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Seon Tae Kim
Alessandro Marchesiani

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Seon Tae Kim
University of Liverpool

Alessandro Marchesiani
University of Liverpool

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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.
Keywords: Money demand, asymmetric information, mechanism design.

"[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.[1]

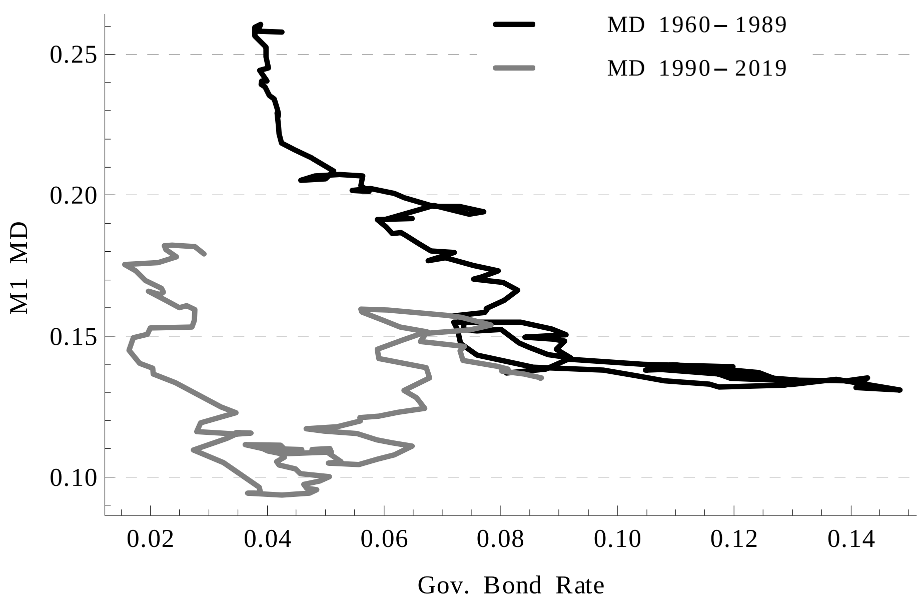

Figure 1: U.S. M1 Money Demand 1960 – 2019

[1] 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), and Berentsen et al. 2015).

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.[2] In other words, standard literature on monetary theory struggles to explain the positive relation between money demand and the interest rate. An exception is Berentsen et al. (2018), who show that limited commitment in credit markets causes the theoretical money demand to be upward-sloping for intermediate-to-high interest rates.

The present paper complements Berentsen et al. (2018) by providing an alternative explanation of the positive relation between money demand and interest rates. The key ingredients in our model are aggregate uncertainty, asymmetric information, and the central bank's use of mechanism design. There is neither a credit market nor limited commitment in our model. As in Berentsen et al. (2018), we predict a positive relation between consumption and the interest rate, for high interest rates, which enables us to fit the U.S. money demand well as compared to traditional models.

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 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.[3]

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).[4] It is mainly gathered with contacts through bilateral conversations conducted via telephone, face-to-face

[2] 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.

[3] 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.

[4] 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.

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 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 market intelligence: asymmetric information and data gathering. Asymmetric information is formalized by assuming private agents are informed about the realized shocks, but the central bank is not. 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.

We show that market intelligence explains well the behavior of the U.S. money demand after 1990. As in Berentsen et al. (2018), our model is able to generate an upward-sloping money demand curve which provides a good fit of the empirical money demand. However, the rationale behind this result is different in the two models. In Berentsen et al. (2018), higher inflation relaxes a buyer's borrowing constraint and thus increases money holdings and consumption as well. In our model, higher inflation increases a buyer's incentive to misreport in the low state. To offset this greater incentive, consumption in the high state must increase over and above the low-state efficient level of consumption, which is what makes the expected money demand curve increase in the interest rate, for high interest rates.

