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Monetary Policy Pass-Through with Central Bank Digital Currency

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Abstract

This paper investigates how the introduction of an interest-bearing central bank digital currency (CBDC) that serves as a perfect substitute for bank deposits as an electronic means of payment affects monetary policy pass-through. When the deposit market is not fully competitive, the CBDC tends to weaken the pass-through of the interest on reserves. The interest on CBDC impacts the deposit market more directly compared with the interest on reserves. The CBDC rate can also have stronger pass-through to the loan market; however, the effect can be dampened by the policy on the interest on reserves. Therefore, coordination between the two policy rates is needed to effectively achieve policy goals.

Topics: Digital currencies and fintech; Monetary policy transmission

JEL codes: E50, E52

1 Introduction

As digital technologies become more prevalent, more businesses have moved online and consumers increasingly turn to the Internet for shopping. For example, according to the Canadian Internet Use Survey, the total spending of Canadian online shoppers reached \$57.4 billion in 2018, compared to \$18.9 billion in 2012, with nearly 84% of Internet users buying goods or services online (the percentage is even higher for younger and richer internet users).[1] This trend is likely to continue in the foreseeable future. Among the payment methods for online shopping, the most common were credit cards and online payment services, such as PayPal or Google Checkout. Other methods for online purchases were electronic bank transfers, rewards points or redemption programs, and a virtual wallet, such as Apple Pay or Masterpass. Traditional paper money issued by central banks cannot be used directly in the digital world, where buyers and sellers are often spatially separate. In addition, cash is losing ground to digital means of payment at points of sale. For example, the Bank of Canada's 2017 Methods-of-Payment Survey (see Henry et al. 2018) suggests that the shares of cash volume (33%) and value (15%) continue to decrease, compared with 2009 (54% and 23%, respectively) and 2013 (44% and 23%, respectively). Similar trends are also observed in many other countries.

The continued decline in cash usage has led to some concerns, including the loss of a public means of payment as an outside option to private payment instruments, and the weakening of the central banks' ability to conduct monetary policies. As a result, several central banks are considering issuing a central bank digital currency (CBDC), a widely accessible digital form of central bank money that can be used for retail payments.[2] In particular, the interest on CBDC can serve as a new policy instrument to complement traditional monetary policy instruments, such as the

[1] https://www150.statcan.gc.ca/n1/pub/89-28-0001/2018001/article/00016-eng.htm

[2] For a comprehensive set of reasons and arguments for issuing a CBDC, see Engert and Fung (2017) and references therein.

interest on central bank reserves (which is a form of central bank digital money that cannot be used directly for retail payments). Some important questions to be explored are: How would the CBDC rate affect the pass-through of more traditional monetary policy instruments, such as the interest on reserves? How would the pass-through of the CBDC rate work? How should the different policy instruments be coordinated to achieve the intended policy objectives? This paper takes the first step to formalize the analysis of monetary policy implementation in the presence of CBDC. We study how an interest-bearing, widely accessible, and deposit-like CBDC (in the sense that it is a perfect substitute for bank deposits in its payment function) interacts with the conventional monetary policy instruments such as the interest on reserves.

Our analytical framework is based on the model developed in Chiu et al. (2019). Private banks create deposits and make loans. Households use demand deposits and the CBDC for online transactions, and entrepreneurs can use loans to invest in projects. Banks are required to hold reserves for the creation of deposits. In this environment, the two policy instruments, the interest on reserves and the interest on CBDC, affect the economy through different channels. The interest on reserves affects deposits and loans by affecting the cost of creating deposits (when the reserve requirement binds) or the attractiveness of loans relative to reserves (when the reserve requirement is slack). The CBDC rate directly affects (and forms the lower bound of) the deposit rate because CBDC is a perfect substitute for bank deposits as an electronic means of payment. Using this framework, we explore how the introduction of the CBDC changes the policy effect of the interest on reserves and how the pass-through of the CBDC rate is affected by the reserve rate.

We find that the CBDC rate, while effective, fully dictates the deposit rate and therefore eliminates the pass-through from the reserve rate to the deposit rate. The effect of the CBDC rate on the pass-through from the reserve rate to the deposit quantity and the loan rate and quantity is more complex and depends on the market structure of the banking sector. When the deposit market is not fully competitive, the CBDC tends to weaken the pass-through of the reserve rate, as the CBDC rate itself dictates the economy. When the deposit market is perfectly competitive, the CBDC tends to strengthen the pass-through from the reserve rate to the loan rate and quantity because the effect of the reserve rate is channelled solely to the loan market, given that the deposit rate is fixed at the CBDC rate.

As a new policy instrument, the CBDC rate has stronger pass-through to the deposit market than the reserve rate when the deposit market is not perfectly competitive. This is because banks do not fully pass the increase in the reserve rate to depositors as a higher deposit rate when they have market powers on the deposit market and households cannot directly hold reserves. In contrast, the CBDC is a perfect substitute for deposits as an electronic means of payment, so the bank is forced to match the CBDC rate one for one.

The effectiveness of the CBDC rate also depends on the reserve rate. For example (when the deposit market is not fully competitive), its positive effect on lending is maximized if the reserve rate is low. The interplay between the two policy instruments suggests that they need to be coordinated to achieve intended policy goals. For example, when the deposit market is not fully competitive, in order to expand lending, the central bank can increase the CBDC rate coordinated with a lower reserve rate. If the central bank wants to improve the efficiency in electronic payments while not expanding the private bank's balance sheet significantly, it should increase both the CBDC rate and the rate on reserves.

This paper contributes to the growing literature on digital currencies and CBDC. It builds on Chiu et al. (2019), who develop a model with an imperfectly competitive banking sector to study how the CBDC affects the intermediation of commercial banks. It is also closely related to Zhu and Hendry (2019), who discuss the optimal monetary policy in the face of a privately issued digital currency. An incomplete list of other related papers includes Keister and Sanches (2019), Andolfatto (2020), Brunnermeier and Niepelt (2019), Davoodalhosseini (2018), and Barrdear and Kumhof (2016).[3]

The general framework follows the New Monetarist models developed by Lagos and Wright (2005) and Rocheteau and Wright (2005). Berentsen, Camera, and Waller (2007) were the first to incorporate banking into the framework. Our banking model differs from Berentsen, Camera, and Waller (2007) in two dimensions. First, banks in our model engage in imperfect competition. Second, banks in our model create inside money that can be used directly as a means of payment.

Some of the results in this paper depend on the market power of banks in the deposit market. Dreschler, Savov, and Schnabl (2017) and Wang et al. (2020) provide empirical evidence that banks engage in imperfect competition in the deposit market and explore the implication of this on monetary policy pass-through. In particular, Dreschler, Savov, and Schnabl (2017) show that market concentration weakens the pass-through from the policy rate to the deposit rate. Dreschler, Savov, and Schnabl (2020) study the effect of this market power on maturity transformation and interest rate risk. Kurlat (2019) shows that this market power raises the cost of inflation.

Lastly, there are several discussion papers on the monetary policy framework with CBDC. These discussion papers include Meaning et al. (2018) and Bordo and Levin (2017). Our paper investigates this issue formally with a model. Unlike many of these papers, this paper focuses on normal period operations and does not consider

[3]For further reference on e-money and digital currency, see Agur, Ari, and Dell'Ariccia (forthcoming); Chapman and Wilkins (2019); Chiu and Wong (2015); Davoodalhosseini and Rivadenyra (2020); Engert and Fung (2017); Fung and Halaburda (2016); Kahn, Rivadeneyra, and Wong (2018); Mancini-Griffoli et al. (2018); Schilling and Uhlig (2019); and references therein.

the issues related to the effective zero lower bound of the nominal interest rate.[4]

The rest of the paper is organized as follows. Section 2 describes the environment. Section 3 characterizes the equilibrium. Section 4 studies the pass-through of monetary policy with a perfectly competitive banking sector. Section 5 investigates the pass-through with an imperfectly competitive deposit market modelled by Cournot competition. Section 6 summarizes the results and concludes.

