Monetary Policy Pass-Through with Central Bank Digital Currency*

Janet Jiang[†]
Bank of Canada

Yu Zhu[‡]
Renmin University of China

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Abstract

We investigate 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. We first discuss how the interest on central bank reserves affects the rates and quantities of deposits and loans in the presence of CBDC, and then the pass-through of the interest on CBDC as a new policy tool in the presence of interest on reserves. We find that the CBDC tends to weaken the pass-through of interest on reserves, and vice versa. In general, coordination between the two policy rates is needed to effectively achieve policy goals.

JEL Codes: E50, E52

Keywords: Central bank digital currency; Monetary policy pass-through; Interest on reserves

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[†]Bank of Canada. Email: jjiang@bankofcanada.ca.

[‡]Renmin University of China. Email: zhuyuzlf57@gmail.com.

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. (2023). 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, i.e., banks hold excess reserves). The CBDC rate directly affects (and forms the lower bound of) the deposit rate because the 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 presence of the CBDC tends to weaken the pass-through of the interest rate on reserves. As a new policy instrument, the CBDC rate has a 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 they must 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 of electronic payments while not expanding its balance sheet significantly, it can increase both the CBDC rate and the rate on reserves when banks do not hold excess reserves.

This paper contributes to the growing literature on digital currencies and CBDC. It builds on Chiu et al. (2023), 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 (2023), Andolfatto (2021), Brunnermeier and Niepelt (2019), Davoodalhosseini (2022), and Barrdear and Kumhof (2022).[3]

[3]For further reference on e-money and digital currency, see Agur, Ari, and Dell'Ariccia (2022); 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 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 (2021) 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, including 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 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 household's and entrepreneur's problems. Section 4.1 studies how the CBDC affects the pass-through of interest on reserves as a monetary policy instrument with a perfectly competitive banking sector. Section 4.2 re-investigates this with an imperfectly competitive deposit market modeled by

[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.

Cournot competition. Section 5 examines how the interest rate on reserves affects the pass-through of the interest rate on CBDC. Section 7 summarizes the results and concludes.

2 Environment

The model follows Chiu et al. (2023). Time is discrete and continues from zero to infinity. There are four types of agents: a continuum of households with a measure 2, a continuum of entrepreneurs with a measure 1, a finite number of N bankers (each running a bank), and the government. The discount factor from the current period to the next is $\beta \in (0, 1)$. In each period t, agents interact sequentially in two stages: a frictional decentralized market (DM) and a Walrasian centralized market (CM). There are two perishable goods: y in the DM and x in the CM.

Households are divided into two permanent types, buyers and sellers, each with measure 1. In the DM, a buyer randomly meets a seller. The meeting probability is $\Omega \in (0, 1]$ for both buyers and sellers. The buyer wants to consume y, which is produced by the seller. The buyer's utility from consumption is $u(y)$ with $u'(0) = \infty$, $u' > 0$, and $u'' < 0$. The seller's disutility from production is normalized to y. Let y^* be the socially efficient DM consumption, which solves $u'(y^*) = 1$. Households lack commitment and cannot enforce debt repayment. As a result, the DM trade must be quid pro quo and buyers must use a means of payment to exchange for y. We will discuss available means of payment later. The terms of trade are determined by buyers making take-it-or-leave-it offers. In the CM, both buyers and sellers work and consume x. Their labor h is transformed into x one-for-one. The utility from consumption is $U(x)$ with $U'(0) = \infty$, $U' > 0$, and $U'' < 0$. Buyers' and sellers' preferences can be summarized respectively by the period utilities

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

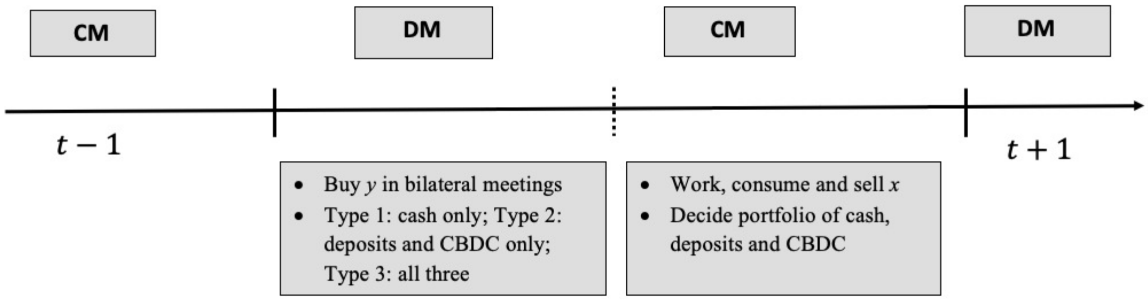
Young entrepreneurs are born in the current CM and become old and die in the next CM. Entrepreneurs cannot work in the CM and consume only when old. Young entrepreneurs are endowed with an investment opportunity that transforms x current CM goods to $f(x)$ CM goods in the next period, where $f'(0) = \infty$, $f'(\infty) = 0$, $f' > 0$, and $f'' < 0$. Entrepreneurs would like to borrow from households to invest. However, entrepreneurs and households lack commitment and cannot enforce debt repayment, so no credit arrangement among them is not viable.

Like entrepreneurs, young bankers are born in the CM, become old and die in the next CM. Bankers cannot work in the CM and consume only when old. Unlike households and entrepreneurs, bankers can commit to repaying their liabilities and enforcing the repayment of debt from entrepreneurs. Therefore, banks can act as intermediaries between households and entrepreneurs to finance investment projects. A bank can finance its loans by issuing two liabilities: liquid checkable deposits and illiquid time deposits. Checkable deposits can be used as a medium of exchange to facilitate trading between buyers and sellers in the DM. Banks are subject to the reserve requirement that a bank's reserve holdings must cover at least a fraction $\chi \geq 0$ of its checkable deposits.

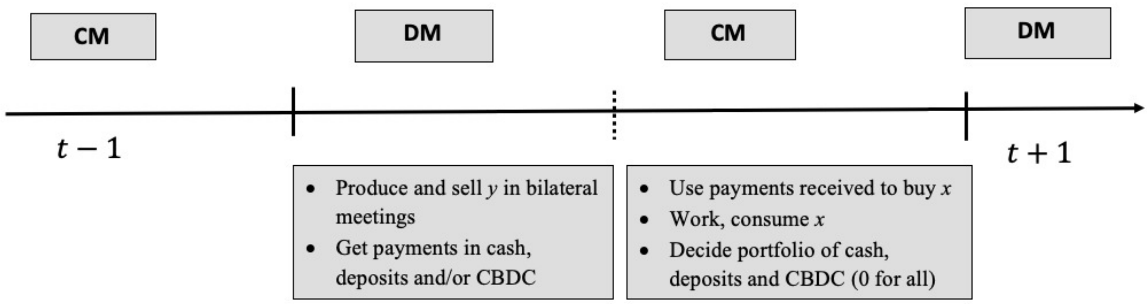
The government is a combination of monetary and fiscal authorities. The monetary authority, or the central bank, issues three forms of liabilities: physical currency (or cash), central bank reserves, and a CBDC. Currency is a physical token, pays a zero interest rate, and can be used as a means of payment. The reserves are electronic balances that pay a net nominal interest rate $i_r \geq 0$; they can be held only by banks and cannot be used for retail payments. The CBDC is a digital token or electronic entry that can be used for retail payments. It pays a net nominal interest i_e. Banks can also use the CBDC to meet the reserve requirement. We focus on stationary monetary policies, where the total liabilities of the central bank (currency, CBDC, and reserves) grow at a constant gross rate $\mu > \beta$ and the central bank stands ready to exchange its three forms of liabilities at par in the CM. We abstract from government purchases. The government collects revenues from the issuance of new liabilities to pay interest on the CBDC and reserves, and the difference finances lump-sum transfers (T) to buyers (a negative T represents lump-sum taxes).

The three types of retail payment instruments, cash, CBDC and checkable deposits, differ in their acceptability in the DM. With probability α_1, a buyer gets into a Type 1 meeting where only the cash can be used. With probability α_2, a buyer gets into a Type 2 meeting where deposits and CBDC can be used. With probability α_3, a buyer gets into a Type 3 meeting where all the three retail payment instruments can be used.