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. Figure 2 shows the best fit calibration of our model (left diagram) as compared to the Lucas' specifications (right diagram). 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.[5]

[5] 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.

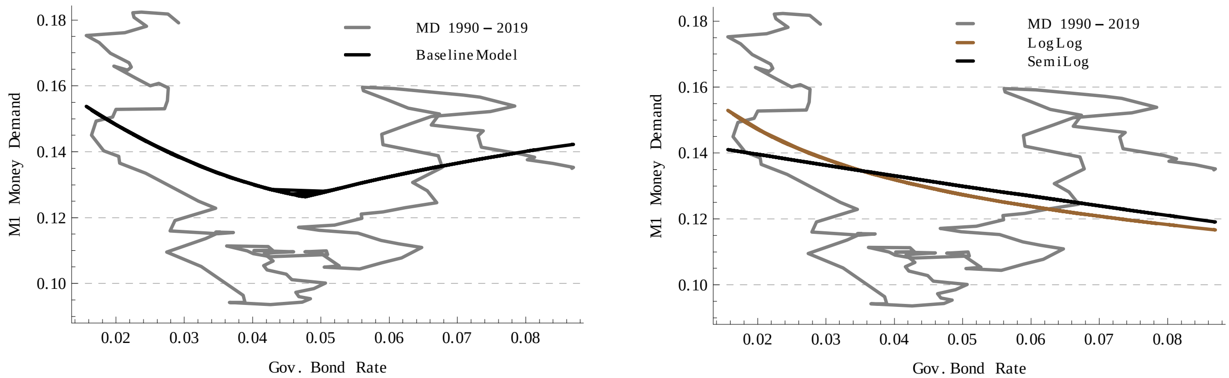

Figure 2: Best Fit Calibration 1990 – 2019

We also perform a comparative statics exercise and show that 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.

The related literature. After 1990, the observed money demand in the U.S. became upward-sloping for high interest rates. This behavior is puzzling according to traditional monetary theory which predicts just the opposite. If interest rates are high, then the cost of holding money is high, and therefore consumption (and the demand for money) should be low.

An exception is the recent work by Berentsen et al. (2018) who use limited commitment in credit markets to get an upward-sloping money demand curve, for intermediate-to-high interest rates. The reason is that a further increase in the interest rate relaxes the buyers' borrowing constraint, which increases the transaction demand for money, and consumption. The borrowing constraint in Berentsen et al. (2018) does not bind, however, and the negative relation is restored for sufficiently high inflation rates.[6]

Our paper complements Berentsen et al. (2018) both theoretically and empirically. Theoretically, we get another rationale for the upward-sloping money demand by using different ingredients: asymmetric information and mechanism design. In our model, if interest rates are high enough, a further

[6] Berentsen et al. (2018) identify four equilibrium regions: type-I, type-II, type-III and type-IV. For intermediate-to-high interest rates, i.e. in the type-III equilibrium, the money demand is upward-sloping. For sufficiently high interest rates, i.e. in type-IV equilibrium, a downward-sloping money demand is restored.

increase in the interest rate reduces a buyer's surplus in the low state, which increases the buyer's incentive to misreport. To offset this stronger incentive, consumption in the high state must increase and be over and above its low-state efficient level. Quantitatively, our model replicates the observed U.S. money demand for high interest rates, not just for intermediate-to-high rates. This improves the overall fit substantially in the period after the 1990s.

Another paper that is close to ours is Berentsen et al. (2015). Both that paper and the present one work on the same dataset and look at the U.S. money demand before and after the 1990s. The two papers have two important differences though. First, Berentsen et al. (2015), in line with traditional monetary models, obtain a monotonically decreasing demand curve, while we do not. This matters when fitting the data in the period after 1990. Second, they use limited participation in financial markets to explain the observed change in both the position and slope of the observed money demand curve. There is no financial market in our model. Instead, we rely on asymmetric information and mechanism design to get the results.