2 Environment

The model follows a version of Chiu et al. (2019). Time is discrete and continues forever from 0 to ∞. There are four types of agents: a continuum of households with measure 2, a continuum of entrepreneurs with measure 1, a finite number of N bankers, and the government. The discount factor from current to the next period is $0 < \beta < 1$. each date t, agents interact sequentially in two stages: a frictional decentralized market (DM), and a frictionless centralized market (CM). There are two perishable goods: good y in the DM, and good x in the CM.

Households are divided into two permanent types, buyers and sellers, each with measure 1. In the CM, both types work and consume x. Their labor h is translated into x one-for-one. In the DM, buyers and sellers meet bilaterally and trade good y. Buyers want to consume y, which can be produced on the spot by sellers. The utility from consumption is $u(y)$ with $u' > 0$ and $u'' < 0$. The disutility from production is y. Let y^* be the socially efficient consumption, which solves $u'(y^*) = 1$. To summarize, buyers and sellers have period utilities given respectively by

$$\begin{aligned}\boldsymbol{U}^B(x,y,h) &= U(x) - h + u(y), \\ \boldsymbol{U}^S(x,y,h) &= U(x) - h - y.\end{aligned}$$

[4] As pointed out by Engert and Fung (2017), the key to breaking the effective lower bound is to eliminate large denomination notes instead of issuing CBDC. Agarwal and Kimball (2015) discuss a way to break the effective lower bound without eliminating bank notes or introducing CBDC.

Young entrepreneurs are born in the CM and will become old and die in the next CM. Entrepreneurs cannot work in the CM and care about only consumption when old. Young entrepreneurs are endowed with an investment opportunity that transforms x current CM goods to $f(x)$ CM goods in the next period, where $f'(0) = \infty$, $f'(\infty) = 0$, $f' > 0$, and $f'' < 0$.

Given the preferences and endowment patterns, there are gains from trade between buyers and sellers and between entrepreneurs and households. Specifically, buyers would like to consume DM goods produced by sellers, and entrepreneurs would like to borrow from households to invest in their investment opportunities. However, we assume that households and entrepreneurs lack commitment and cannot enforce debt repayment, so credit arrangement among them is not viable.

Like entrepreneurs, young bankers are born in the CM and become old and die in the next CM. They cannot work in the CM and care about only consumption when old. Unlike households and entrepreneurs, bankers can commit to repay and enforce payment. As a result, banks can act as intermediaries between households and entrepreneurs to finance the investment projects, and bank deposits can be used as a medium of exchange to facilitate trading between buyers and sellers in the DM.

The government issues three instruments. First, it issues two forms of fiat objects—physical cash (or money) and digital cash (or CBDC)—that can be used as means of payment. The supplies of cash and CBDC, M_t and H_t, grow at a constant gross rate μ. The government also issues reserves, which can only be held by banks and cannot be used for retail payments. The government stipulates a reserve requirement that χ fraction of banks' deposits must be held in cash and/or reserves (but not CBDC).[5] Cash pays no interest, while the CBDC and reserves earn nominal interest rates i_H and i_R, respectively. Interest payments on CBDC and reserves,

[5]The assumptions that the supplies of cash and CBDC grow at the same rate, and that CBDC cannot be used to meet reserve requirements, can be relaxed.

and changes in money supplies, are implemented through lump-sum transfer to or taxes on households.

There are three types of meetings in the DM, depending on which means of payment can be used for transactions. From a buyer's perspective, with α_1 probability, a buyer enters into a type 1 meeting, where only physical cash/money can be used. With α_2 probability, a buyer enters into a type 2 meeting, where only electronic means of payments, bank deposits and CBDC, can be used. With α_3 probability, a buyer enters into a type 3 meeting, where all three means of payments can be used. The three types of meetings can be interpreted as follows. Type 1 meetings are transactions in local stores that do not have access to devices that enable electronic payments; type 2 meetings are online transactions where the buyers and sellers are spatially separated and can only use electronic means of payment; and type 3 meetings occur at local stores with point-of-sale (POS) machines, and hence both physical and electronic payment methods are accepted.

Agents in our model economy engage in the following activities. In every CM, young bankers issue deposits to households in exchange for cash and also issue some deposits to entrepreneurs as loans. Entrepreneurs can use deposits to buy x from buyers to invest. Another interpretation is that entrepreneurs hire buyers to produce x and use borrowed deposits to pay wages. In the DM, buyers use a combination of cash, CBDC, and deposits to purchase good y from sellers. In the next CM, entrepreneurs sell some of the investment output to obtain cash or deposits, which are used to pay back the loans, and retain some output for their own consumption. Old bankers then use the loan payments to extinguish the deposits held by the households and retain some payments from the entrepreneurs for their own consumption.

3 Equilibrium

In this section, we characterize the equilibrium of the economy. We will lay out the problems faced by the household (without CBDC and with CBDC), the entrepreneur and the bank. We then combine the solutions to all agents' problem to define the equilibrium of the economy.

3.1 Households

We first examine the buyer's maximization problem and then the seller's problem. Before that, we introduce some notations that we will use in this subsection. Let W and V be the value function of households in the CM and DM, respectively. Let ϕ and φ be respectively the value of cash and CBDC in terms of CM good. We suppress the time subscript and use the accent "ˆ" to denote variables in the next period.

3.1.1 No CBDC

We first analyze the case without CBDC. In the CM, the buyer chooses consumption x, labor h, and the real cash balance and the deposit balance in the next period, $\hat{z}^M$ and $\hat{d}$, to solve[6]

$$\begin{aligned} W^B\left(z^M, d\right) &= \max_{x,h,\hat{z}^M,\hat{d}} \left\{U(x) - h + \beta V^B\left(\hat{z}^M, \hat{d}\right)\right\} \\ \text{st. } x &= h + z^M + d + T - \frac{\phi}{\hat{\phi}}\hat{z}^M - \psi\hat{d}, \end{aligned}$$

where $\psi\hat{d}$ is the real value of deposits today. The real return on cash balances is $\hat{\phi}/\phi - 1$, and the real interest rate on deposits is $1/\psi - 1$. Substitute out h using the budget equation and rewrite the buyer's CM problem as

$$W^B\left(z^M, d\right) = z^M + d + T + \max_x \left[U(x) - x\right] + \max_{\hat{d},\hat{z}^M} \left\{-\frac{\phi}{\hat{\phi}}\hat{z}^M - \psi\hat{d} + \beta V^B\left(\hat{z}^M, \hat{d}\right)\right\}.$$

[6] The type of DM meeting is not revealed until the start of the DM. Therefore, buyers hold a portfolio of fiat money and bank deposits.

This shows that $W^B(z,d)$ is linear in z and d. The first-order conditions (FOCs) are

$$
\begin{aligned}
x &: U'(x) = 1 \\
\hat{Z} &: \frac{\phi}{\hat{\phi}} \geq \beta V_1^B\left(\hat{z}^M, \hat{d}\right), \text{ with equality if } \hat{z}^M > 0 \\
\hat{D} &: \psi \geq \beta V_2^B\left(\hat{z}^M, \hat{d}\right), \text{ with equality if } \hat{d} > 0,
\end{aligned}
$$

where the subscripts indicate the derivative with respect to corresponding arguments. Two standard results are that all buyers will choose the same portfolio $(\hat{z}^M, \hat{d})$, and $W^B(z^M, d)$ is linear in (z^M, d) with $W_1^B(z^M, d) = W_2^B(z^M, d) = 1$.