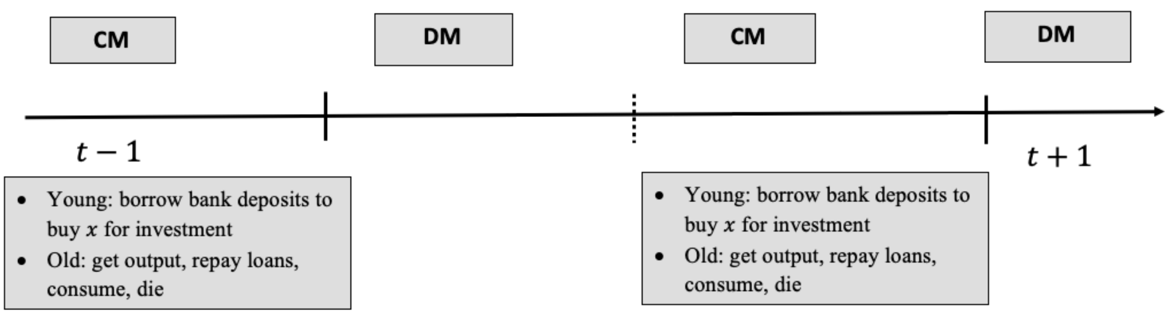
We focus on stationary monetary policies and stationary equilibria where real allocations are constant over time. It takes four steps to solve for the equilibrium. First, characterize the household's problem to derive the demand for cash, CBDC, and bank deposits as functions of the deposit rate. Second, solve the Cournot game for banks, incorporating the household demand for deposits, to derive the aggregate deposit supply and loan supply as functions of the competitive loan rate. Third, derive the aggregate demand for loans from entrepreneurs. Finally, equate the supply and demand for loans to derive the equilibrium loan rate and loan quantity and plug them into the solutions to private agents' problems to obtain other equilibrium objects, such as the rate and quantity of deposits.



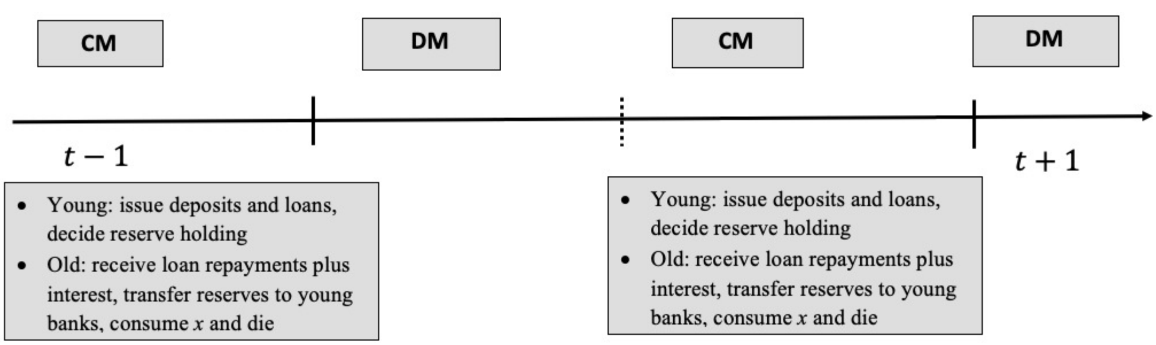
(a) Buyers



(b) Sellers



(c) Entrepreneurs



(d) Bankers

Figure 1: Timeline

3 Households and Entrepreneurs

In this section, we characterize the demand for deposits as a function of the interest rate on deposits and loans as a function of the loan rate by solving the optimization problems of households and entrepreneurs, respectively. Detailed analysis can be found in Chiu et al. (2023). We use i to denote net nominal return. We use subscript z to indicate cash, e to indicate CBDC, d to denote demand deposits, and ℓ to denote loans. For example, the net nominal interest on cash is $i_z = 0$.

The entrepreneurs maximize profits by choosing the quantity of loans, taking the loan rate i_ℓ as given,

$$\max_{\ell}\{f(\ell) - \ell(1+i_\ell)/\mu\}.$$

The first order condition is $f'(\ell) = (1+i_\ell)/\mu$, which defines the aggregate loan demand function,

$$\mathbf{L}_d(i_\ell) = f'^{-1}(1+i_\ell/\mu),$$

The loan demand decreases with the loan rate.

The solution to the household's problem leads to the inverse demand for demand deposits.[5] To characterize the demand for the deposits with a CBDC, it is useful to first characterize the demand without a CBDC denoted by $\hat{\mathbf{D}}(i_d)$ (from now on, we will use the accent "^" to denote variables or functions if there is no CBDC). If there is no CBDC, z and d solve the following system of equations given i_d and μ,

$$\frac{\mu}{\beta} - 1 = \alpha_1\lambda(\mathcal{L}_1) + \alpha_3\lambda(\mathcal{L}_3), \tag{1}$$

$$\frac{\mu}{\beta(1+i_d)} - 1 = \alpha_2\lambda(\mathcal{L}_2) + \alpha_3\lambda(\mathcal{L}_3) \tag{2}$$

[5]The demand for time deposits is separable from the demand for liquid assets and is given by $R_b = 1/\beta$. Since time deposits have no liquidity value, their return must compensate for discounting across time.

where

$$\begin{aligned}\mathcal{L}_1 &= z/\mu, &(3)\\ \mathcal{L}_2 &= d(1+i_d)/\,u, &(4)\\ \mathcal{L}_3 &= z/\mu + d(1+i_d)/\mu, &(5)\end{aligned}$$

and $\lambda(\mathcal{L}) = \max\{u'(\mathcal{L}) - 1, 0\}$ is the liquidity premium. For each value of i_d, this system of equations uniquely determines d, which leads to the demand for deposits $\hat{\mathbf{D}}(i_d)$. To ensure that $\hat{\mathbf{D}}(i_d)$ is an increasing function, we further assume that $-u''(y)y/u'(y) < 1$. The corresponding inverse demand function is $\hat{\mathbf{i}}_d(d) = \hat{\mathbf{D}}^{-1}(d)$.

With a CBDC, households hold only the electronic payment instrument that bears a higher rate of return. Therefore, the demand for deposits becomes

$$\mathbf{D}(i_d) = \begin{cases} 0 & \text{if } i_d < i_e, \\ \left[0, \hat{\mathbf{D}}(i_d)\right] & \text{if } i_d = i_e, \\ \hat{\mathbf{D}}(i_d) & \text{if } i_d > i_e. \end{cases}$$

The corresponding inverse demand is

$$\mathbf{i}_d(d) = \begin{cases} [0, i_e) & \text{if } d = 0, \\ i_e & \text{if } d \in (0, \hat{\mathbf{i}}_d^{-1}(i_e)], \\ \hat{\mathbf{i}}_d(d) & \text{if } d > \hat{\mathbf{i}}_d^{-1}(i_e). \end{cases}$$

Figure 2 illustrates the inverse demand function with and without a CBDC. The solid line represents the demand with a CBDC, and the dashed line represents the demand without a CBDC. The two functions overlap if $i_d > i_e$. Once i_d is below i_e, the demand for checkable deposits drops to zero.

In the rest of the paper, we analyze the bank's problem and how introducing CBDC affects the monetary policy pass-through of the traditional monetary policy instrument, the interest rate on reserves and study the pass-through of the new monetary policy instrument, the interest rate on the CBDC. Section 4 focuses on the former and 5 focuses on the latter. In each section, we separate the analysis for different market structures of the deposit market.

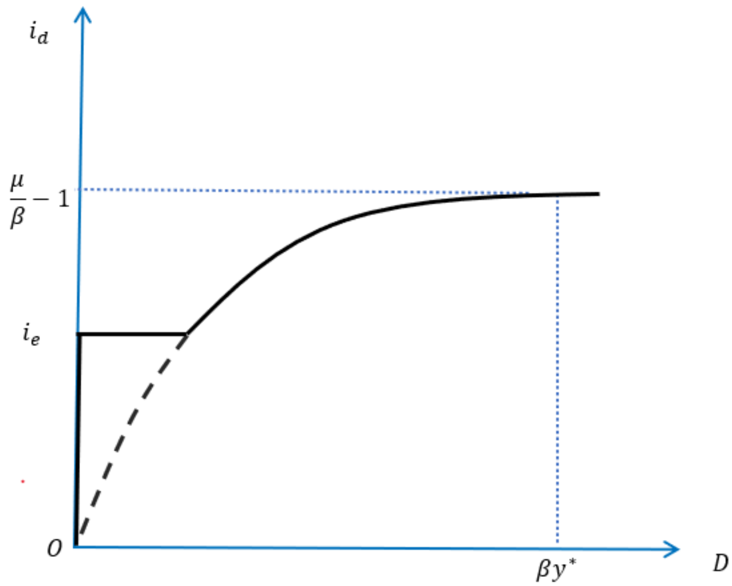


Figure 2: Inverse Demand for Checkable Deposits

Notes. The solid line is the inverse demand for checkable deposits with a CBDC, $\mathbf{i}_d(d)$; and the dashed line is the inverse demand for checkable deposits without a CBDC, $\hat{\mathbf{i}}_d(d)$. The two lines coincide with each other if $i_d > i_e$.

4 Pass-Through of Interest Rate on Reserves

Section 4.1 studies the pass-through of interest on reserves in the case with a perfectly competitive deposit market and Section 4.2 studies the case with a Cournot deposit market. For each market structure of the deposit market, we first analyze the pass-through mechanisms in an economy without a CBDC, and then investigate how they are affected by the introduction of a CBDC.

