gamma = \tilde{\gamma}$. Therefore, consumption must be state contingent in the type-II equilibrium as well, at $\gamma = \tilde{\gamma}$. Hence, $\tilde{\gamma}$ must be strictly greater than $\breve{\gamma}$.

We now show that, if $\gamma > \tilde{\gamma}$, then (19) implies $q_h > q_l^* > q_l$ and $dq_h/dq_l < 0$. To see that (19) implies $q_h > q_l^* > q_l$, first observe that $q_h > q_l$ because $\gamma > \tilde{\gamma}$. Clearly, it cannot be the case that $q_l^* > q_h > q_l$ because a buyer's surplus in the low state is maximized at q_l^* and u is concave. For the same reason, it cannot be the case that $q_h > q_l > q_l^*$. Therefore, it must be that $q_h > q_l^* > q_l$.

To see that $\gamma > \tilde{\gamma}$ implies $dq_h/dq_l < 0$, take the total differential of (19) with respect to q_h and q_l

and rearrange terms to get

$$\frac{dq_h}{dq_l} = \frac{\varepsilon_l u'(q_l) - 1}{\varepsilon_l u'(q_h) - 1}. \tag{26}$$

The numerator is always positive because $q_l < q_l^*$. The denominator is negative because $q_h > q_l^*$. Hence, $dq_h/dq_l < 0$.

In other words, consumption quantities in the low state and high state move in opposite directions as a function of γ, for γ greater than $\tilde{\gamma}$. An increase in the inflation rate decreases q_l when $\gamma > \tilde{\gamma}$. This reduces the right-hand side of (19) as well, because $q_l < q_l^*$, which then implies that q_h has to increase because $q_h > q_l^*$. The reason is that a smaller q_l reduces the buyer's surplus from truth-telling in state l. In order for the buyer to truthfully report in state l, the surplus from lying must be lower as well. This is only possible if q_h increases.[25]

Unlike the symmetric information case, where the curvature of the utility function is crucial to have an upward sloping consumption in the high state (Proposition 1), risk aversion does not matter to have an increasing consumption in the type-II region. Indeed, the magnitude of u'' only affects the speed at which consumption grows, not the slope. For the latter, we only need u to be concave.

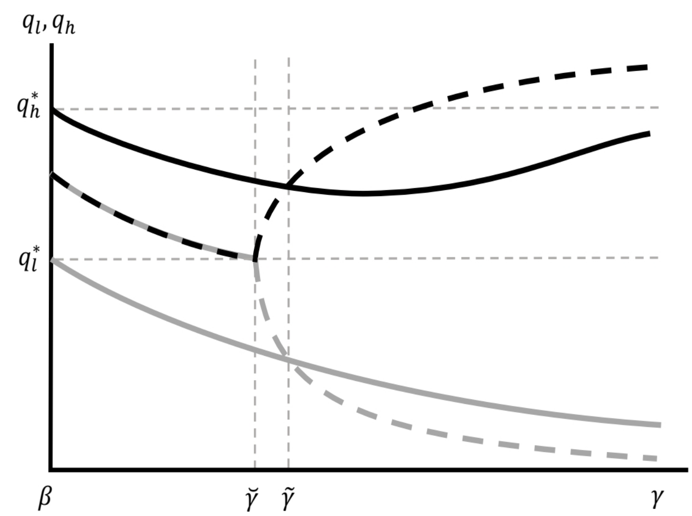

Figure A1. Type-I and type-II equilibria

To summarize, we showed that consumed quantities in the symmetric information case are different in the two states. Therefore, the threshold level $\tilde{\gamma}$ that separates the two equilibria (i.e. type-I and type-II) can only be in the region where $q_h > q_l$, i.e. where $\gamma > \breve{\gamma}$. We also showed that q_h is increasing in inflation while q_l is decreasing for γ greater than $\tilde{\gamma}$. Finally, unlike the symmetric