There is an already large literature that studies money demand and its instability in the data.[7] Two main approaches have been used. One is to introduce frictions into the model such as financial innovation, limited participation, and limited commitment (e.g., Berentsen et al. 2015, 2018). Such frictions affect the shape of the money demand curve and thus help to explain the observed change in the money demand. The other 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). This second approach builds on the argument that there is a measurement problem behind the instability of the money demand. We follow the first approach.

Most of the papers mentioned above are of an empirical nature and do not have any microfoundations of money. We stand apart from this trend, and use a microfounded monetary model, as we think the role of money should be taken seriously when studying money demand. Thus, 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 —as in Berentsen and Waller (2011)— 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.[8]

[7] Some of the first works on this topic are Baumol (1952), Tobin (1956), and Bailey (1956). See Berentsen et al. (2015) and (2018) for a detailed review of the literature on the instability of money demand.

[8] 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.

We are not the first to apply mechanism design to the setup of Lagos and Wright (2005).[9] 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) with some features of Berentsen and Waller (2011). 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 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, $c(q) = q$. 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

[9] 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).

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. As in Berentsen and Waller (2011), 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

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

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, $T_t = \tau M_t$, 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, after the aggregate state is realized but before the goods transactions take place, the central bank injects $\mathcal{T}_{tj} = \tau_j M_t$, 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, as in Berentsen and Waller (2011).

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.

Let $V_2(m)$ denote the value function of an agent entering the settlement market with m units of money. Then the agent's problem in the settlement market is

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

subject to

$$x + \phi m_{+1} = h + \phi m - \phi \mathcal{T} + \phi T.$$

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

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

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

$$\frac{\partial V_2}{\partial m} = \phi. \tag{1}$$

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

$$V_1^s(m) = \max_{q_s} -q_s + V_2(m + pq_s + \mathcal{T}).$$

The first-order condition for this problem is $1/p = \partial V_2/\partial m$, which can be rewritten as

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

by (1). The envelope condition is

$$\frac{\partial V_1^s}{\partial m} = \phi. \tag{3}$$

Let $V_1^b(m)$ be the value function of a buyer entering the goods market with m units of money. Then the buyer's problem in the goods market is

$$V_1^b(m) = \max_{q_b} \varepsilon u(q_b) + V_2(m - pq_b + \mathcal{T})$$

subject to the constraint $m - pq_b + \mathcal{T} \geq 0$. Buyers in the goods market decide how much to consume, q_b, taking the price, p, of the special good as given, subject to the constraint that they cannot spend more money 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

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

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

$$\frac{\partial V_1^b}{\partial m} = \phi + \lambda. \tag{5}$$

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

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

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

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

Using (3), (4), and (5), $\partial V_1(m)/\partial m$ can be rewritten as,

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

We can use (2)–(5), and the first-order condition for the settlement market to update $\partial V_1(m)/\partial m$ one period, obtaining

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

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

The central bank maximizes social welfare –the short-term goal– by choosing the state-contingent money transfers which depends on the available information. 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, and another version where the central bank is not informed, but the agents are. We refer to these 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 problem is

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

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. 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.

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 central bank uses a mechanism to characterize the set of incentive-feasible allocations, and the other one where it does not.

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.[10] 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.

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

[10] 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.

spend less money than what the buyer has. That buyer receive $\mathcal{T}_h$ and has to spend it all, and purchase q_h, in order for the transaction to be executed.[11]

We characterize constrained-efficient allocations as allocations that maximize social welfare subject to incentive-compatibility constraints. The incentive constraints require that buyers truthfully reveal their private information.

The central bank's problem under this mechanism is

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

subject to (9), and

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

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.