The buyer's DM problem is

$$
\begin{aligned}
V^B\left(z^M, d\right) &= \alpha_1\left[u \circ Y\left(z^M\right) - P\left(z^M\right)\right] + \alpha_2\left[u \circ Y(d) - P(d)\right] \\
&\quad + \alpha_3\left[u \circ Y\left(z^M + d\right) - P\left(z^M + d\right)\right] + W^B\left(z^M, d\right),
\end{aligned} \tag{1}
$$

where $Y(\cdot)$ and $P(\cdot)$ are the terms of trade (TOT) and represent the amount of good y being traded and the amount of payment, respectively. We will discuss the determination of the TOT later.

Now we characterize the seller's problems. A standard result in the literature is that the seller will choose to enter the DM with zero liquidity balances, or $\hat{z}^M = \hat{d} = 0$, because he/she does not need (costly) liquidity in the DM. Using this result, we can formulate the seller's CM problem as

$$
\begin{aligned}
W^S\left(z^M, d\right) &= \max_{x,h}\left\{U(x) - h + \beta V^S(0,0)\right\} \\
\text{st. } x &= h + z^M + d + T.
\end{aligned}
$$

Similar to the buyer's maximization problem, we have $U'(x) = 1$, and W^S is linear in z^M and d. The seller's DM problem is

$$
\begin{aligned}
V^S(0,0) &= \alpha_1\left[P(\tilde{z}) - Y(\tilde{z})\right] + \alpha_2\left[P\left(\tilde{d}\right) - Y\left(\tilde{d}\right)\right] \\
&\quad + \alpha_3\left[P\left(\tilde{z} + \tilde{d}\right) - Y\left(\tilde{z} + \tilde{d}\right)\right] + W^S(0,0),
\end{aligned}
$$

where $\tilde{d}$ and $\tilde{z}$ are the cash and deposit holdings of his trading partner.

The TOT are determined by buyers making take-it-or-leave-it offers. Let $\mathcal{L}$ be the buyer's total available liquidity, which is equal to $\hat{z}^M$ in type 1 meetings, $\hat{d}$ in type 2 meetings, and $\hat{d} + \hat{z}^M$ in type 3 meetings. The buyer offers output-payment pair (y, p) to

$$\max_{y,p} \left[u\left(y\right) - p\right] \text{ s.t. } p \geq y \text{ and } p \leq \mathcal{L},$$

where the first constraint is the seller's participation constraint and the second is the liquidity constraint. The TOT as a function of the buyer's total available liquidity $\mathcal{L}$ is

$$Y\left(\mathcal{L}\right) = P\left(\mathcal{L}\right) = \min(y^*, \mathcal{L}). \tag{2}$$

In other words, if the real value of available payment balances is enough to purchase the optimal amount, then the optimal amount is traded; otherwise, the buyer spends all available payment balances.

Combining the FOCs of buyers, (1) and (2), we obtain the buyer's demand for payment balances,

$$\begin{aligned} \frac{\phi}{\beta\hat{\phi}} &\geq \alpha_1\lambda\left(\hat{z}^M\right) + \alpha_3\lambda\left(\hat{z}^M + \hat{d}\right) + 1, \text{ with equality iff } \hat{z}^M > 0, && (3) \\ \frac{\psi}{\beta} &\geq \alpha_2\lambda\left(\hat{d}\right) + \alpha_3\lambda\left(\hat{z}^M + \hat{d}\right) + 1, \text{ with equality iff } \hat{d} > 0, && (4) \end{aligned}$$

where $\lambda\left(\mathcal{L}\right) = \max\left[u'\left(\mathcal{L}\right) - 1, 0\right]$ is the liquidity premium. At the steady state, $\phi/\hat{\phi} = \mu$, and the above two equations reduce to

$$\begin{aligned} \iota &\geq \alpha_1\lambda\left(z^M\right) + \alpha_3\lambda\left(z^M + d\right), \text{ with equality iff } z^M > 0, && (5) \\ \frac{\psi}{\beta} - 1 &\geq \alpha_2\lambda\left(d\right) + \alpha_3\lambda\left(z^M + d\right), \text{ with equality iff } d > 0, && (6) \end{aligned}$$

where $\iota = \mu/\beta - 1$ is the nominal interest rate using the Fisher's equation. Here, (5) defines the aggregate demand for cash balances z^M as a function of d. Given this, (6) defines the aggregate inverse demand function for deposits d given ι, i.e.,

$\psi = \Psi(d;\iota)$. In the following, we suppress the dependence of Ψ on ι to ease notations.

These two equations are intuitive. The first one states that the marginal cost of holding one unit of cash (the left-hand side) should be equal to its marginal benefit (the right-hand side), which comes from the fact that the buyer can use the marginal unit of cash in type-1 and type-3 meetings to derive $\lambda\left(z^M\right)$ and $\lambda\left(z^M+d\right)$ additional units of utility, respectively, from consumption. As shown in Chiu et al. (2019), the demand function $\Psi(d)$ is downward sloping.

3.1.2 With CBDC

With CBDC, the buyer's problem becomes

$$\begin{aligned} W^B\left(z^H, z^M, d\right) &= \max_{x,h,\hat{z}^H,\hat{z}^M,\hat{d}} \left\{U(x) - h + \beta V^B\left(\hat{z}^H, \hat{z}^M, \hat{d}\right)\right\} \\ \text{st. } x &= h + z^H + z^M + d + T - \frac{\varphi}{\hat{\varphi}(1+i_H)}\hat{z}^H - \frac{\phi}{\hat{\phi}}\hat{z}^M - \psi\hat{d}, \end{aligned}$$

where $\hat{z}^H$ is the real value of CBDC that the buyer brings into the next period and φ is the price of CBDC in terms of the CM good and i_H is the CBDC rate. The real return on CBDC balances is $(1+i_H)\hat{\varphi}/\varphi - 1$. Similar to the case without CBDC, $W^B\left(z^H, z^M, d\right)$ is linear in z^H, z^M and d.

Because CBDC is a perfect substitute for bank deposits, i.e., it can be used in transactions where deposits can be used, the buyer's DM problem can be written as

$$\begin{aligned} V^B\left(z^H, z^M, d\right) &= \alpha_1\left[u\circ Y\left(z^M\right) - P\left(z^M\right)\right] + \alpha_2\left[u\circ Y\left(d+z^H\right) - P\left(d+z^H\right)\right] \quad (7) \\ &\quad + \alpha_3\left[u\circ Y\left(z^H+z^M+d\right) - P\left(z^H+z^M+d\right)\right] + W^B\left(z^H, z^M, d\right). \end{aligned}$$

Following the same calculation as in the case without CBDC, we obtain the following conditions that characterize the steady state equilibrium (where $\varphi/\hat{\varphi} = \mu$):

$$\frac{1+\iota}{1+i_H} - 1 \geq \alpha_2 \lambda \left(z^H + d\right) + \alpha_3 \lambda \left(z^H + z^M + d\right), \text{ with equality iff } z^H > 0, \quad (8)$$

$$\iota \geq \alpha_1 \lambda \left(z^M\right) + \alpha_3 \lambda \left(z^H + z^M + d\right), \text{ with equality iff } z^M > 0 \quad (9)$$

$$\frac{\psi}{\beta} - 1 \geq \alpha_2 \lambda \left(z^H + d\right) + \alpha_3 \lambda \left(z^H + z^M + d\right), \text{ with equality iff } d > 0. \quad (10)$$

As before, this system of equations defines the inverse demand for bank deposits when there is CBDC, which is denoted as $\tilde{\Psi}(d)$ to distinguish it from the demand for deposits when there is no CBDC, $\Psi(d)$. Also define $\underline{d}$ such that $\left(z^M, \underline{d}\right)$ solves equations (5) and (6). Then, we have the following Lemma:

Lemma 1 *$\tilde{\Psi}(d)$ is decreasing in d and increasing in ι. In addition, there exists $\underline{d}$ such that $\tilde{\Psi}(d) = \frac{1+i_h}{\mu_h}$ if $d \in [0, \underline{d}]$ and $\tilde{\Psi}(d) = \Psi(d)$ if $d > \underline{d}$.*

Lemma 1 says that introducing the CBDC truncates the original inverse demand function for deposits. With the CBDC, bankers can no longer drive the deposit rate below $\frac{1+i_h}{\mu} - 1$, the rate of return offered by the CBDC; otherwise, buyers will choose to hold the CBDC instead.