[25] Also, note that the constraint (17) is non-binding whenever (16) is binding, since $\varepsilon_h > \varepsilon_l$. To see this, rewrite (17) using (19) to get $\varepsilon_h [u(q_h) - u(q_l)] \geq \varepsilon_l [u(q_h) - u(q_l)]$, which is satisfied with strict inequality if $\varepsilon_h > \varepsilon_l$. Also, (14) is non-binding in the type-II region since $q_l < q_l^*$, and q_l is decreasing in γ, when $\gamma > \tilde{\gamma}$. Because (17) is non-binding, then (15) must be non-binding too in the type-II region.

information case, risk aversion does not matter to obtain an upward sloping consumption in the high state when the central bank is uninformed and a mechanism is in place. The mechanism is the main driving force in this case.

11 Appendix III: Proofs

Proof of Proposition 1. Assume a CARA utility function. This class of functions implies $u''(q) = -\alpha u'(q)$ where $\alpha > 0$ is the risk aversion parameter. Using this expression into (12), we obtain

$$\frac{\varepsilon_h u'(q_h) - 1}{\varepsilon_h u'(q_h)} = \frac{\varepsilon_l u'(q_l) - 1}{\varepsilon_l u'(q_l)},$$

or, rearranging terms, $\varepsilon_h u'(q_h) = \varepsilon_l u'(q_l)$. Take the total differential and rearrange terms to obtain:

$$\frac{dq_h}{dq_l} = \frac{\varepsilon_l u''(q_l)}{\varepsilon_h u''(q_h)} > 0, \tag{27}$$

because we have assumed $u''(q) < 0$. Hence, q_h and q_l move in the same direction. To show that they are both decreasing with inflation, take the total differential of (9) with respect to γ, q_h, and q_l:

$$\begin{aligned}
\frac{1}{\beta(1-n)} &= \pi_h \varepsilon_h u''(q_h) \frac{dq_h}{d\gamma} + (1-\pi_h) \varepsilon_l u''(q_l) \frac{dq_l}{d\gamma} \\
&= \pi_h \varepsilon_h u''(q_h) \frac{dq_h}{d\gamma} \frac{dq_l}{dq_l} + (1-\pi_h) \varepsilon_l u''(q_l) \frac{dq_l}{d\gamma} \\
&= \pi_h \varepsilon_h u''(q_h) \frac{\varepsilon_l u''(q_l)}{\varepsilon_h u''(q_h)} \frac{dq_l}{d\gamma} + (1-\pi_h) \varepsilon_l u''(q_l) \frac{dq_l}{d\gamma} \\
&= \varepsilon_l u''(q_l) \frac{dq_l}{d\gamma} \\
&> 0.
\end{aligned}$$

Since the left hand side of the last expression is positive, $\frac{dq_l}{d\gamma} < 0$ because $u''(q) < 0$. Then, it must hold that $\frac{dq_h}{d\gamma} < 0$ by (27). In other words, both q_h and q_l decrease as inflation increases. It is evident that this is true for any $\beta < \gamma < \infty$.

Assume a CRRA utility function, which implies $u''(q) = -\frac{\alpha}{q} u'(q)$ where $\alpha > 0$ is a risk aversion parameter. Using this expression into (12) yields

$$\begin{aligned}
\frac{\varepsilon_h u'(q_h)}{\varepsilon_h u''(q_h)} - \frac{1}{\varepsilon_h u''(q_h)} &= \frac{\varepsilon_l u'(q_l)}{\varepsilon_l u''(q_l)} - \frac{1}{\varepsilon_l u''(q_l)}, \\
-\frac{q_h}{\alpha} - \frac{1}{\varepsilon_h u''(q_h)} &= -\frac{q_l}{\alpha} - \frac{1}{\varepsilon_l u''(q_l)}, \\
\frac{q_h}{\alpha} + \frac{1}{\varepsilon_h u''(q_h)} &= \frac{q_l}{\alpha} + \frac{1}{\varepsilon_l u''(q_l)}.
\end{aligned}$$