The first-order conditions of the central bank problem under the mechanism are

$$\begin{aligned} & \left(1-\pi_h\right)(1-n)\left[\varepsilon_l u'\left(q_l\right)-1+\tilde{\lambda}\varepsilon_l u''\left(q_l\right)\right] \\ & +\left(\lambda_{IC_l}+\lambda_{PT_l}\right)\left[\varepsilon_l u'\left(q_l\right)-1\right]-\lambda_{IC_h}\left[\varepsilon_h u'\left(q_l\right)-1\right] \\ = \; & 0, \end{aligned} \tag{18}$$

[11] 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.

and

$$
\begin{aligned}
& \pi_h (1-n) \left[\varepsilon_h u'(q_h) - 1 + \tilde{\lambda}\varepsilon_h u''(q_h)\right] \\
& -\lambda_{IC_l} \left[\varepsilon_l u'(q_h) - 1\right] + (\lambda_{IC_h} + \lambda_{PC_h}) \left[\varepsilon_h u'(q_h) - 1\right] \\
= \; & 0, \qquad (19)
\end{aligned}
$$

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. It is evident that a buyer never misreports in the high state, i.e., (17) is never binding. We show below that the constraint (17) is non-binding if $q_l < q_h < q_h^*$. Conversely, $q_h \geq q_l^*$ if $q_l < q_l^*$. The intuition behind this second result is straightforward. To see this, suppose $q_l < q_l^*$. Then, in order for the buyer to truthfully report in state l, lying must yield a lower surplus, hence it cannot be the case that $q_h < q_l^*$. A buyer who misreports in state l has to consume q_h. That there is less surplus from consuming q_h, instead of q_l, implies that $q_h > q_l^*$. The higher the q_h the smaller the surplus from misreporting, when $q_h > q_l^*$.

Table 1 identifies the following two regions of equilibria depending on the value of the Lagrange multipliers.

TABLE 1: EQUILIBRIUM REGIONS

		Lagrange multipliers			
Regions	γ	λ_{IC_l}	λ_{IC_h}	λ_{PC_l}	λ_{PC_h}
Type-I region	$\gamma < \tilde{\gamma}$	$= 0$	$= 0$	$= 0$	$= 0$
Type-II region	$\gamma > \tilde{\gamma}$	> 0	$= 0$	$= 0$	$= 0$

Let $\tilde{\gamma}$ be the cutoff value of γ that separates the two regions. If $\gamma < \tilde{\gamma}$, all four constraints (14)–(17) are slack. In this region, 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. If $\gamma > \tilde{\gamma}$, then all the constraints except (16) are slack.

We now characterize the equilibrium allocation in the two regions $\gamma < \tilde{\gamma}$ and $\gamma > \tilde{\gamma}$. We refer to these regions as "type-I" and "type-II", respectively. A type-I equilibrium is a pair $\{q_l, q_h\}$ satisfying (9) and

$$
\frac{\varepsilon_h u'(q_h) - 1}{\varepsilon_h u''(q_h)} = \frac{\varepsilon_l u'(q_l) - 1}{\varepsilon_l u''(q_l)}, \qquad (20)
$$

where the last expression is derived using (18) and (19). Similarly, a type-II equilibrium is a pair $\{q_l, q_h\}$ satisfying (9) and

$$
\varepsilon_l u(q_h) - q_h = \varepsilon_l u(q_l) - q_l. \qquad (21)
$$

The last expression comes from the binding incentive compatibility constraint in the low state. In the type-II equilibrium, q_h is increasing in γ while q_l is decreasing. This dynamics can be understood from the condition (21). If q_l decreases, the right-hand side decreases as well because $q_l < q_l^*$. This implies that q_h has to increase to keep (21) satisfied since $q_h > q_l^*$. 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 and $q_h > q_l^*$.[12]

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 directly, the mechanism reveals the 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.[13] In the asymmetric information model with the mechanism, consumption in the high state is increasing in inflation because of the truth-telling constraint, (16), which is binding for high inflation. 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, consumption in the high state is increasing because of the specific assumptions regarding the agents' risk aversion. For example, for a CRRA utility function,

[12] Also, note that the constraint (17) is non-binding whenever (16) is binding, since $\varepsilon_h > \varepsilon_l$. To see this, rewrite (17) using (21) 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.