3.2 Entrepreneurs

The entrepreneurs are price takers and hence decide their demand for loans given the loan rate ρ. Their problem is

$$\max_{\ell} \{f(\ell) - (1+\rho)\ell\}.$$

This implies that the inverse loan demand for a firm is $f'(\ell) = 1 + \rho$, which defines the aggregate inverse loan demand function,

$$L^d(\rho) = f'^{-1}(1+\rho).$$

Obviously $L^d(\cdot)$ is a decreasing function, i.e., the demand for loans decreases with the loan rate.

3.3 Bankers

We assume that the lending market is perfectly competitive and that banks engage in a Cournot competition in the deposit market (as the number of banks approaches infinity, the deposit market will become perfectly competitive as well). Bankers face a reserve requirement. At the end of each CM, the real value of a bank's reserve holding must be at least χ fractions of its total deposits, where χ is set exogenously by the government. Banks buy cash in the CM and translate it into reserves at the central bank. The central bank pays interest on reserves at rate i_R. We assume that the CBDC cannot be used to satisfy the reserve requirement. As households value the CBDC due to its payment function, the bank will find it too expensive to hold CBDC (see Chiu et al. 2019). In addition, as reserves pay interest while cash does not, the bank will hold only reserves to meet the reserve requirement. In the analysis below, we use these results and exclude CBDC and cash from the bank's balance sheet.

Banker j chooses deposits d_j, loans ℓ_j, and reserves z_j to maximize its utility, taking the market loan rate ρ and other banks' deposits $d_{-j} = \sum_{i \neq j} d_i$ as given:

$$\begin{aligned} \max_{z_j, \ell_j, d_j} & \left\{ (1+\rho)\,\ell_j + \frac{(1+i_R)\,z_j}{\mu} - d_j \right\} \\ \text{st} \quad & \ell_j + z_j = \Psi\left(d_{-j} + d_j\right) d_j, \\ & z_j \geq \chi \Psi\left(d_{-j} + d_j\right) d_j. \end{aligned} \tag{11}$$

The banker receives the repayment of loans from entrepreneurs (principal plus interest) $(1+\rho)\,\ell_j$, the post-inflation value of reserve holdings, and redeems the deposits d_j. The first equation in the constraint is the balance sheet identity of the bank at the end of the first CM. The right-hand side is the liability, the real value of deposits. The left-hand side is the asset, which includes reserves and loans. The second constraint reflects the reserve requirement. Using the balance sheet identity and the reserve requirement to eliminate z_j, one can rewrite the problem as

$$\max_{z_j,\ell_j,d_j}\left\{\left(1+\rho-\frac{1+i_R}{\mu}\right)\ell_j-\left[d_j-\frac{(1+i_R)\,\Psi\left(d_{-j}+d_j\right)d_j}{\mu}\right]\right\} \tag{12}$$

$$\text{st}\quad \ell_j\leq(1-\chi)\,\Psi\left(d_{-j}+d_j\right)d_j. \tag{13}$$

Given each ρ, this defines a best response function that maps d_{-j} to d_j. We look for a symmetric equilibrium where all banks issue the same amount of deposits, i.e., $d_{-j}=(N-1)\,d_j$ for every j. Once we solve for d_j, we can compute the loan supply at ρ. Throughout the paper, we assume that the following holds.

Assumption 1 *a) Given any $d_{-j}\in[0,y^*)$ and $\kappa>\beta$, either there exists a unique $d_j>0$ such that $\Psi'\left(d_{-j}+d\right)d+\Psi\left(d_{-j}+d\right)\gtreqless\kappa$ if $d\lesseqgtr d_j$, or $\Psi'\left(d_{-j}+d\right)d+\Psi\left(d_{-j}+d\right)<\kappa$ for all $d\geq 0$. b) In addition, $\Psi'(Nd)\,d+\Psi(Nd)$ decreases with d on $[0,y^*/N)$.*

Part (a) of this assumption states that $\Psi'\left(d_{-j}+d\right)d+\Psi\left(d_{-j}+d\right)$ as a function of d should cross the horizontal axis from the above and at most once, and ensures that the best response of banker j to any amount of deposits (less than y^*) created by other banks is unique. Part (b) ensures that there is at most one symmetric Nash equilibrium of the Cournot game.[7]

Chiu et al. (2019) show that under Assumption 1, there is a unique symmetric equilibrium in the Cournot game for each ρ, which gives us the loan supply curve $L^s(\rho)$ without CBDC. If there is CBDC, the bankers' problem is modified slightly, with Ψ replaced by $\tilde{\Psi}$. Again, under Assumption 1, there is a unique symmetric equilibrium in the Cournot game, which determines the loan supply curve with CBDC $\tilde{L}^s(\rho)$.

[7]One can show that this assumption holds if u is CRRA utility with a coefficient less than 1 and $\alpha_3=0$. By continuity, this would hold if α_3 is sufficiently small and if the utility function is given by

$$u(y)=\frac{(y+\varepsilon)^{1-\sigma}-\varepsilon^{1-\sigma}}{1-\sigma},$$

where $\sigma<1$ and ε is sufficiently small.

3.4 Equilibrium

Given Ψ and $\tilde{\Psi}$, which are solved from the households' problem, the loan supply functions $L^s(\rho)$ and $\tilde{L}^s(\rho)$ are obtained from Cournot competition among banks. Then the equilibrium loan rate with or without CBDC is determined by $L^s(\rho) = L^d(\rho)$ or $\tilde{L}^s(\rho) = L^d(\rho)$. Because L^d is strictly decreasing, the equilibrium with or without CBDC is unique if L^s or $\tilde{L}^s$ is weakly increasing. Chiu et al. (2019) show that if $D\Psi(D)$ is increasing, both $L^s(\rho)$ and $\tilde{L}^s(\rho)$ are increasing, and hence the following proposition holds.

Proposition 1 *If Assumption 1 holds and $D\Psi(D)$ is increasing, there is a unique equilibrium with or without CBDC.*

4 Pass-Through: Competitive Deposit Market

In the rest of the paper, we analyze how introducing CBDC affects the monetary policy pass-through and how to coordinate the interest on reserves i_R and and the interest on CBDC i_H when there is CBDC. To achieve this, we first analyze the economy without CBDC and then the economy with CBDC. To provide a benchmark, we first investigate the case where banks are perfectly competitive in the deposit market as well. In this case, we can obtain analytical results. In the next section, we will analyze the pass-through when banks have market powers in the deposit market through numerical analysis.