Take the total differential of this expression to get

$$\begin{aligned}
\frac{1}{\alpha} dq_h - \frac{1}{\varepsilon_h} \frac{u'''(q_h)}{[u''(q_h)]^2} dq_h &= \frac{1}{\alpha} dq_l - \frac{1}{\varepsilon_l} \frac{u'''(q_l)}{[u''(q_l)]^2} dq_l, \\
\frac{1}{\alpha} dq_h + \frac{1+\alpha}{q_h \varepsilon_h u''(q_h)} dq_h &= \frac{1}{\alpha} dq_l + \frac{1+\alpha}{q_l \varepsilon_l u''(q_l)} dq_l, \\
\left[1 + \frac{\alpha(1+\alpha)}{q_h \varepsilon_h u''(q_h)}\right] dq_h &= \left[1 + \frac{\alpha(1+\alpha)}{q_l \varepsilon_l u''(q_l)}\right] dq_l, \\
\left[1 - \frac{1+\alpha}{\varepsilon_h u'(q_h)}\right] dq_h &= \left[1 - \frac{1+\alpha}{\varepsilon_l u'(q_l)}\right] dq_l,
\end{aligned}$$

or

$$\frac{dq_h}{dq_l} = \frac{[\varepsilon_l u'(q_l) - 1 - \alpha]\, \varepsilon_h u'(q_h)}{[\varepsilon_h u'(q_h) - 1 - \alpha]\, \varepsilon_l u'(q_l)}, \tag{28}$$

where we have used $\frac{u'''(q)}{u''(q)} = -\frac{1+\alpha}{q}$.

From (9) and (12), if $\gamma = \beta$ then $\varepsilon_h u'(q_h) = \varepsilon_l u'(q_l) = 1$, and so $\left.\frac{dq_h}{dq_l}\right|_{\gamma=\beta} = 1$. By continuity, this is true also for small deviations from $\gamma = \beta$. In other words, for γ greater than but sufficiently close to β, q_h and q_l are both decreasing in γ and both the numerator and the denominator of (28) are negative. As γ continues to increase, $u'(q_l)$ and $u'(q_h)$ both increase but the former increases at a higher rate than the latter (due to CRRA preferences), until the numerator becomes zero. Let $\hat{\gamma}$ denote the cutoff value of γ such that $\frac{dq_h}{dq_l} = 0$. Namely, the cut-off value $\hat{\gamma}$ solves

$$\varepsilon_l u'(q_l) = 1 + \alpha.$$

Since we have assumed $u''(q) < 0$, then $\hat{\gamma}$ exists and is unique. Now, q_h is horizontal at $\gamma = \hat{\gamma}$, but q_l is downward sloping in γ. A further increase in γ, above $\gamma = \hat{\gamma}$, turns the numerator of (28) into a positive number. Since the denominator is still negative, then $\frac{dq_h}{dq_l} < 0$. In other words, q_h increases (and hence, $u'(q_h)$ decreases so that the denominator keeps staying negative) and q_l decreases as inflation increases above $\hat{\gamma}$. However, q_h is bounded above by q_h^*, so $q_h \to q_h^*$ and $q_l \to 0$ as $\gamma \to \infty$. This pattern is consistent with (9), (12) and (28). ■