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

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.

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.

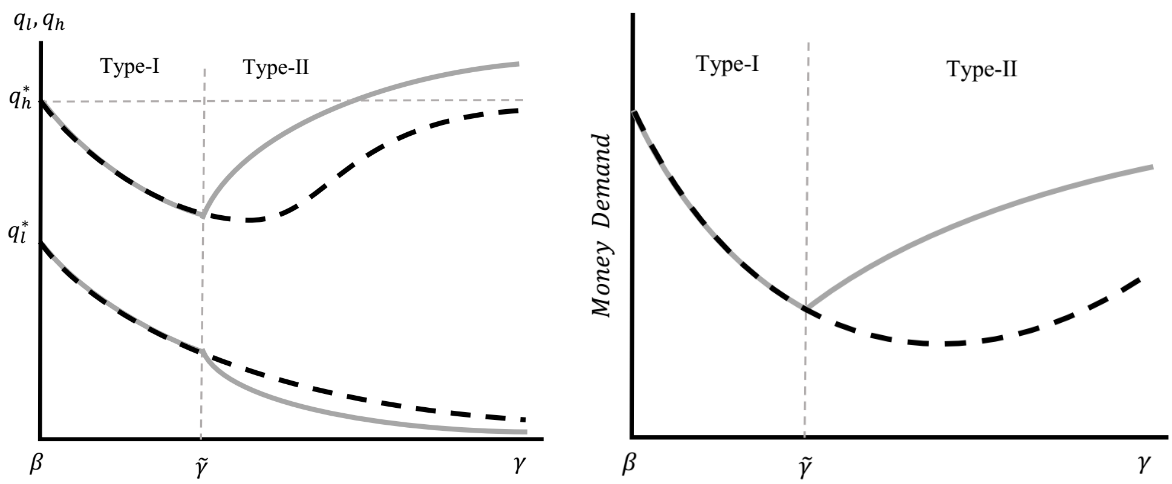

Figure 3: Consumption and Money Demand

For low inflation, the two models yield the same allocation. Therefore, welfare is the same under symmetric information as it is under asymmetric information with the mechanism. For high inflation rates, the symmetric information model leads to higher welfare than the asymmetric information model with the mechanism. This is because the latter has one additional constraint as opposed to the former: the binding truth-telling constraint (16). This additional constraint reduces the set of incentive feasible allocations, 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, by the central bank, to choose the allocation. In such an environment, the central bank's problem is

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

subject to

$$\begin{aligned} \frac{\gamma - n\beta}{\beta(1-n)} &= \pi_h \varepsilon_h u'(q_h) + (1-\pi_h) \varepsilon_l u'(q_l), \\ 0 &= (q_l^* - q_l)(q_h - q_l). \end{aligned}$$

One can immediately to 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. 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. For sufficiently large money injections, consumption differs across states and we have $q_l = q_l^* < q_h$. A buyer is not cash constrained in the low state, and thus consumes the efficient quantity, but is cash constrained in the high state. In contrast, if a buyer's money holdings, after the non–state-contingent money injection, is not large enough then the buyer is cash constrained in both states, and therefore the buyer's consumption is the same in the two states, i.e., $q_l = q_h < q_l^*$.

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 rates, buyers hold sufficient amounts of money, so they consume the efficient quantity of goods in the low state (i.e., $q_l^* = q_l$); in the high state (i.e., $q_l < q_h \leq q_h^*$), they are cash constrained, and consume an inefficient quantity of goods. For high inflation rates, buyers' money holdings are such that they are cash constrained, and so consumption is the same in both states (i.e., $q_l < q_l^*$ and $q_l = q_h$). We refer to these two cases as type-A and type-B, respectively.