4.1 Competitive Deposit Market

No CBDC With competitive deposit and loan markets, banks choose deposits (d), loans (ℓ), and reserves (z) given the loan rate (i_ℓ), the deposit rate (i_d), the reserve rate (i_r).

$$\max_{d,\ell,z} \quad \left\{ i_\ell \ell + i_r z - i_d d \right\}$$
$$\text{s.t. } \ell + z = d,$$
$$z \geq \chi d.$$

The first constraint is the balance sheet identity, and the second constraint is the reserve requirement. Combining the bank's problem, the checkable deposit demand curve from the household, and the loan demand curve from the entrepreneur, we can solve the equilibrium rates and quantities of deposits and loans and the quantity of reserves held by the bank $(i_d, i_\ell; d, \ell, z)$. The equilibrium has two regimes. In the first regime, the reserve requirement binds and in the second regime, the reserve requirement is slack. One can check that the first regime occurs if $i_r < \bar{i}_r$ and the second regime occurs if $i_r > \bar{i}_r$, where $\mathbf{L}_d(\bar{i}_r) = (1-\chi)\hat{\mathbf{D}}(\bar{i}_r)$. Intuitively, if i_r is sufficiently low, reserves are dominated in rate of return by loans and banks hold just enough reserves to satisfy the reserve requirement. If i_r is sufficiently high, the amount of reserves held by the banks strictly exceeds the reserve requirement.

We next discuss the equilibrium and the pass-through of i_r in the two regimes distinguished by whether the reserve requirement is loose or tight. We focus on the equilibrium interest rates on loans and checkable deposits, i_ℓ and i_d. The effect of i_r on the quantities of loans and checkable deposits, L and D, can be obtained from $L = \mathbf{L}_d(i_\ell)$ and $D = \hat{\mathbf{D}}(i_d)$.

If $i_r < \bar{i}_r$, the reserve requirement binds. The equilibrium interest rates on loans and checkable deposits, i_ℓ and i_d, are determined by

$$(1-\chi)\, i_\ell + \chi i_r = i_d \tag{6}$$

$$\mathbf{L}_d\,(i_\ell) = (1-\chi)\,\hat{\mathbf{D}}\,(i_d)\,, \tag{7}$$

Equation (6) states that marginal benefit of checkable deposits equals the marginal cost, both measured in nominal terms. The left-hand side is the marginal benefit, a weighted sum of the loan rate and the reserve rate, where the weights are determined by the reserve requirement. The right-hand side is the marginal cost, captured by the deposit rate. Equation (7) is the binding reserve requirement.

To investigate the pass-through of i_r, we totally differentiate the equilibrium conditions to obtain

$$\frac{\partial i_d}{\partial i_r} = \frac{\chi \mathbf{L}'_d(i_\ell)}{\mathbf{L}'_d(i_\ell) - (1-\chi)^2 \hat{\mathbf{D}}'(i_d)} > 0. \tag{8}$$

$$\frac{\partial i_\ell}{\partial i_r} = \frac{(1-\chi)\chi \hat{\mathbf{D}}'(i_d)}{\mathbf{L}'_d(i_\ell) - (1-\chi)^2 \hat{\mathbf{D}}'(i_d)} < 0, \tag{9}$$

A higher i_r lowers the lending rate and raises the deposit rate. Intuitively, when the reserve requirement binds, holding reserves is a cost for deposit taking and lending: lending yields a higher return, but the bank must hold some 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 upward pressure on the deposit rate and downward pressure on the loan rate.

If $i_r > \bar{i}_r$, the reserve requirement is slack. In this case, the equilibrium loan rate, reserve rate and the deposit rate are equal to each other. To see this, first note that when the reserve requirement is slack, the two assets, reserves and loans, must give the same return; otherwise, the bank can allocate more funds to the asset with a higher return. Second, given that banks are competitive, the marginal benefit and cost of deposits are equal (which is the same as in the case where the reserve requirement binds). Altogether, it follows that $i_\ell = i_d = i_r$.

It is then straightforward that there is a 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 two assets, reserves and loans, 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 to invest in reserves.

Figure 3 shows the results from a numerical exercise to illustrate the theoretical results.[6] The solid blue lines summarize the pass-through of i_r when there is no CBDC. The first column shows pass-through to the interest rates on checkable deposits and loans. The second column shows pass-through to quantities of checkable deposits and loans. In all panels, the blue curve kinks at $i_r = \bar{i}_r = 1.2\%$, which separates the regime with a binding reserve requirement and the one with a non-binding reserve requirement.

We start with the pass-through to the deposit rate i_d. Qualitatively, the pass-through of i_r to i_d is always positive. Quantitatively, the pass-through to i_d is weak if $i_r < \bar{i}_r$. In this regime, an increase in i_r improves the rate of return on reserves, which is only χ fraction of the banks' assets. As a result, banks cannot increase the deposit rate much. If $i_r > \bar{i}_r$, an increase in i_r increases the return on all bank assets because banks must be indifferent between loans and reserves. Because of perfect competition, banks fully pass the increase in i_r to the deposit rate.

Now we move to the pass-through to the loan rate i_ℓ. The effects are qualitatively different across the two regimes. If $i_r < \bar{i}_r$, a higher i_r reduces the lending rate. In this regime, a higher i_r reduces the cost of lending, which is the lower return from reserves. Banks pass a part of the benefits to the borrowers by reducing the loan rate. Therefore, there is a negative pass-through to the loan rate. If $i_r > \bar{i}_r$, banks are indifferent between loans and reserves and an increase in i_r raises the loan rate by the same amount. The effect of i_r on the quantity of checkable deposits and loans follows the effect on rates.

[6] In this example, $u(y) = [(y+\varepsilon)^{1-\sigma} - \varepsilon^{1-\sigma}]/(1-\sigma)$ and $f(\ell) = A\ell^\eta$. We set $\alpha_1 = 0.0222$, $\alpha_2 = 0.1268$, $\alpha_3 = 0.3509$, $\sigma = 0.1592$, $\eta = 0.66$, $A = 1.15$, $\beta = 0.96$, $\varepsilon = 10^{-9}$, $\mu = 1.02$ and $\chi = 0.15$.

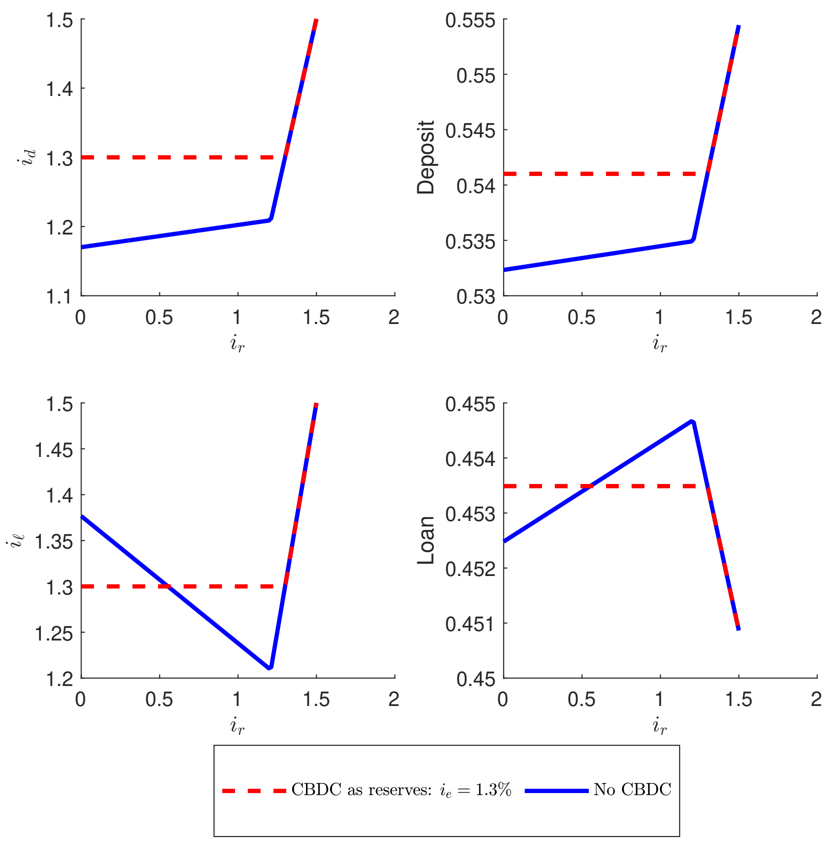


Figure 3: Pass-through of i_r with Competitive Deposit Market

Notes. Solid blue line: without CBDC. Red dash line: with CBDC.