4.1 Without CBDC

With competitive deposit and loan markets, banks take the policy rate i_R and the market interest rates ρ (loan rate) and ψ (deposit price) as given to solve

$$\max_{z,\ell,d} \left\{ (1+\rho)\,\ell - d + \frac{z\,(1+i_R)}{\mu} \right\}$$
$$\text{st.} \quad \ell + z = \psi d,\ z \geq \chi\psi d.$$

To simplify the analysis, we rewrite the problem as

$$\max_{z,\ell} \left\{ i_\ell \ell + i_R z - i_d(\ell + z) \right\}$$
$$\text{st.} \quad z \geq \frac{\chi}{1-\chi}\ell,$$

where

$$i_\ell \equiv \mu(1+\rho) - 1,$$
$$i_d = \frac{\mu}{\psi} - 1,$$

are the nominal loan rate and the nominal deposit rate, respectively. To study the effect of reserve rate i_R on the quantity and rates of loans and deposits, we distinguish two cases. In the first case, the reserve requirement binds, and in the second case, the reserve requirement is slack.

When the reserve requirement binds, the equilibrium loan and demand rates (i_ℓ, i_d) solve

$$(1-\chi)\, i_\ell + \chi i_R = i_d$$
$$\ell\,(i_\ell) = (1-\chi)\, \hat{D}\,(i_d)\,,$$

where $\hat{D} = \psi D = \frac{\mu}{1+i_d} D(i_d)$ and $D\,(i_d)$ is the demand function for deposits obtained from the household's problem. The first equation says that the deposit rate is the weighted average of the nominal return of the bank's assets, loans, and reserves, so that the bank earns zero profits in equilibrium. The second equation is the reserve requirement at equality. This case arises in the equilibrium if and only if the (i_ℓ, i_d) that solve the above two equations satisfy $i_\ell > i_d > i_R$, which occurs when i_R is sufficiently low.

To investigate the pass-through of i_R, we totally differentiate the equilibrium conditions and obtain

$$\partial i_\ell / \partial i_R = \frac{(1-\chi)\,\chi \hat{D}'(i_d)}{\ell'(i_\ell) - (1-\chi)^2 \hat{D}'(i_d)} < 0, \tag{14}$$

$$\partial i_d / \partial i_R = \frac{\chi \ell'(i_\ell)}{\ell'(i_\ell) - (1-\chi)^2 \hat{D}'(i_d)} > 0. \tag{15}$$

This means that increasing i_R decreases the lending rate and increases the deposit rate. The intuition is as follows. When the reserve requirement binds, the bank's two asset categories, reserves and loans, are complements and bundled together and must change in the same direction. A higher reserve rate increases the return of the bank's asset bundle and a competitive bank passes the higher return on its assets to households by offering a higher deposit rate. This causes deposits to expand and enables the bank to issue more loans, inducing a downward pressure on the loan rate. From an alternative perspective, when the reserve requirement binds, the reserve requirement consists of a cost for deposit taking and lending: lending gives a higher return, but the bank must invest on the reserves with a lower return. A higher i_R reduces the cost of holding reserves and encourages the bank to expand deposits and lending, which puts an upward pressure on the deposit rate and a downward pressure on the loan rate.

Now consider the case where the reserve requirement is slack, which is likely to occur when i_R is sufficiently large. In this case, the equilibrium loan and deposit rates must satisfy $i_\ell = i_d = i_R$; otherwise, banks earn either negative profits or unbounded profits, which cannot arise in the equilibrium. In this case, there is perfect pass-through from the reserve rate to the deposit and loan rate as $\partial i_\ell / \partial i_R = \partial i_d / \partial i_R = 1$. When the reserve requirement is slack, the bank invests on the two assets such that the rates of return on reserves and loans are equalized, and by perfect competition, banks offer the same rate to depositors. In this case, the two assets are substitutes. If i_R increases, then banks will substitute out of loans into reserves until the loan rate equals i_R. At the same time, the competitive bank offers a higher deposit rate and attracts more deposits. The bank hold the additional deposits in the form of reserves.

Note that the pass-through of the reserve rate depends crucially on whether the reserve requirement binds. From equations (14) and (15), we have $\partial i_\ell / \partial i_R > -1$ and $\partial i_d / \partial i_R < 1$ if χ is small because $\ell'(i_\ell) < 0$. This suggests that the pass-through from i_R to i_d and i_ℓ may be imperfect when the reserve requirement binds. In contrast, when the reserve requirement is slack, there is perfect pass-through from i_R to i_d and i_ℓ. Another related result is that imperfect pass-through does not necessarily suggest that banks have market powers.[8]

4.2 With CBDC

Now we introduce CBDC that pays a nominal interest rate i_H. The CBDC rate forms a lower bound on i_d. If i_H is less than or equal to the deposit rate in the absence of CBDC (call it i_d^0), then i_H does not affect the economy, and the equilibrium and the pass-through of i_R remain the same as in the case without CBDC. In other words, the cutoff value for i_H at which CBDC starts to affect the economy is i_d^0 (which depends on the reserve rate i_R). In the analysis below, we introduce CBDC to the economy in two cases, depending on whether the reserve requirement binds (in the absence of CBDC).

First suppose that the reserve requirement binds in the absence of CBDC, which implies $i_R < i_d^0 < i_\ell^0$.[9] For the CBDC to affect the economy, the CBDC rate must be set to be larger i_d^0, which will force the bank to offer $i_d = i_H$. The loan rate as a function of the two policy rates, i_R and i_H, is given by

$$(1-\chi)\, i_\ell + \chi i_R = i_H.$$

[8] Another remark is that the results we obtained above remain valid even if the central bank lends to commercial banks. As long as there is a limit to central bank lending, the pass-through is imperfect if the bank's borrowing constraint is binding, and perfect if the constraint is slack. In the special case with unconstrained central bank lending, the pass-through is perfect.

[9] One observation is that i_H must be larger than i_R if the CBDC affects the economy.

The pass-through from i_R to i_d and i_ℓ is described by

$$\frac{\partial i_d}{\partial i_R} = 0, \tag{16}$$
$$\frac{\partial i_\ell}{\partial i_R} = -\chi/(1-\chi) < 0. \tag{17}$$

Obviously, when the CBDC rate dictates the deposit rate, the reserve rate does not affect the deposit rate.[10] Similar to the case without the CBDC, a higher i_R lowers the loan rate because it lowers the cost of holding reserves, and the pass-through from i_R to i_ℓ is imperfect when χ is small in the sense that $\partial i_\ell/\partial i_R > -1$. However, quantitatively CBDC strengthens the pass-through of i_R, which can be seen by comparing (14) with (17). Intuitively, without CBDC, an increase in i_R leads to an increase in i_d. This increases the funding cost of banks and hence partially offsets the positive effect of i_R. In contrast, if the bank is forced to pay depositors the CBDC rate, which is already higher than the deposit rate in the absence of CBDC, then it will not increase the deposit rate in response to a change in i_R.[11]

The loan quantity can be calculated from the loan demand function $\ell(i_\ell)$. The amount of deposits can be derived from the binding reserve requirement as $\hat{d} = \frac{1}{1-\chi}\ell$. Note that since CBDC and deposits are perfect substitutes, the CBDC rate determines the demand for total electronic liquidity through the household's liquidity demand function $\tilde{D}(i_d)$. The effects of the reserve rate on the amounts of loans and deposits are described by

$$\frac{\partial \ell}{\partial i_R} = \ell^{d\prime}(i_\ell)\frac{\partial i_\ell}{\partial i_R} = -\frac{\chi}{1-\chi}\ell^{d\prime}(i_\ell) > 0,$$
$$\frac{\partial \hat{d}}{\partial i_R} = \frac{1}{1-\chi}\frac{\partial \ell}{\partial i_R} = -\frac{\chi}{(1-\chi)^2}\ell^{d\prime}(i_\ell) > 0.$$

[10] When CBDC forces the bank to pay a high deposit rate compared to the equilibrium without CBDC. A slight increase in i_R is not enough to compensate for an increase in i_d. Hence, banks keep the deposit rate fixed.