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

$$\begin{aligned} \frac{\gamma - n\beta}{\beta(1-n)} &= \pi_h \varepsilon_h u'(q_h) + (1-\pi_h), \\ q_l^* &= q_l, \end{aligned}$$

in the type-A region, and

$$\begin{aligned}\frac{\gamma - n\beta}{\beta(1-n)} &= [\pi_h \varepsilon_h + (1-\pi_h)\varepsilon_l]\, u'(q_l)\,, \\ q_h &= q_l,\end{aligned}$$

in the type-B region. Figure 4 displays consumption quantities across states, as a function of the inflation rate, in this economy. The type-A region is the equilibrium region for all inflation rates such that $\gamma < \bar{\gamma}$; the type-B region is the equilibrium region for all $\gamma > \bar{\gamma}$. The cut-off inflation rate that separates the two regions satisfies the following equation:

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

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.

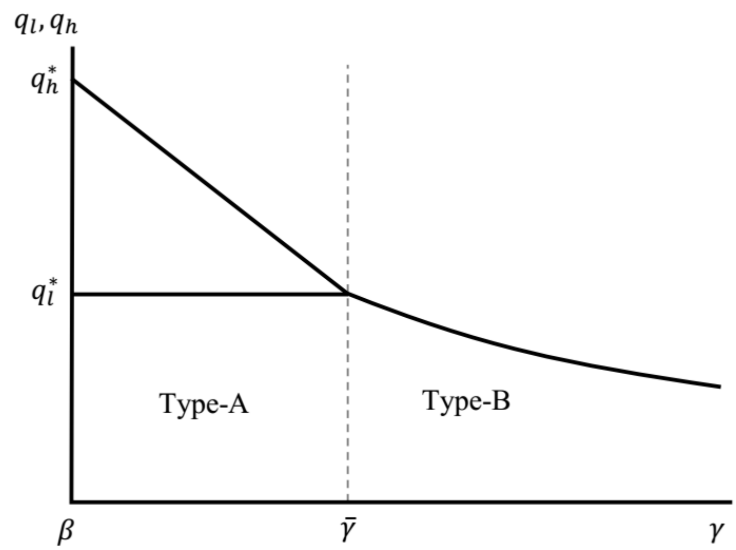

Figure 4: Goods Market Consumption

6 Quantitative Analysis

We can now compare the asymmetric information models with and without the mechanism and address some of the questions above. It is not easy to show, analytically, whether the mechanism is welfare improving or not. We show that the mechanism is welfare improving, however, in the region of parameters that are relevant to the calibration. We also show that the mechanism explains the observed behavior since the 1990s of the U.S. money demand reasonably well.

6.1 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.[14]

The calibration of our three models is more sophisticated and follows the same method as in Berentsen et al. (2018). 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.[15]

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.[16] 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.[17] In search-based monetary models, the measure of sellers n

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

[15] 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.

[16] 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.

[17] Some studies use the yield on corporate bonds with a remaining maturity of 20 years instead (e.g., Aruoba et al.

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 2 shows the targets that are matched directly with the moments in the data.

TABLE 2: 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 2 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 A is chosen such that the velocity of money in the model is equal to the average velocity of money in the data. The parameters Δ_ε and α are jointly chosen by minimizing the sum of squared differences between the model-implied and the observed money demand.[18] 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 3. Table 3 also reports the estimates of the Lucas' methodology.

TABLE 3: CALIBRATION FROM 1990 TO 2019.[a]

Methodology	A	α	Δ_ε	$\widetilde{\gamma}$	Δ	Σ sq. diff.
Symmetric Info.	0.901	0.08	0.01	-	0.0017	0.0471
Asymm. Info. with Mechanism	0.776	0.15	0.06	1.0264	0.0069	0.0512
Asymm. Info. without the Mechanism	0.395	0.51	0.14	1.0595	0.0041	0.0712
Log-Log	0.079	0.16	-	-	0.0019	0.0647
Semi-Log	0.146	2.38	-	-	0.0078	0.0706

[a]Table 3 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.