Notice that if the reserve requirement is binding, the pass-through from i_r to i_d and i_ℓ is imperfect even though the banking sector is perfectly competitive. Therefore, an imperfect pass-through impies that banks have market power only if banks hold excess reserves.[7]

Introducing CBDC Now we introduce a CBDC that pays a nominal interest rate i_e. The CBDC affects agents in two ways. Households can use the CBDC instead of bank deposits for payments hence the CBDC rate forms a lower bound on i_d. Banks have the CBDC as an additional investment asset and means to satisfy

[7]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.

the reserve requirement. The effective return on assets held to satisfy the reserve requirement becomes $i_{er} \equiv \max\{i_e, i_r\}$.

When banks are competitive, the deposit rate that they offer is at least i_{er}.[8] As a result, from the household's point of view, the CBDC is weakly dominated by deposits, so the CBDC does not pose a meaningful threat to deposits as an electronic means of payment.[9] For $i_r < i_e$, banks use the CBDC to meet the reserve requirement, the deposit and loan rates and quantities are fixed at their values in the case where there is no CBDC and the reserve rate is equal to i_e. Therefore, the pass-through of i_r to the rates and quantities of deposits and loans is muted. For $i_r \geq i_e$, banks use reserves to satisfy reserve requirement, and the CBDC is not utilized because its rate is less than i_{er}. Therefore, the pass-through of i_r to the economy is unaffected by the CBDC.

The red dashed line in figure 3 illustrates the effect of introducing a CBDC with $i_e > \bar{i}_r$. In this case, strictly speaking, for $i_r < i_e$, deposits are indeterminate on the interval $[\mathbf{L}(i_e)/(1-\chi), \hat{\mathbf{D}}(i_e)]$. Banks can issue deposits to satisfy all the demand for the electronic liquidity $\hat{\mathbf{D}}(i_e)$, or to just meet the reserve requirement $\mathbf{L}(i_e)/(1-\chi)$. For every dollar of deposits above $\mathbf{L}(i_e)/(1-\chi)$, banks invest on CBDC and earn zero profit. The red dashed line assumes that banks satisfy all the demand for electronic liquidity. One can see that the red dashed line is constant if $i_r < i_e$ and joins the blue curves to the right of the kinks. If $i_e < \bar{i}_r$, the graphs are similar except that the red curve would join the blue curves to the left of the kinks.

In summary, with competitive banking, when the CBDC is effective as an alternative asset to meet the reserve requirement, it dictates the economy. As a result, the pass-

[8] Notice that i_d is at least i_e because the CBDC is a perfect substitute for deposits. In addition, i_d is at least i_r because banks pass all the investment return to households under perfect competition.

[9] In Appendix B, we analyze the case where banks *cannot* use the CBDC to meet their reserve requirement. In that case the CBDC rate becomes a binding lower bound for the deposit rate for i_r sufficiently low as shown in figure 9.

through from i_r to the economy is dampened (muted).

4.2 Cournot Deposit Market

If banks engage in Cournot competition in the deposit market (we keep the assumption that the loan market is competitive), bank j takes i_ℓ and the deposit supply of all other banks $D_{-j} = \sum_{i \neq j} d_i$ as given and solves

$$\begin{aligned}\max_{d_j, \ell_j, z_j} & \left[i_\ell \ell_j + i_r z_j - \mathbf{i}_d(d_j + D_{-j}) d_j \right] \\ \text{st. } & \ell_j + z_j = d_j, \\ & z_j \geq \chi d_j.\end{aligned}$$

The problem is similar to the case with a competitive deposit market except that bank j takes into account its impact on the market deposit rate. Solving the Cournot game leads to the aggregate deposit supply curve $\mathbf{D}_s(i_\ell)$ and loan supply curve $\mathbf{L}_s(i_\ell)$. We can combine these with the aggregate loan demand of entrepreneurs to determine the equilibrium.

No CBDC The blue curves in Figure 4 show the pass-through of i_r to interest rates and quantities of checkable deposits and loans when the deposit market features Cournot competition. The patterns are qualitatively similar to those under perfect competition. If the reserve requirement binds, then banks pass through the benefit of a higher i_r as higher i_d and lower i_r. If the reserve requirement is loose, then banks move investment from loans to reserves, resulting in higher loan rate, and they pass through the benefit of a higher i_r as a lower deposit rate. The quantitative results differ from the competitive case, which we explain below.

If the reserve requirement binds, the equilibrium (D, i_ℓ) is characterized by

$$(1-\chi) i_\ell + \chi i_r = \hat{\mathbf{i}}_d(D) + \hat{\mathbf{i}}_d'(D) \frac{D}{N}, \tag{10}$$

$$\mathbf{L}_d'(i_\ell) = (1-\chi) D; \tag{11}$$

and other equilibrium objects can be obtained accordingly. Equation (10) says that the marginal benefit of checkable deposits equals the marginal cost. It is the counterpart of (6) under Cournot competition. The difference is that banks now considers its impact on the interest rate while creating deposits, which is captured by the term $\mathbf{i}_d'(D)D/N$. Equation (11) is the loan market clearing condition under a binding reserve requirement.

Use the two equations, one can show

$$\frac{\partial i_d}{\partial i_r} = \frac{\chi \hat{\mathbf{i}}_d'(D)\mathbf{L}_d'(i_\ell)}{\left[\hat{\mathbf{i}}_d''(D)D/N + \hat{\mathbf{i}}_d'(D)(1+1/N)\right]\mathbf{L}_d'(i_\ell) - (1-\chi)^2} > 0, \tag{12}$$

$$\frac{\partial i_\ell}{\partial i_r} = \frac{\chi(1-\chi)}{\left[\hat{\mathbf{i}}_d''(D)D/N + \hat{\mathbf{i}}_d'(D)(1+1/N)\right]\mathbf{L}_d'(i_\ell) - (1-\chi)^2} < 0. \tag{13}$$

Qualitatively, (when the reserve requirement binds) the pass-through of i_r to deposit and loan rates is similar when the bank has market power on the deposit market and when banks are competitive: the bank passes the benefit of a higher reserve rate as higher deposit rate and lower loan rate. The magnitude of the pass through varies with the market structure of the deposit market. If $N = \infty$, (12) and (13) coincide with (8) and (9), and the Cournot equilibrium collapses into the competitive equilibrium. If $N < \infty$, the pass-through of i_r to i_d and i_ℓ tends to be lower with Cournot deposit market if $\hat{\mathbf{i}}_d'' > 0$.

If the reserve requirement is slack, then $i_\ell = i_r$ and the equilibrium quantity of checkable deposits and loans satisfy

$$i_r = \hat{\mathbf{i}}_d(D) + \hat{\mathbf{i}}_d'(D)\frac{D}{N}, \tag{14}$$

$$L = \mathbf{L}_d(i_r), \tag{15}$$

and the interest rate on checkable deposits is $i_d = \hat{\mathbf{i}}_d(D)$. The reserve requirement is slack when $L < (1-\chi)D$, which occurs if and only if $i_r > \tilde{i}_r$, where $\mathbf{L}_d(\tilde{i}_r) = (1-\chi)\tilde{D}$

and $\tilde{i}_r = \hat{\mathbf{i}}_d(\tilde{D}) + \hat{\mathbf{i}}'_d(\tilde{D})\tilde{D}/N$. Then the pass-through of i_r can be calculated as

$$\frac{\partial i_d}{\partial i_r} = \frac{\hat{\mathbf{i}}'_d(D)}{\hat{\mathbf{i}}''_d(D)D/N + \hat{\mathbf{i}}'_d(D)(1+1/N)} > 0, \tag{16}$$

$$\frac{\partial i_\ell}{\partial i_r} = 1. \tag{17}$$

Because the loan market is perfectly competitive, there is a perfect pass-through of i_r to i_ℓ. By contrast, because the deposit market is imperfectly competitive, the pass-through of i_r to i_d is less than perfect (but still has the same sign as in the case with a competitive deposit market). As $N \to \infty$, the pass-through gets close to being perfect.

Introducing CBDC Similar to the analysis with competitive banking, the CBDC directly affects agents' decisions in two ways. For the household, the CBDC is an alternative payment method and the CBDC rate, i_e, forms a lower bound on i_d. For banks, the CBDC is an additional investment asset, and an alternative means to satisfy the reserve requirement. The effective return on assets held to satisfy the reserve requirement becomes i_{er}.

Conceptually, one can follow a two-step procedure to analyze the effect of CBDC. In step one, suppose banks can use it as an investment asset and a means to satisfy the reserve requirement, but the CBDC cannot be used as a means of payment by households. This is equivalent to studying the case with no CBDC but with a higher rate on reserves (i.e., the rate is i_{er} instead of i_r). In step 2, suppose the CBDC can be used for payments and see if it poses an effective threat to deposits as a means of payment.