Proof of Lemma 2. The first-order conditions of the central bank problem under the mechanism are

$$\begin{aligned} & (1-\pi_h)(1-n)\left[\varepsilon_l u'(q_l) - 1 + \tilde{\lambda}\varepsilon_l u''(q_l)\right] \\ & +(\lambda_{IC_l} + \lambda_{PT_l})\left[\varepsilon_l u'(q_l) - 1\right] - \lambda_{IC_h}\left[\varepsilon_h u'(q_l) - 1\right] \\ = \; & 0, \end{aligned} \tag{29}$$

and

$$\begin{aligned} & \pi_h(1-n)\left[\varepsilon_h u'(q_h) - 1 + \tilde{\lambda}\varepsilon_h u''(q_h)\right] \\ & -\lambda_{IC_l}\left[\varepsilon_l u'(q_h) - 1\right] + (\lambda_{IC_h} + \lambda_{PC_h})\left[\varepsilon_h u'(q_h) - 1\right] \\ = \; & 0, \end{aligned} \tag{30}$$

where λ_{PC_l}, λ_{PC_h}, λ_{IC_l}, and λ_{IC_h} are the Lagrange multipliers for (14), (15), (16), and (17), respectively. In a type-I equilibrium, the constraints (14)-(17) are all slack so the respective multipliers are zero. Hence, the first order conditions (29) and (30) reduce to

$$\varepsilon_l u'(q_l) - 1 + \tilde{\lambda}\varepsilon_l u''(q_l) = 0$$

and

$$\varepsilon_h u'(q_h) - 1 + \tilde{\lambda}\varepsilon_h u''(q_h) = 0,$$

respectively, which implies (18). ■

Proof of Lemma 3. In a type-II equilibrium, the constraints (14), (15), and (17) slack. Equation (19) comes directly from the constraint (16) which is binding. ■

Proof of Proposition 4. The cutoff value $\tilde{\gamma}$ is the value of γ such that consumption quantities in Lemma 2 and Lemma 3 are the same. In other words, $\tilde{\gamma}$ solves

$$\frac{\tilde{\gamma} - n\beta}{\beta} = (1-n)\left[\pi_h \varepsilon_h u'(q_h) + (1-\pi_h)\varepsilon_l u'(q_l)\right]$$

whereas q_l and q_h solve

$$\begin{aligned} \frac{\varepsilon_h u'(q_h) - 1}{\varepsilon_h u''(q_h)} &= \frac{\varepsilon_l u'(q_l) - 1}{\varepsilon_l u''(q_l)}, \\ \varepsilon_l u(q_h) - q_h &= \varepsilon_l u(q_l) - q_l. \end{aligned}$$

A lower γ is associated with a higher surplus for a buyer in the low state, which gives the buyer less incentive to misreport. This is the case in the type-I equilibrium. In contrast, for high γ, the surplus may be so low that (16) must bind to prevent a buyer from misreporting in the low state. This happens in the type-II region. ■

Proof of Proposition 5.

Let $\left\{q_l^M, q_h^M\right\}$ and $\left\{q_l^N, q_h^N\right\}$ denote the implemented allocation in the economy with and without the mechanism, respectively. To prove that the mechanism is welfare improving it is sufficient to show that $\left\{q_l^N, q_h^N\right\}$ is feasible in the economy *with* mechanism but it is never implemented in such an economy, i.e. a different allocation $\left\{q_l^M, q_h^M\right\} \neq \left\{q_l^N, q_h^N\right\}$ is chosen in the two economies, for any $\gamma > \beta$. In other words, if $\left\{q_l^N, q_h^N\right\}$ implies (9), (14)-(17) for any γ, but not vice versa, then the mechanism is welfare improving. Notice that the constraints (9), (14) and (15) show up in both problems with and without mechanism, so we can just focus on (16) and (17).