2011, and Berentsen et al. 2011 and 2015). Here, we follow Berentsen et al. (2018) and use the 10-year government bonds because this measure is widely available across countries and thus can be useful for future comparison.

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

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 0.051. The best fit calibration is provided by the symmetric information model, with a sum of squared differences equal to 0.047.

The preference shock parameter, Δ_{ε}, is 6% in the case of the asymmetric information model with mechanism design, and 1% in the case of the symmetric information model. The values of the other parameters, A and α, are in line with previous studies.

The asymmetric information model without the mechanism is the worst in fitting the data, with a sum of squared differences of 0.0712. 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 5.

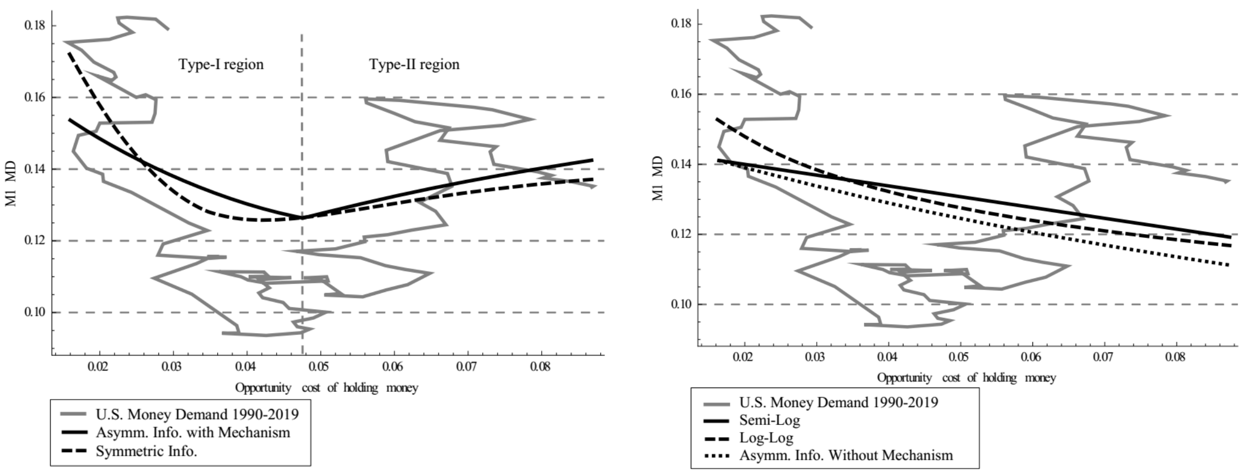

Figure 5: Best Fit Calibration

The left panel of Figure 5 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 5 shows that it is monotonically decreasing in the inflation rate for all of them.

6.2 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.

Table 4: Welfare effects.[a]

	$\pi = 0$	$\pi = 0.01$	$\pi = 0.03$	$\pi = 0.05$	$\pi = 0.1$
Welfare Benefit of the Mechanism	0.0006	0.0011	0.0014	0.0017	0.0032
Welfare Cost of Asymmetric Information	0.0006	0.0011	0.0014	0.0018	0.0034
Combined Welfare Cost	0	0	0	0.0001	0.0002

[a] Table 4 presents the effect of asymmetric information and mechanism design on welfare for different inflation rates.

Table 4 reports the welfare benefit of mechanism design, the welfare cost of asymmetric information, and the combined welfare cost of asymmetric information and mechanism design where this last measure is the sum of the first two measures. Five different hypothetical inflation rates are considered. For inflation rates below 2.64%, the combined welfare cost of asymmetric information and mechanism design is clearly zero as it is the case of type-I equilibrium in which the baseline model collapses to the symmetric information model. The welfare benefit of the mechanism is positive and equal to 0.06% and 0.11% for zero inflation and 1% inflation, respectively. This is because the allocation of the asymmetric information model with the mechanism is different from that of the asymmetric information model without the mechanism.