There are three ways that the CBDC can affect the economy (relative to the no-CBDC world) depending on whether banks find it more attractive than reserves, whether households find it more attractive than deposits, or both. The first case, labeled "reserves only," occurs when the CBDC rate is higher than the rate on reserves so that banks hold the CBDC as reserves, but lower than the deposit rate offered by banks without CBDC (with the effective return on reserves as i_e) so households do not find it attractive. This case tends to happen when i_r and i_e are small. Compared with the no-CBDC world, households enjoy a higher deposit rate and firms enjoy a lower loan rate because banks partially pass on the benefit of a higher effective return on reserves. The second case is the "payments only" case, which occurs when the CBDC rate is lower than the rate on reserves so that banks do not invest in the CBDC, but higher than the deposit rate offered by banks with no CBDC, so that banks are forced to offer i_e to their depositors. In this case, the level of deposits is determined by the CBDC rate. The rate and level of loans are also determined by the CBDC rate if the reserve requirement binds. The bank's balance sheet expands relative to the no-CBDC world. The third case is the "both reserves and payments" case, where the CBDC rate is higher than both the interest on reserves and the deposit rate offered by the bank in the no-CBDC world. In this case, banks invest in CBDC and are forced to match the deposit rate to the CBDC rate.

If the CBDC forms an effective lower bound for deposits, and the reserve requirement binds, then i_d and i_ℓ in the equilibrium with a CBDC are determined by

$$\begin{aligned} i_d &= i_e, \\ \mathbf{L}_d(i_\ell) &= (1-\chi)\hat{\mathbf{D}}(i_e). \end{aligned}$$

This regime occurs if the i_ℓ that solves the above equations is greater than i_r, which implies that i_r is sufficiently small. Notice that the pass-through of i_r to i_d and i_ℓ are muted. Because banks have market power, they do not pass through the increase in i_r to either the deposit or the loan market, and simply enjoy higher profits.

If the CBDC rate forms an effective lower bounds for the deposit rate, and the reserve requirement is slack, then $i_d = i_e$ and $L = \mathbf{L}_d(i_r)$. In this regime, the amount of checkable deposits, $\hat{\mathbf{D}}(i_e)$, is larger than $L/(1-\chi)$. Banks hold the difference in reserves. A higher i_r does not affect the deposit rate but increases the loan rate one-for-one. As a result, banks make fewer loans and hold more reserves.[10]

The dashed red curves in Figure 4 show the pass-through of i_r with the CBDC when i_e forms an effective threat to deposits as a means of payment. When i_r is low, introducing a CBDC raises the interest rate on checkable deposits and the deposit quantity (relative to the case without a CBDC). This leads to more loans and a lower loan rate compared to the equilibrium with no CBDC. Moreover, the pass-through of i_r to the economy is completely muted for low i_r, i.e., both the rates and the quantities do not change with i_r. As i_r increases, the reserve requirement becomes slack (as the red dashed loan rate curve switches from being flat to 45^o line). After that, the loan rate increases and the loan quantity decrease with i_r. The deposit rate is fixed by i_e and deposit quantity stay unchanged as well. As i_r increases further, the CBDC becomes ineffective (as the blue and red curves join each other). Banks offer interest rate higher than the CBDC rate and passes increases in i_r to the interest rate on checkable deposits. Deposit quantity increases as well.

It is also possible that $i_e > i_r$ *but it does not pose an effective threat to deposits as a payment method* (the reserve requirement tends to bind). In this case, the CBDC rate controls the economy as well, but unlike in figure 4, $i_d \neq i_e$. The economy functions like in a no-CBDC world with i_r fixed at i_e.

We now summarize the results obtained so far. If there is no CBDC, the pass-through of i_r depends on whether the reserve requirement is binding and the market structure of the banking sector. If the reserve requirement binds, a higher i_r increases i_d and decreases i_ℓ. The pass-through is less than perfect, i.e., 1% change in i_r leads

[10] Again, strictly speaking, there is an indeterminacy: Banks may create just enough deposits to finance loans and households hold some CBDC, or banks create enough deposits to satisfy all the demand for electronic liquidity and households do not hold the CBDC. We choose the latter equilibrium in our analysis.

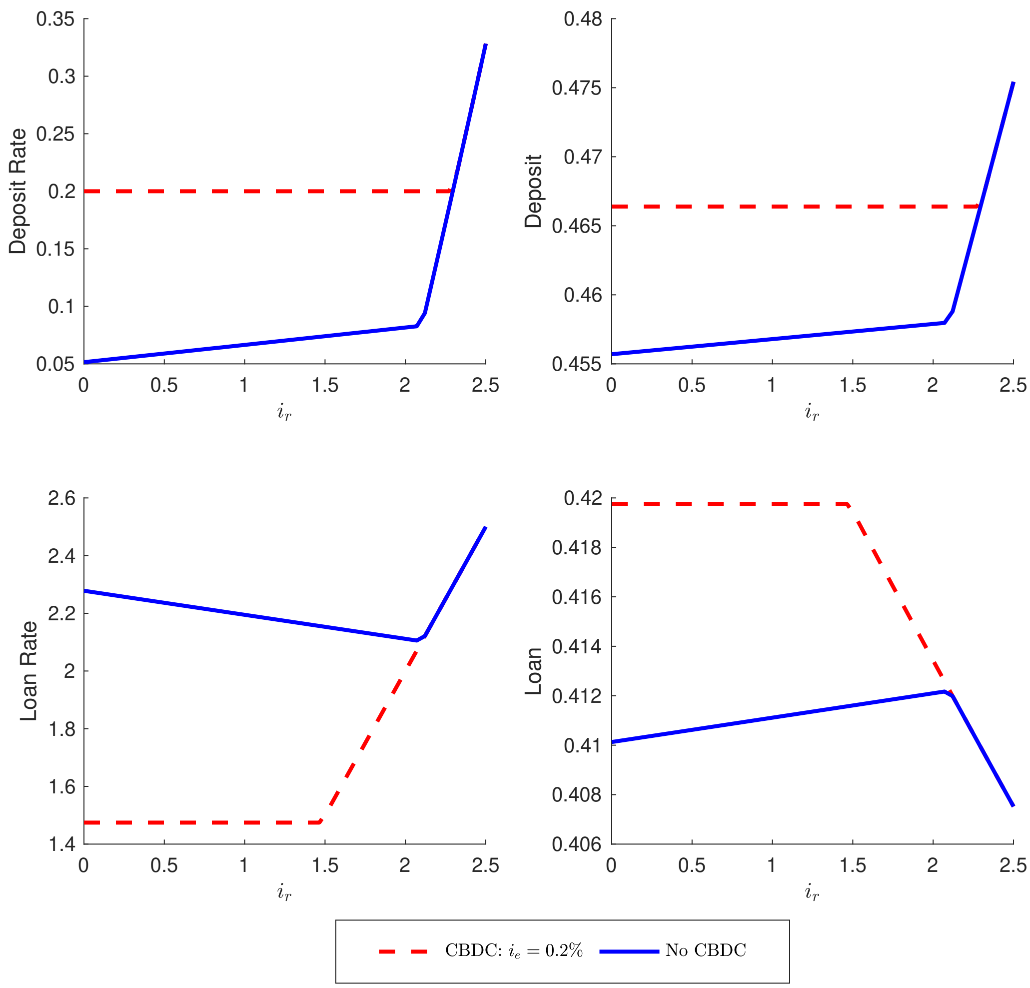


Figure 4: Pass-Through of i_r with Cournot Deposit Market
Notes. Along the flat part of the red curves, i_e forms an effective threat to deposits as a means of payment. Note that when $i_r < 0.2\%$, banks hold CBDC as reserves, but they do not pass the benefit to their customers; they simply earn higher profits.

to less than 1% change (in absolute value) in i_d and i_ℓ. If the reserve requirement is loose, i_r increases both i_d and i_ℓ. The pass-through of i_r to i_ℓ is perfect, while the pass-through to i_d can be perfect or imperfect depending on whether the deposit market is perfectly competitive or not.

Introducing the CBDC tends to weaken the pass-through of interest on reserves. While effective, the CBDC rate dictates the deposit rate and quantity and therefore completely mutes the pass-through of interest on reserves to the deposit market. Moreover, if the interest rate on reserves is low, the CBDC also mutes the pass-through of interest on reserves to the loan market. However, the mechanism varies with the market structure. When the deposit market is perfectly competitive, the CBDC mutes the pass-through of the interest on reserves to the economy because banks stop investing on reserves and instead on CBDC (not because the CBDC poses a meaningful threat to deposits as a means of payment). When the deposit market is imperfectly competitive, then the CBDC can mute this pass-though even if banks hold reserves (by forcing banks to pay deposits the CBDC rate). Intuitively, under perfect competition, banks always pass-through changes in the reserve rate to deposits and loans unless they do not hold reserves at all. By contrast, when banks have market power, they may not pass-through changes in the reserve rate even if they hold reserves on their balance sheets.