In the type-A equilibrium ($\beta < \gamma < \bar{\gamma}$), $q_l^* = q_l^N < q_h^N < q_h^*$. This implies $\varepsilon_l u\left(q_l^*\right) - q_l^* > \varepsilon_l u\left(q_h^N\right) - q_h^N$ and $\varepsilon_h u\left(q_h^N\right) - q_h^N > \varepsilon_h u\left(q_l^*\right) - q_l^*$, therefore both (16) and (17) slack. In the type-B equilibrium ($\gamma > \bar{\gamma}$), $q_l^N = q_h^N < q_l^* < q_h^*$. This implies (16) and (17) are both binding. Therefore, $\left\{q_l^N, q_h^N\right\}$ implies (16) and (17) for any $\gamma > \beta$. To see that (16) and (17) do not imply $\left\{q_l^N, q_h^N\right\}$, observe that the central bank's choice in the economy with the mechanism is $q_l^M < q_l^* < q_h^M$ for any $\gamma > \beta$. In other words, $q_l^M \neq q_l^*$ in the region $\beta < \gamma < \bar{\gamma}$, and $q_l^M \neq q_h^M$ in the region $\gamma > \bar{\gamma}$. Consequently, $\left\{q_l^M, q_h^M\right\} \neq \left\{q_l^N, q_h^N\right\}$ for any $\gamma > \beta$. ■

Proof of Proposition 6. (i) Consider the symmetric information case. For simplicity, assume a CARA utility function, which implies $u''(q) = -\alpha u'(q)$ where α is the risk aversion coefficient. This facilitates the analysis as the equilibrium equations

$$\frac{\gamma - n\beta}{\beta} = (1-n)\left[\pi_h \varepsilon_h u'(q_h) + (1-\pi_h)\varepsilon_l u'(q_l)\right]$$

and

$$\frac{\varepsilon_h u'(q_h) - 1}{\varepsilon_h u''(q_h)} = \frac{\varepsilon_l u'(q_l) - 1}{\varepsilon_l u''(q_l)}$$

simplify to

$$\frac{\gamma - n\beta}{\beta} = (1-n)\varepsilon_l u'(q_l), \tag{31}$$

$$\varepsilon_h u'(q_h) = \varepsilon_l u'(q_l), \tag{32}$$

respectively.

Let us study the effect of π_h on welfare. Observe that the probability of the high state occurring, π_h, is neither in (31) or (32), which implies both q_h and q_l are independent of π_h, i.e. $\frac{dq_l}{d\pi_h} = \frac{dq_h}{d\pi_h} = 0$.

From (32),

$$\frac{dq_h}{dq_l} = \frac{\varepsilon_l u''(q_l)}{\varepsilon_h u''(q_h)} = \frac{\varepsilon_l u'(q_l)}{\varepsilon_h u'(q_h)} = 1.$$

Take the partial derivative of the expected welfare function with respect to π_h to obtain

$$\begin{aligned} \frac{\partial W}{\partial \pi_h} \frac{1}{(1-n)} &= [\varepsilon_h u(q_h) - q_h] - [\varepsilon_l u(q_l) - q_l] \\ &\quad + \pi_h \left[\varepsilon_h u'(q_h) - 1\right] \frac{dq_h}{d\pi_h} + (1-\pi_h) \left[\varepsilon_l u'(q_l) - 1\right] \frac{dq_l}{d\pi_h} \\ &= [\varepsilon_h u(q_h) - q_h] - [\varepsilon_l u(q_l) - q_l] \\ &> 0, \end{aligned}$$

because $\varepsilon_h u(q_h) - q_h > \varepsilon_h u(q_l) - q_l > \varepsilon_l u(q_l) - q_l$, and $\frac{dq_l}{d\pi_h} = \frac{dq_h}{d\pi_h} = 0$.

To study the effect of n on welfare, take the total differential of (31) and (32) with respect to n, q_h, and q_l, to obtain

$$0 = \left[1 - \varepsilon_l u'(q_l)\right] dn + (1-n) \varepsilon_l u''(q_l) \, dq_l,$$

and

$$\frac{dq_h}{dq_l} = \frac{\varepsilon_l u''(q_l)}{\varepsilon_h u''(q_h)} = \frac{\varepsilon_l u'(q_l)}{\varepsilon_h u'(q_h)} = 1,$$