For 5% and 10% inflation, the combined welfare cost is positive as the equilibrium is of type-II, where the baseline model and the symmetric information model yield different allocations. The combined welfare cost is 0.01% and 0.02% for an inflation rate of 5% and 10%, respectively. The welfare benefit of mechanism design alone is much larger and equal to 0.17% and 0.32%, respectively.

For 3% inflation, the welfare benefit of the mechanism is sizable (0.14%) so that the combined welfare cost is very small.

At the calibrated inflation rate of 2.4%—not reported in the Table—the composite welfare cost is clearly zero while the welfare benefit of the mechanism is 0.13%. It is also evident that at the Friedman rule the welfare benefit of the mechanism and the composite welfare cost are both zero.

The second row in Table 4 reports the welfare cost of asymmetric information. For low inflation rates (i.e. $\pi < 2.64\%$), this measure and the welfare benefit of the mechanism are of the same magnitude. Therefore, the combined effects of asymmetric information and mechanism design on welfare cancel out. For high inflation rates (i.e. $\pi > 2.64\%$), the welfare cost of asymmetric information has a larger magnitude than the welfare benefit of the mechanism. Therefore, the asymmetric model with the mechanism, as opposed to the symmetric information model, reduces welfare for high interest rates.

6.3 Discussion

The calibration results in Table 3 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 5. 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 5.

The calibration results 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. As Figure 6 shows, the mechanism is the driving force in getting an upward-sloping money demand curve. Thus, we argue that mechanism plays a crucial role in improving the fit of the data in an environment where the central bank is not informed about shocks.

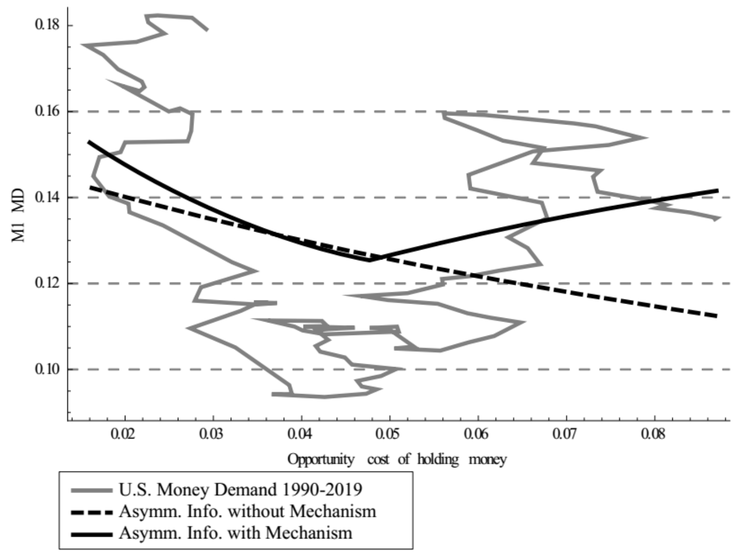

Figure 6: Best Fit Calibration

As discussed earlier, the mechanism is successful in mitigating the inefficiency caused by asymmetric information. In fact, both the baseline model, where both symmetric information and mechanism design coexist, and the symmetric information model, where both are absent, perform very similarly in fitting the observed money demand. This is confirmed by the static analysis in Table 5. The composite welfare cost of asymmetric information and mechanism design is null, or very small, compared to the welfare benefit of the mechanism.

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, e.g., in the form of market intelligence, could have, together with other factors studied in this literature, such as financial innovation, increased financial market participation, and limited commitment, explained part of the behavior of the money demand. Our paper complements this literature.

7 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

8 Appendix I: Robustness

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 0.1037 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	0.577	0.39	0.15	1.094	0.0045	0.1037
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.

8.0.1 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.

9 Appendix II: Data sources

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

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