5 Pass-through of the Interest Rate on CBDC

We now study the pass-through of the CBDC rate, i_e, and how it depends on the interest rate on reserves, i_r. We will first analyze the case where the deposit market is competitive, and then the case where the deposit market features Cournot competition.

5.1 Competitive Deposit Market

With competitive banking, the CBDC is effective only if $i_e > i_r$. As discussed earlier in the section on the pass-through of interest on reserves, the bank chooses between reserves and CBDC to satisfy the reserve requirement and as an investment asset, and offers a deposit rate that is at least i_{er}. The CBDC does not pose an effective threat to deposits as a payment method. While effective, the pass-through of i_e is similar to the pass-through of i_r when there is no CBDC, as described in section 4.1. When the reserve requirement binds, which occurs when $i_e < \bar{i}_e$, with $i_e < \bar{i}_e$ solving $\mathbf{L}_d(\bar{i}_e) = (1-\chi)\hat{\mathbf{D}}(\bar{i}_e)$, the pass-through of i_e is similar to the pass-through of i_r as shown in equations (8) and (9). When the reserve requirement is loose, there is perfect pass-through of i_e, as $i_\ell = i_d = i_r$.

Figure 5 shows the pass-through of i_e under $i_r = 0$ (the solid blue) and $i_r > 0$ (the dashed red) if the banking sector is perfectly competitive. For the case with $i_r = 0$, banks hold only the CBDC as reserves. The reserve requirement binds for small i_e, and is loose for large i_e. For the case with $i_r = 1.2\%$, the CBDC becomes effective only when $i_e > i_r$, and the reserve requirement is loose. Notice that if i_r is higher, the CBDC stays ineffective for a wider range of i_e. As a result, the pass-through of i_e is muted for a wider range of i_e.

5.2 Cournot Deposit Market

As discussed in the Section on the pass-through of interest rate on reserves, the CBDC can affect the economy in different ways depending on whether the bank finds it a better investment asset than the reserves, and whether the rate on CBDC functions as an effective lower bound for deposits. It also depends on whether the reserve requirement binds or not.

If i_e forms an effective lower bound for deposits, and the reserve requirement binds,

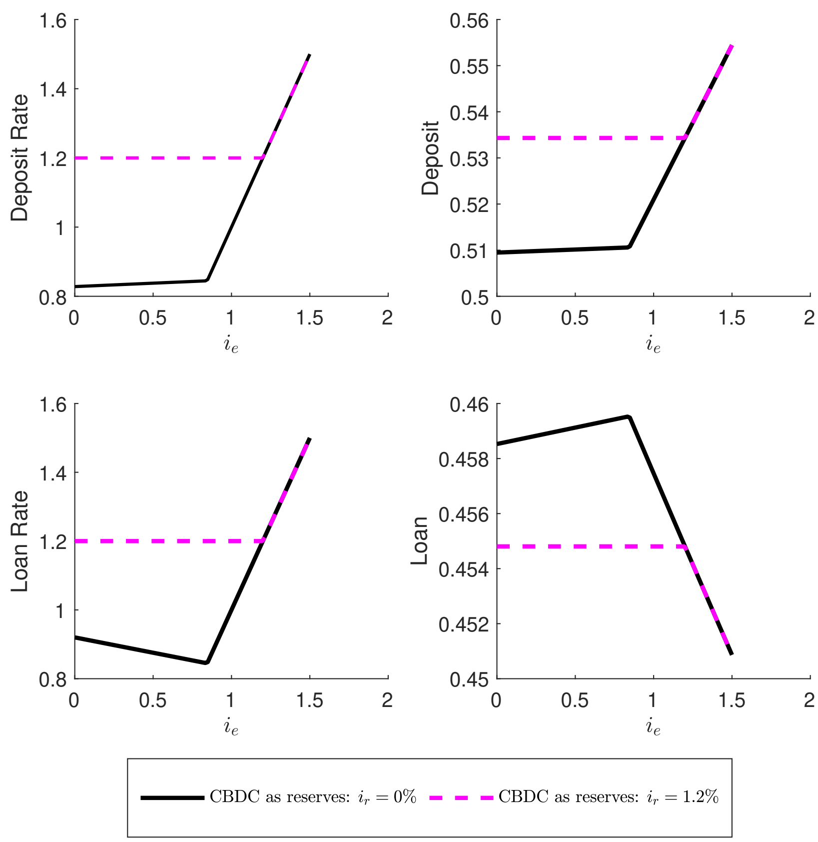


Figure 5: Pass-Through of i_e with Competitive Deposit Market

Notes. Solid black line: $i_r = 0$. Red dashed line: $i_r = 1.2\%$.

the pass-through of i_e is given by

$$\frac{\partial i_d}{\partial i_e} = 1,$$
$$\frac{\partial i_\ell}{\partial i_e} = (1-\chi) f'\left(\hat{\mathbf{D}}(i_e)(1-\chi)\right)\hat{\mathbf{D}}'(i_e).$$

If i_e forms an effective lower bound for deposits, and the reserve requirement is slack, the pass-through is

$$\frac{\partial i_d}{\partial i_e} = 1,$$
$$\frac{\partial i_\ell}{\partial i_e} = 0.$$

In this case, the CBDC rate dictates the deposit rate and the interest rate on reserves dictates the lending rate.

If $i_e > i_r$ but is not an effective lower bound for deposits, and the reserve requirement binds, then the pass-through of i_e is similar to the pass-through of i_r in the no-CBDC world as shown by equations (10) and (11).

Figure 6 shows the pass-through of i_e if the deposit market is imperfectly competitive. The blue solid curve is under $i_r = 0$ and the red dashed curve is under $i_r > 0$. If $i_r = 0$, a negative CBDC rate does not affect the interest rate on checkable deposits: the bank does not hold CBDC because it is dominated in return by reserves, and the deposit rate offered by the bank is positive so the household does not find it attractive either. For slightly positive i_e, the bank holds CBDC in place of reserves, and a higher i_e slightly increases the deposit rate and reduces the loan rate as the bank partially passes on the benefit of a higher yield (this case only lasts for a very small interval of i_e and does not show conspicuously in the figure). As i_e continues to rise, it becomes higher than the deposit rate offered by banks in the case where the CBDC cannot be used as a payment method (but can be held by banks) and there is perfect pass-through to the interest rate on checkable deposits. This raises households' demand for checkable deposits, which leads to higher deposit quantity. As the bank attracts more deposits, they lend out more, which leads to a drop in the loan rate. Therefore, the pass-through from the CBDC rate to the loan rate is negative until i_e reaches a threshold where banks' profits reach zero (the lowest point of the loan rate curve). As i_e continues to rise, banks behave as if they are perfectly competitive, and the pass-through from the CBDC rate to the loan rate becomes positive.

If $i_r > 0$, the pass-through to the deposit rate and quantity is largely unaffected compared with the case where $i_r = 0$.[11] However, the interest on reserves hampers the pass-through of i_e to the loan market for an intermediate range of i_e values (see the second flat parts of the red loan rate and loan curves). In that range, the reserve requirement becomes slack and i_r dictates the loan rate and quantity. As $i_e > i_r$, the interference of i_r stops and the blue and red curves coincide.

To sum up, the pass-through from i_e to i_d is perfect if i_e forms an effective lower bound for the deposit rate. The pass-through to i_ℓ changes signs depending on whether the banks have positive profits, as shown in Chiu et al. (2023). A higher i_r tends to weaken the pass-through from i_e to i_ℓ by relaxing the reserve requirement.

6 Policy Coordination

In previous sections, we analyze the pass-through of i_r and how it depends on the interest rate of the CBDC, and the pass-through of i_e and how it is depends on the value of the interest rate on reserves.

One possible policy is to vary both rates, for example, policy makers could increase both rates while maintaining a constant spread between them with $i_e < i_r$. Under

[11] For low i_e (see the first flat parts of the dashed red lines), the deposit rate shifts slightly upward and the loan rate shifts slightly downward because the reserves are a better investment asset for the bank.