respectively. Combining these two expressions yields

$$\frac{dq_l}{dn} = \frac{1 - \varepsilon_l u'(q_l)}{\alpha (1-n) \varepsilon_l u'(q_l)} < 0,$$

because $u''(q) = -\alpha u'(q)$ and $1 - \varepsilon_l u'(q_l) < 0$. This means that consumption, in the high state and low state, move one-to-one and they are both decreasing in n. Next, take the partial derivative of the expected welfare function with respect to n,

$$\begin{aligned} \frac{\partial W}{\partial n} &= -\left\{\pi_h [\varepsilon_h u(q_h) - q_h] + (1-\pi_h) [\varepsilon_l u(q_l) - q_l]\right\} \\ &\quad + (1-n) \left[\varepsilon_l u'(q_l) - 1\right] \frac{dq_l}{dn} \\ &< 0, \end{aligned}$$

because $\frac{dq_l}{dn} < 0$.

(ii) Consider now the asymmetric information case without mechanism. In this case, we do not impose any restrictions on the utility function, so the results are more general. Let us first study the effect of π_h on welfare. In the type-A equilibrium, $q_l^* = q_l$. Take the total differential of

$$\frac{\gamma - n\beta}{\beta(1-n)} = \pi_h \varepsilon_h u'(q_h) + (1 - \pi_h)$$

with respect to π_h and q_h, to obtain

$$\frac{dq_h}{d\pi_h} = -\frac{\varepsilon_h u'(q_h) - 1}{\pi_h \varepsilon_h u''(q_h)} > 0.$$

This implies

$$\begin{aligned} \frac{\partial W}{\partial \pi_h} \frac{1}{(1-n)} &= \varepsilon_h u(q_h) - q_h - \varepsilon_l u(q_l^*) + q_l^* + \pi_h \left[\varepsilon_h u'(q_h) - 1\right] \frac{dq_h}{d\pi_h} \\ &> 0, \end{aligned}$$

because $\varepsilon_h u(q_h) - q_h > \varepsilon_h u(q_l^*) + q_l^* > \varepsilon_l u(q_l^*) + q_l^*$. In the type-B region, $q_h = q_l = q$. Take the total differential of

$$\frac{\gamma - n\beta}{\beta(1-n)} = [\pi_h \varepsilon_h + (1 - \pi_h)\varepsilon_l] u'(q),$$

with respect to π_h and q, to get

$$\frac{dq}{d\pi_h} = -\frac{[\varepsilon_h - \varepsilon_l] u'(q)}{[\pi_h \varepsilon_h + (1 - \pi_h)\varepsilon_l] u''(q)} > 0.$$

This implies

$$\begin{aligned} \frac{\partial W}{\partial \pi_h} \frac{1}{1-n} &= (\varepsilon_h - \varepsilon_l) u(q) + \left\{[\pi_h \varepsilon_h + (1 - \pi_h)\varepsilon_l] u'(q) - 1\right\} \frac{dq}{d\pi_h} \\ &> 0, \end{aligned}$$

because $[\pi_h \varepsilon_h + (1 - \pi_h)\varepsilon_l] u'(q) > \varepsilon_l u'(q) > 1$.

Let us study now the effect of n on welfare. In a type-A equilibrium, $q_l^* = q_l$. Take the total differential of

$$\frac{\gamma - n\beta}{\beta(1-n)} = \pi_h \varepsilon_h u'(q_h) + (1 - \pi_h),$$

with respect to n and q_h, to get

$$\frac{dq_h}{dn} = \frac{\pi_h [\varepsilon_h u'(q_h) - 1]}{(1-n)\pi_h \varepsilon_h u''(q_h)} < 0.$$

This implies,

$$\begin{aligned}\frac{\partial W}{\partial n} &= -\left\{\pi_h\left[\varepsilon_h u\left(q_h\right)-q_h\right]+\left(1-\pi_h\right)\left[\varepsilon_l u\left(q_l^*\right)-q_l^*\right]\right\} \\ &\quad +\left(1-n\right)\pi_h\left[\varepsilon_h u'\left(q_h\right)-1\right]\frac{dq_h}{dn} \\ &< 0.\end{aligned}$$