[11] Note that if i_R keeps increasing, then the implied i_d in the absence of CBDC may exceed i_H, and the CBDC will stop affecting the economy.

Given that the deposit rate is fixed at i_H, a higher i_R allows the bank to pass the benefit to borrowers by offering them a lower loan rate. This lower loan rate induces an expansion of loans ($\ell \uparrow$), which is supported by higher deposit taking ($\hat{d} \uparrow$). Given that the demand for total electronic liquidity is fixed against i_R, a higher reserve rate induces the household to substitute out of CBDC into deposits: $\frac{\partial z^h}{\partial i_R} = -\frac{\partial \hat{d}}{\partial i_R} < 0$.

The pass-through of the CBDC rate to the deposit and loan rates is described by

$$\frac{\partial i_d}{\partial i_H} = 1, \tag{18}$$

$$\frac{\partial i_\ell}{\partial i_H} = 1/\left(1-\chi\right) > 0. \tag{19}$$

The effects of the CBDC rate on the quantities are given by

$$\begin{aligned}
\frac{\partial \ell}{\partial i_H} &= \ell^{d\prime}\left(i_\ell\right)\frac{\partial i_\ell}{\partial i_H} = \ell^{d\prime}\left(i_\ell\right)\frac{1}{1-\chi} < 0, \\
\frac{\partial \hat{d}}{\partial i_H} &= \frac{1}{1-\chi}\frac{\partial \ell}{\partial i_H} = \frac{1}{\left(1-\chi\right)^2}\ell^{d\prime}\left(i_\ell\right) < 0.
\end{aligned}$$

Imposing an effective CBDC rate forces the bank to offer a higher deposit and raises the bank's funding cost. In order to finance the higher funding cost, the bank must scale back its loans ($\ell \downarrow$) to earn higher return ($i_\ell \uparrow$). The shrinkage in assets implies that the liabilities also shrink ($\hat{d} \downarrow$). Note that the demand for electronic liquidity is higher after CBDC is introduced because the households earn a higher rate on their electronic payment instruments. Given that bank deposits have decreased, the slack is made up by CBDC balances.

Now we introduce CBDC to an economy where the <u>reserve requirement is loose</u> (in absence of CBDC). In this case, the bank's two types of assets, reserves and loans, have the same return, which is also equal to the deposit rate: $i_R = i_d^0 = i_\ell^0$. Setting the CBDC rate higher than the current deposit rate will force the bank to scale back its loans in order to increase the return on its loans. This implies that the return of loans will exceed the return on reserves, and the wedge between the two

	i_d	i_ℓ	D	L	Z^M	Z^H
No CBDC						
i_R(binding RR)	$+$ (< 1)	$-$ (> -1)	$+$	$+$	$+$	N/A
i_R(non-binding RR)	1	1	$+$	$-$	$+$	N/A
CBDC with binding RR ($i_R \leq i_H$)						
i_R	0	$-\frac{\chi}{1-\chi}$	$+$	$+$	$+$	$-$
i_H	1	$\frac{1}{1-\chi}$	$-$	$-$	$-$	$+$
CBDC with non-binding RR ($i_R > i_H$)						
i_R	1	1	$+$	$-$	$+$	0
i_H	0	0	0	0	0	0

** RR: reserve requirement

Table 1: Pass-Through with Perfect Competition in the Deposit Market.

rates of return implies that the reserve requirement will start to bind and the effect of CBDC will follow the analysis earlier. As a result, the CBDC only affects the economy when the reserve requirement binds.

Table 1 summarizes the pass-through with perfect competition in both the deposit and loan markets. The main message is that if the reserve requirement is binding, CBDC eliminates the pass-through from i_R to i_d but strengthens the pass-through from i_R to i_ℓ. The CBDC rate i_H has full pass-through to the deposit rate, while i_R may have only partial pass-through. Hence, the CBDC rate is a more effective policy tool for the deposit market. Note also that i_H and i_R have opposite effects on the lending rate and amount of loans. Hence, coordination between i_R and i_H is needed to achieve certain policy goals. If the reserve requirement is slack, then CBDC does not have any effect on the pass-through of i_R.

5 Pass-Through: Cournot Competition

If banks engage in Cournot competition in the deposit market, then it is less straightforward to obtain analytical results. Instead, we evaluate the pass-through of the reserve rate with and without CBDC, and the pass-through of the CBDC rate itself, through numerical examples. To this end, we use parameter values in Chiu et al. (2019), where the model is calibrated to match the US data.

5.1 Pass-Through of the Reserve Rate

Figure 1 shows the pass-through of the reserve rate to the rates and quantities of deposits and loans with and without the CBDC. The horizontal axis is the reserve rate i_R. The deposit and loan rates are nominal. All rates are in percentage terms. To illustrate the effect of the CBDC rate on the pass-through of the reserve rate, we graph the case with no CBDC (the red solid line) and three cases with CBDC at three levels of CBDC rate i_H. The dashed blue line shows the case with $i_H = 0.07\%$, the dashed red curve represents the case with $i_H = 0.1\%$, and the dotted red line describes the case with $i_H = 0.2\%$.

We will first discuss the case without CBDC (the red solid curves). On the deposit market, an increase in i_R increases the deposit rate. If i_R is small and the reserve requirement binds, an increase in i_R affects the deposit rate only slightly. This is not surprising given that i_R does not fully pass-through to the deposit rate even under perfect competition. If i_R is sufficiently high, then the reserve requirement is slack and the pass-through is strengthened. However, unlike the case with perfect competition, where the pass-through from i_R to i_d is perfect when the reserve requirement is slack, the pass-through from i_R to i_d is far from perfect in the case with Cournot competition due to the bank's market power in the deposit market. These changes in the deposit rate translate to the deposit quantity. The quantity of deposit increases slowly when i_R is small and increases faster when i_R is sufficiently large so that the reserve requirement becomes loose.

On the loan market, as i_R increases, the loan rate first decreases and then increases. When i_R is small, the reserve requirement binds, reserves and loans are complements.