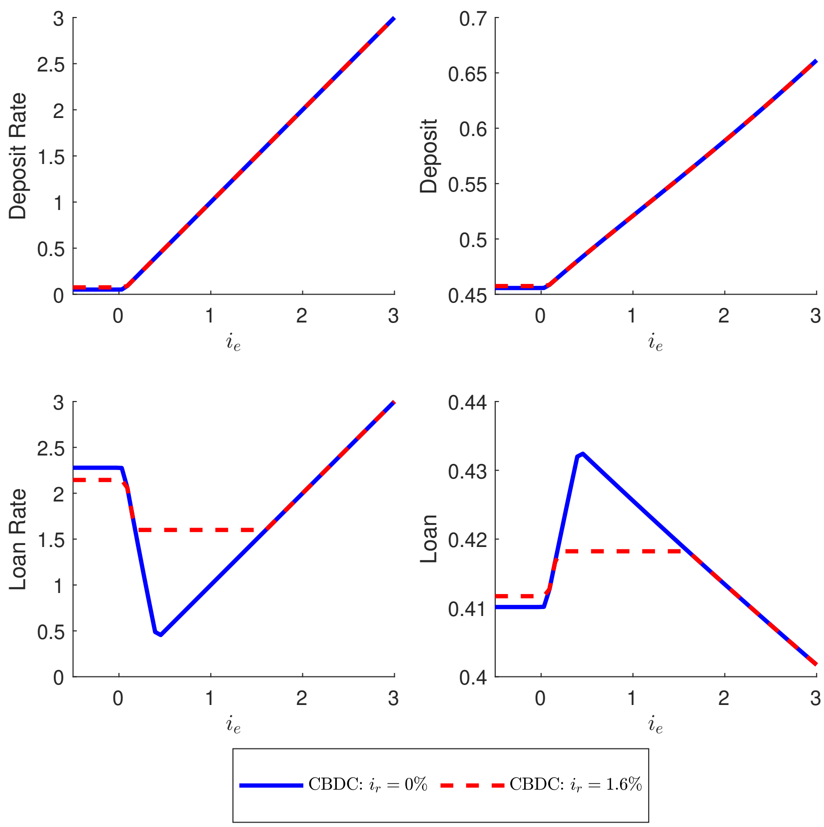


Figure 6: Pass-Through of i_e with Cournot Deposit Market

this policy, the bank does not hold CBDC as it is dominated in return by reserves.

Figure 7 shows the pass-through of this combo policy when the deposit market features Cournot competition. The blue curves represent the case without CBDC, and the red dashed curves represent introducing the CBDC and the CBDC rate is set 0.8% lower than the interest on reserves. For low i_r and therefore i_e, the CBDC does not pose a threat to deposits and therefore the combo policy affects the economy only through i_r and the two curves coincide. In this segment, as i_r increases, without the CBDC, the bank passes the benefit of a higher i_e to both households (as a higher deposit rate) and firms (as a lower loan rate). The changes in the rates are moderate as reserves are only a small fraction of the bank's total assets and in addition banks have market power. Once i_r exceeds a threshold, the CBDC rate under the combo policy becomes an effective lower bound for the deposit rate, and it starts to control the economy. After that, the deposit rate is equal to the CBDC rate, which increases at the same rate with the reserve rate because $i_e = i_r - 0.8\%$. As i_r and i_e continue to increase, households demand more deposits and banks are willing to satisfy all this demand as long as their profit margin is positive. Loans expand and the loan rate decreases. However, if i_r is sufficiently high, the loan rate hits the rate on reserves and the reserve requirement becomes loose. After that, the loan rate grows with the interest on reserves along the 45^o line. Notice that under this coordinated policy combo, the CBDC no longer weakens the the pass-through of i_r. Instead, it strengthens this pass-through when the reserve requirement is loose. In this region, increases in i_r and i_e both increase deposit and loan quantities and decrease the loan rate.

7 Conclusion

This paper analyzes how the introduction of a CBDC affects the pass-through of the traditional monetary policy instrument, in particular, the interest on reserves.

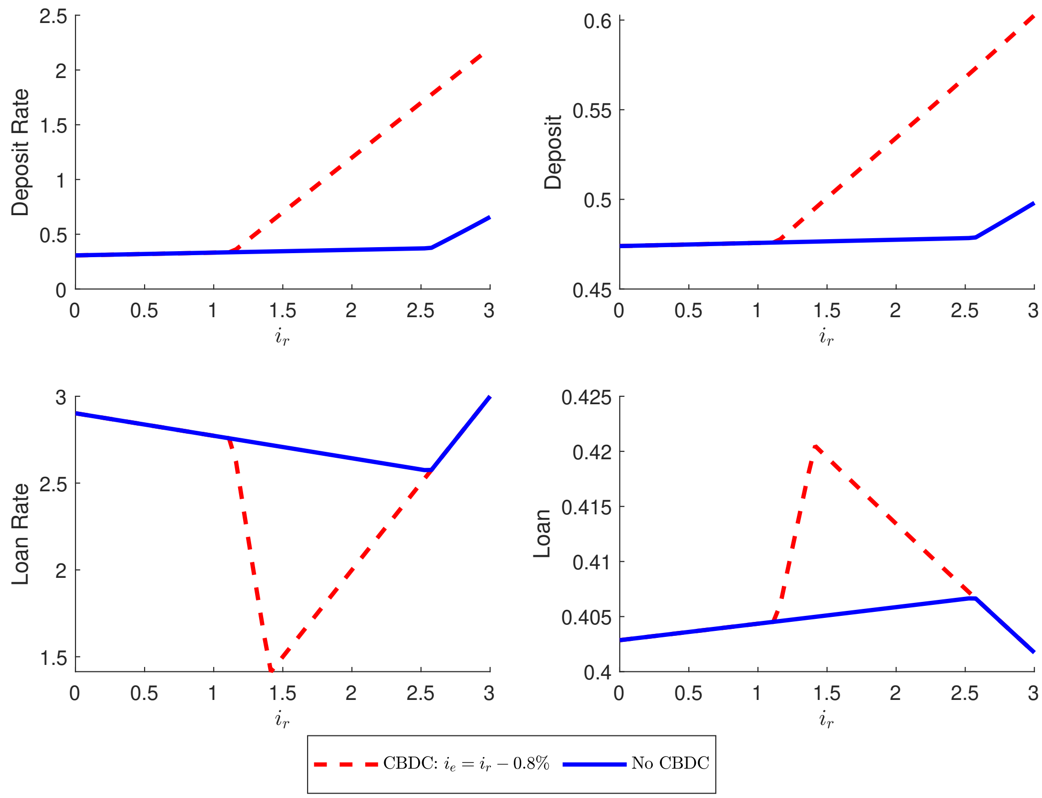


Figure 7: Pass-Through of i_r and i_e with a Constant Spread with Cournot Deposit Market

When the CBDC is a perfect substitute for deposits in terms of the payment function and can be held by commercial bank to satisfy the reserve requirement, the CBDC, when effective, tends to weaken the pass-through from the reserves to the economy. Indeed, the CBDC rate can dictate the deposit and loan rates, making the reserve rate irrelevant.

The CBDC rate also 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 dictate 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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In this Appendix, we show additional figures, and discuss the pass-through with the introduction of a CBDC that replicates the payment functionality of deposits but cannot be used by banks to meet their reserve requirement.

A Additional Figures

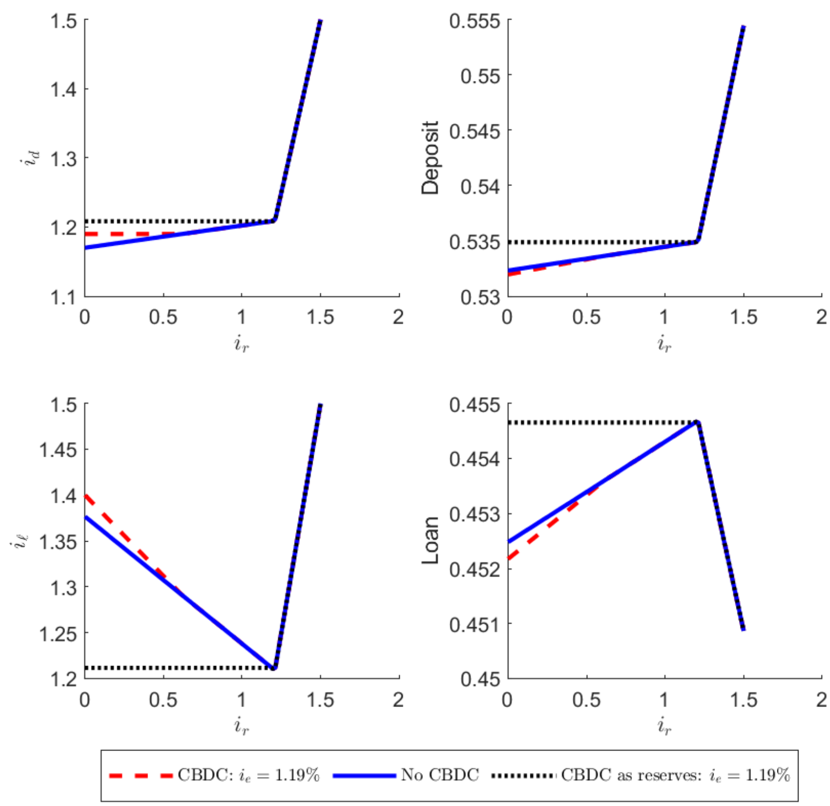

Figure 8: Pass-through of i_r with Competitive Deposit Market: Banks Can Hold CBDC as Reserves

Notes. Solid blue line: without CBDC. Red dashed line: with CBDC, Black dotted line: Banks can hold CBDC. This figure shows $i_e < \bar{(i)}_r$. Along the flat part of the black dotted lines, the reserve requirement binds, the bank holds CBDC as reserves and offers a deposit rate higher than i_e.