In the type-B region, $q_h = q_l = q$. Therefore, the total differential of

$$\frac{\gamma - n\beta}{\beta\left(1-n\right)} = \left[\pi_h\varepsilon_h + \left(1-\pi_h\right)\varepsilon_l\right]u'\left(q\right)$$

with respect to n and q is

$$\frac{dq}{dn} = \frac{\left[\pi_h\varepsilon_h + \left(1-\pi_h\right)\varepsilon_l\right]u'\left(q\right)-1}{\left(1-n\right)\left[\pi_h\varepsilon_h + \left(1-\pi_h\right)\varepsilon_l\right]u''\left(q\right)} < 0.$$

The numerator is positive because $\left[\pi_h\varepsilon_h + \left(1-\pi_h\right)\varepsilon_l\right]u'\left(q\right) > \varepsilon_l u'\left(q\right) > 1$. The denominator is negative because $u''\left(q\right) < 0$, therefore $\frac{dq}{dn} < 0$. This implies

$$\begin{aligned}\frac{\partial W}{\partial n} &= -\left\{\left[\pi_h\varepsilon_h + \left(1-\pi_h\right)\varepsilon_l\right]u\left(q\right)-q\right\} \\ &\quad +\left(1-n\right)\left\{\left[\pi_h\varepsilon_h + \left(1-\pi_h\right)\varepsilon_l\right]u'\left(q\right)-1\right\}\frac{dq}{dn} \\ &< 0.\end{aligned}$$

The first term on the right hand side is negative because $\left[\pi_h\varepsilon_h + \left(1-\pi_h\right)\varepsilon_l\right]u\left(q\right) > \varepsilon_l u\left(q\right) > q$. The second term is negative as well, because $\frac{dq}{dn} < 0$. Therefore, $\frac{\partial W}{\partial n} < 0$. ■

Proof of Proposition 7. The cutoff value $\bar{\gamma}$ satisfies

$$\frac{\bar{\gamma} - n\beta}{\beta} = \left(1-n\right)\left[\pi_h\varepsilon_h u'\left(q_h\right) + \left(1-\pi_h\right)\varepsilon_l u'\left(q_l\right)\right],$$

with $q_h = q_l$ and $q_l = q_l^*$ or, equivalently,

$$\bar{\gamma} = \beta n + \beta\left(1-n\right)\left(\pi_h\frac{\varepsilon_h}{\varepsilon_l} + 1 - \pi_h\right),$$

because $\varepsilon_l u'\left(q_l^*\right) = 1$. Take the partial derivative of $\bar{\gamma}$ with respect to π_h and n, and obtain

$$\frac{\partial\bar{\gamma}}{\partial\pi_h} = \beta\left(1-n\right)\left(\frac{\varepsilon_h}{\varepsilon_l} - 1\right) > 0$$

and

$$\frac{\partial \bar{\gamma}}{\partial n} = \beta \pi_h \left(1 - \frac{\varepsilon_h}{\varepsilon_l}\right) < 0,$$

respectively. Hence, $\bar{\gamma}$ is increasing in π_h and decreasing in n. ■

12 Appendix III: Data sources and data availability statement

The data we used for the calibration is downloadable from the Federal Reserve Bank of St. Louis FRED database. For all time series, we use quarterly data for the period 1960:Q1 to 2019:Q1. Table A.4 gives a brief overview of the data sources.

Table A.4: U.S. Data source

Description	Identifier
M1	M1
Gross domestic product	GDP
Long-term government bond yield	IRLTLT01USQ156N

DATA AVAILABILITY STATEMENT

The data and code that support the findings of this study are openly available in OPENICPSR at https://doi.org/10.3886/E195342V1, openicpsr-195342.

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