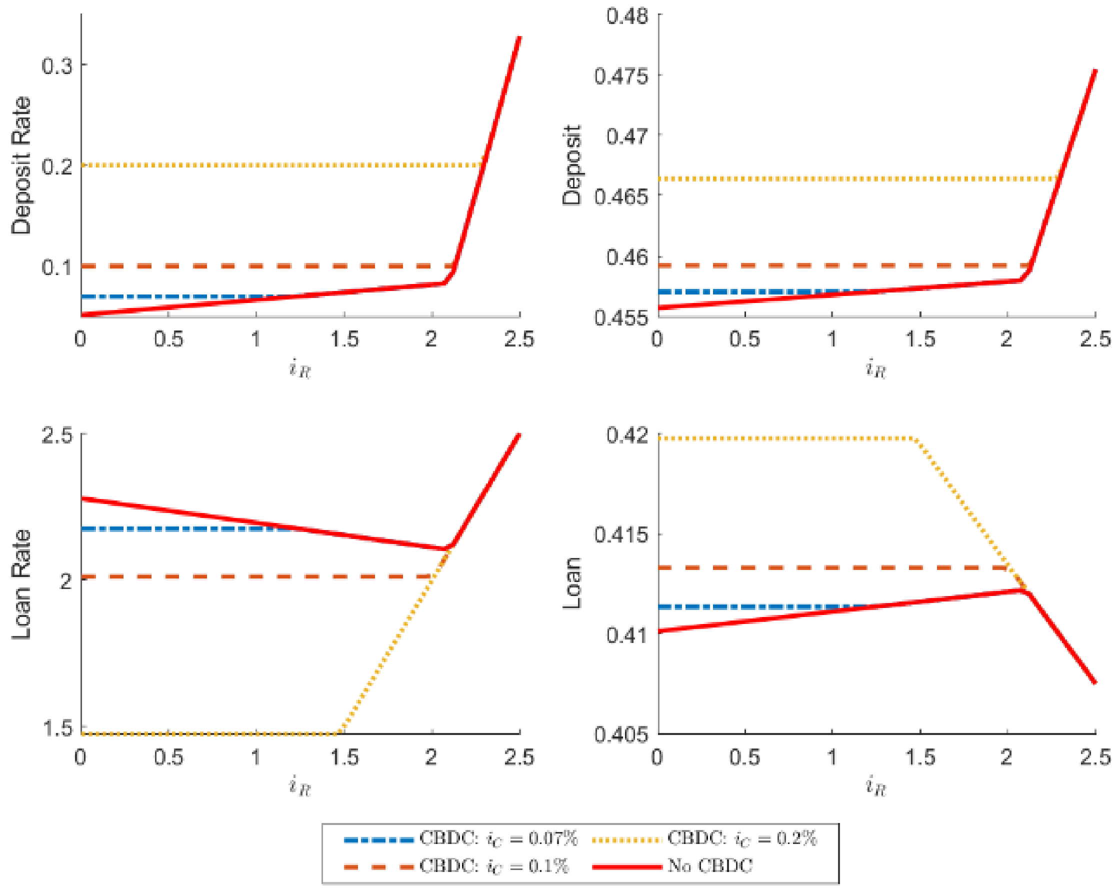

Figure 1: Pass-Through of the Reserve Rate

Increasing i_R reduces the cost of holding reserves and increases the overall return of the bank's assets. As a result, banks are willing to expand deposits and loans, putting a downward pressure on the loan rate. When i_R is sufficiently high, the reserve requirement becomes slack, and reserves and loans become substitutes. A higher return on reserves induces banks to switch from loans to reserves until the rate of return from loans is equal to the reserve rate; in this case, there is a full pass-through of i_R to the loan rate (recall that the loan market is competitive).

Now we examine how the CBDC affects the pass-through of the reserve rate. First suppose the CBDC rate is at a modest level $i_H = 0.07\%$ (see the blue dashed lines). The CBDC rate affects the economy when i_R is low, and its effects stop when i_R is sufficiently high. Intuitively, when i_R is low, the return from the bank's assets is low and the bank offers a low deposit rate (and the bank exploits its market power to set the deposit rate lower than the case with a competitive deposit market). The CBDC introduces competition on the deposit market and forces the bank to match the CBDC rate. This increases the deposit rate and quantity (as compared with the case without CBDC). The bank loans a fraction of the deposits to entrepreneurs subject to the reserve requirement, and the higher supply of the loans suppresses the loan rate (as compared with the case without CBDC). As long as i_R is small enough so that the deposit rate offered in the absence of CBDC is lower than i_H, the CBDC rate dictates the economy and eliminates the pass-through from i_R to i_d and i_ℓ, and the quantities of deposits and loans (as shown by the flat sections of the blue lines).[12] Once i_R increases to the point where the deposit rate offered in absence of CBDC exceeds $i_H = 0.07\%$, the CBDC stops affecting the economy and the blue lines join the red solid lines. In terms of transmission of the reserve rate, when i_R is low and the CBDC rate dictates the economy, it eliminates the pass-through from i_R to the economy. When i_R is sufficiently high, the effect of CBDC is lifted and

[12]When the CBDC rate is effective, as banks are already forced to pay a higher deposit rate, they have no incentive to increase it even if i_R becomes higher.

the pass-through of i_R reverts back to the case without CBDC.

If the CBDC rate increases, the region where the CBDC rate dictates the economy expands. When the CBDC rate is moderate (say, at 0.07%), as i_R increases, the economy goes through three regions characterized by whether the CBDC is effective and whether the reserve requirement binds. In the first region (when the curve is flat), CBDC is effective and the reserve requirement binds. In the second region, CBDC is ineffective and the reserve requirement binds. In the third region, CBDC is ineffective and the reserve requirement is loose. When the CBDC rate is high (say, at 0.2%), the economy goes through three regions as well. The first and third regions are similar to the case where $i_H = 0.07\%$. The second region is different, where CBDC is effective and the reserve requirement is loose. A higher level of CBDC rate therefore changes the threshold value of i_R, at which the reserve requirement becomes loose. The reason is that CBDC forces the bank to pay a high deposit rate and attract more deposits and issue more loans. When the CBDC rate is high enough, the induced expansion in loans (represented by the height of the flat segment of the loan quantity curve) implies a lower return (recall that there is diminishing return to investment) than the threshold value of i_R, at which the reserve requirement starts to be loose without CBDC). In the second region of the yellow curve, both the CBDC and reserve rates affect the loan market; more specifically, the CBDC rate determines the deposit rate and quantity, and the reserve rate determines the loan rate and how deposits are split between reserves and loans.

Finally, we would like to compare the economies with Cournot and perfect competition. In the absence of the CBDC, the two economies respond to the reserve rate qualitatively in a similar way. When the reserve rate is low, the reserve requirement binds and reserves and loans are complements. A higher reserve rate induces the bank to expand deposits and loans, offer a higher deposit rate, and charge a lower loan rate. The reverse happens when the reserve rate increases to a point where the reserve requirement is loose.

The two economies exhibit more differences when the CBDC is introduced (in a way that the CBDC rate is effective). The pass-through from the reserve rate to the deposit rate is shut down in both economies. However, the similarity stops there. The response of the quantity of deposits, the loan rate, and the amount of loans to the reserve rate look quite different in the two economies. Under perfect competition, when the deposit rate is flat against the reserve rate, the CBDC rate fully dictates the rates and quantities of deposits and loans (and the demand for CBDC is zero) and the reserve rate does not affect the economy. In the case of a competitive deposit market, the reserve rate still affects the loan rate and the quantities of deposits and loans. As i_R increases, the bank passes the benefit of a higher reserve rate to borrowers by offering them a lower loan rate (the deposit rate is already high and fixed at the CBDC rate). This results in a higher amount of loans supported by a higher amount of deposit taking. Given that the total electronic liquidity is fixed and determined by the CBDC rate, households reduce their holdings of CBDC. Another difference is that CBDC may shrink the region of i_R where the reserve requirement binds when the deposit market features Cournot competition, while the opposite may happen in the case of a competitive deposit market. A related difference is that the CBDC rate may affect the economy when the resource constraint is loose with an imperfectly competitive deposit market, while in the case of a competitive deposit market, the CBDC rate is only effective when the reserve requirement binds.

5.2 Pass-Through of the CBDC Rate

Now we investigate the pass-through of the CBDC rate and illustrate it in Figure 2. To see how the pass-through of the CBDC rate is affected by the reserve rate, we show the pass-through of i_H at different levels of i_R. The case with $i_R = 0$ is represented by the blue solid line, the case with $i_R = 1\%$ by the red dashed line, and the case with $i_R = 1.6\%$ by the orange dotted line. The effect of the CBDC rate on the deposit rate is straightforward and remains qualitatively the same for different values of the reserve rate i_R: the CBDC rate i_H has full pass-through to the deposit rate as long as it is sufficiently high. Intuitively, if the deposit rate is below the CBDC rate, then the demand for deposits drops to 0. Therefore, banks are forced to offer $i_d = i_H$ at sufficiently high i_H. Note that this result also applies to the case of a perfectly competitive deposit market.

The effects of the CBDC rate on the quantity of deposits and the loan market is more complex. When reserves do not pay interest, or $i_R = 0$, the deposit quantity first increases and then decreases with i_H. Intuitively, a higher i_H increases the deposit rate and therefore the demand for deposits. Banks cater to this demand as long as the profit per unit of deposit is positive, which happens if i_H is not too high. If i_H is sufficiently high, such that the bank just manages to break even when offering depositors the CBDC rate, then the response of the loan rate and the quantities of deposits and loans will be the same as in the case with a competitive deposit market: the bank must raise the loan rate to finance the higher deposit rate, and a higher loan rate reduces the loan quantity and the need to take deposits. Note that the result that the CBDC expands loans and deposits only occurs when the deposit market is not fully competitive and when banks are earning positive profits. Also note that when i_H increases the loan rate, the pass-through is more than 100%. Since banks must hold reserves to satisfy the reserve requirement, the loan rate must increase by more than 100% to compensate for both the deposit interest and the reserve cost.

Paying reserves a positive interest rate makes deposits expand with i_H for a wider range of values of i_H (relative to the case where $i_R = 0$). A higher reserve rate i_R reduces the reserve cost for banks, so banks can make positive profits while accommodating a higher interest on deposits. In particular, the quantity of deposits increases with i_H until the CBDC rate i_H reaches i_R. At $i_H = i_R$, banks are indifferent between a range of deposit quantities, as shown by the vertical segment of the red and orange curves in Figure 2. The upper limit of this range represents the total demand for electronic payment balances by consumers when the payment instrument pays a return of i_R. Moving along the vertical segment, the bank cuts deposits and reduces reserves at the same time. Above the lower limit of this range, banks hold excess reserves. At the lower limit, banks hold just enough reserves to support loans earning a rate of return of i_R. During the process, the bank's profits are unchanged because deposits and reserves have the same return. From the household's point of view, the total amount of electronic liquidity remains the same on the vertical segment. At the upper point of the vertical line, households use deposits to satisfy all their electronic liquidity needs. Moving downward along the vertical line, households start to use CBDC in place of deposits.

As i_R increases, the pass-through from i_H to loans is dampened. The maximum effects of i_H become smaller, and i_H does not affect the loan rate and quantity for a range of values (see the flat segment of the red and orange curves). When reserves earn a higher return, they become more attractive, and banks choose to hold reserves instead of making loans. Along the flat part, the reserve requirement is slack and the loan rate and quantity are determined by the reserve rate.

6 Discussions and Conclusion

This paper analyzes how the introduction of a CBDC affects the pass-through of the traditional monetary policy instrument, such as the interest on reserves. When the CBDC is introduced as a perfect substitute for deposits in terms of the payment function, the CBDC rate, while effective, fully dictates the deposit rate (and therefore eliminates the pass-through from the reserve rate to the deposit rate). The

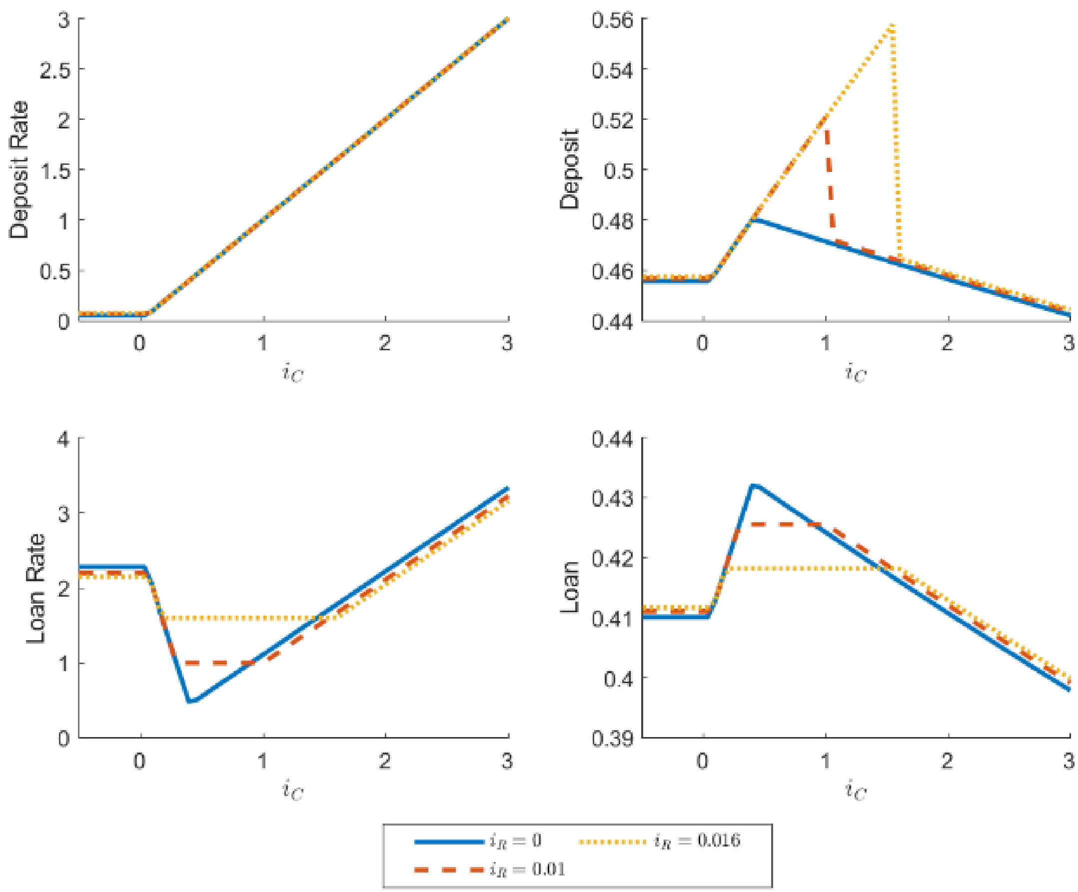

Figure 2: Pass-Through of the CBDC Rate

effect on the pass-through from the reserve rate to the deposit quantity and the loan rate and quantity is more complex and depends on the market structure of the banking sector. When the deposit market is not fully competitive, the CBDC tends to weaken the pass-through of the reserve rate as the CBDC rate itself dictates the economy. When the deposit market is perfectly competitive, the CBDC tends to strengthen the pass-through from the reserve rate to the loan rate quantity because the effect of the reserve rate passes only onto the loan rate, given that the deposit rate is fixed at the CBDC rate.

At the same time, the CBDC rate serves as a new policy instrument. Compared to the reserve rate, the CBDC rate has more direct effects on and hence stronger pass-through to the deposit rate and quantity, and could also have stronger pass-through to the loan market. However, the effect of the CBDC rate on the loan market depends on the level of the reserve rate. For instance, with Cournot competition in the deposit market, a higher reserve rate could weaken the pass-through from the CBDC rate to the loan rate and loan quantity by making the reserve requirement slack and therefore dictates the loan market.

As the effect of the reserve rate depends on the CBDC rate and vice versa, the policy maker must consider how the change in one policy instrument affects the effectiveness of the other instrument. Another insight is that the two policy instruments can be combined or coordinated to achieve certain policy objectives. For example, in order to improve electronic payment efficiency without crowding out bank deposits, the central bank may increase both the CBDC rate and the reserve rate simultaneously. In a world with an imperfectly competitive deposit market, the central bank can boost lending and hence output by increasing the CBDC rate while keeping the reserve rate constant or even reducing it.

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