B Pass-through of Interest on Reserves

If banks cannot hold CBDC as reserves, the CBDC becomes effective only when the CBDC rate forms an effective lower bound for the deposit rate. In this Appendix and the next one, we analyze how the pass-through of interest on reserves is affected by the CBDC, and how the pass-through of CBDC rate is affected by the interest on reserves. Again, we will distinguish between competitive and Cournot deposit market.

B.1 Competitive Banking

If i_e is less than the equilibrium deposit rate in the absence of a CBDC (call it i_d^0), then i_e does not affect the economy, and the equilibrium and the pass-through of i_r remain the same as in the case without a CBDC (see Section 4.1). In the analysis below, we focus on the case where $i_e \geq i_d^0$ so that introducing a CBDC changes the equilibrium and the bank is forced to pay i_e to its deposits. Again, the equilibrium has two regimes distinguished by whether the reserve requirement binds or not.

Introducing an effective CBDC tends to tighten the reserve requirement (or expand the region where the reserve requirement binds). With an effective CBDC, the deposit rate increases, and the bank raises the loan rate to break even. Fixing r, this enlarges the wedge between the reserve rate and the loan rate. If the reserve requirement is tight without a CBDC, then this wedge becomes bigger and the reserve requirement continues to bind (and becomes more binding). If the reserve requirement is loose without a CBDC, then after introducing an effective CBDC, in the right neighbourhood of the original switching point, the reserve requirement changes from being loose to tight. Finally, when i_r is high enough, the implied deposit rate without a CBDC exceed the CBDC rate and the CBDC does not affect the economy anymore.

First, suppose that the reserve requirement binds with the CBDC, in which case $i_r < i_e = i_d < i_\ell$. In equilibrium, the marginal benefit and cost of deposits are equalized and the bank earns zero profits:

$$(1-\chi)\, i_\ell + \chi i_r = i_e.$$

From this equation, we can derive the equilibrium loan rate i_ℓ. Then, the equilibrium loan quantity is $L = \mathbf{L}_d(i_\ell)$, the quantity of checkable deposits is $D = L/(1-\chi)$, the amount of total electronic liquidity balance is $\hat{\mathbf{D}}(i_e)$, and the CBDC holding is $E = \hat{\mathbf{D}}(i_e) - D \geq 0$.

The pass-throughs from i_r to i_d and i_ℓ are described by:

$$\frac{\partial i_d}{\partial i_r} = 0, \tag{18}$$

$$\frac{\partial i_\ell}{\partial i_r} = -\chi / (1-\chi) < 0. \tag{19}$$

Because the CBDC rate dictates the deposit rate, the reserve rate does not affect the deposit rate.[12] Similar to the regime with binding reserve requirement 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 (9) with (19). Intuitively, because banks earn zero profit under perfect competition, a change in i_r is passed completely to the deposit rate and the loan rate. When there is no CBDC, both the deposit and loan rates will respond. When there is a CBDC, the deposit rate is dictated by the CBDC rate and does not respond, and only the loan rate responds. Therefore, the magnitude of the change in loan rate tends to be larger than in the case without a CBDC.[13]

Next, consider the regime where the reserve requirement is loose, in which case $i_e = i_d = i_r = i_\ell$. This implies that without a CBDC the reserve requirement is also loose and $i_d = i_r = i_\ell$. Therefore, the equilibrium loan quantity and the quantity of electronic payment balances stay at $\mathbf{L}_d(i_r)$ and $\hat{\mathbf{D}}(i_r)$, which are not affected by the CBDC. However, the quantity of checkable deposits can be any value between $[\mathbf{L}_d(i_r)/(1-\chi), \hat{\mathbf{D}}(i_r)]$ because households are indifferent between checkable deposits and the CBDC. Notice that this equilibrium is a knife-edge case. It occurs only if the reserve requirement is not binding without a CBDC and i_e is equal to i_r. Generically, the equilibrium is either not affected by the CBDC or the reserve requirement is binding with the CBDC.

[12] When the 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.

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

The regime with a non-binding reserve requirement does not contribute to the pass-through of i_r because it is a knife-edge case. As a result, CBDC changes the pass-through of i_r only if the resulting equilibrium has a binding reserve requirement. This occurs if i_r is low. If i_r is sufficiently large, the interest rate on the checkable deposits is higher than the CBDC rate even without the CBDC and the CBDC does not affect the equilibrium and the pass-through.

The dashed red line in Figure 9 shows the pass-through of i_r with a CBDC. We again start with the pass-through to i_d. Introducing the CBDC raises i_d if i_r is small, i.e., the dashed red curve is above the blue curve. But if i_r is sufficiently large, the CBDC does not affect the equilibrium, i.e., the dashed red and the blue curve overlap. If i_r is small, the red dashed curve is flat: the CBDC dictates i_d and the pass-through from i_r to i_d is completely muted. If i_r is sufficiently large, the pass-through of i_r is not affected by the CBDC because it is not effective. Next, we move to the loan rate (i_ℓ). The dashed red curve above the blue curve if i_r is small: because the CBDC raises the deposit rate, banks have to charge a higher loan rate to break even. The dashed red curve is downward-sloping and is steeper than the blue curve. The change in i_r is only passed to i_ℓ because i_d does not respond. Therefore, the pass-through of i_r to i_ℓ strengthens after the CBDC is introduced.

Now we analyze the quantity of checkable deposits and loans. The dashed red curves are below the red curve if i_r is low. This implies that the CBDC disintermediates banks, i.e., reduces both checkable deposits and loans, under perfect competition. The effect of i_r on deposits and loans largely follows the effect of i_r on the rates. Interestingly, the quantity of checkable deposits jumps up as i_r exceeds a threshold so that the reserve requirement becomes slack. But the loan quantity changes continuously with i_r. Intuitively, when the reserve requirement is binding (i_r is low), banks create just enough checkable deposits to satisfy lending needs, which is below households' need for electronic payment balances. Therefore, households hold a positive amount of CBDC. When the i_r is above the threshold, the return on reserves is sufficiently high. Banks are willing to raise the interest rate on checkable deposits above the CBDC rate. Therefore, households move all their CBDC holdings to checkable deposits, leading to the jump in checkable deposits. Banks invest these additional checkable deposits in reserves. Therefore, the quantity of loans does not have a jump.

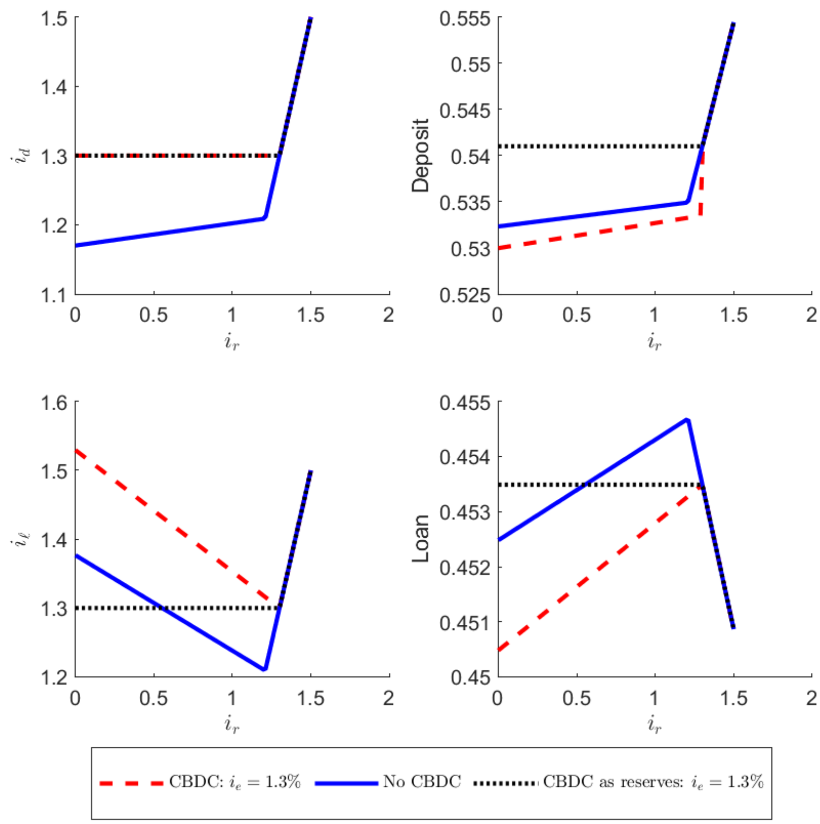

Figure 9: Pass-through of i_r with Competitive Deposit Market ($i_e > \hat{i}_r$)

Notes. This graph shows the effect of a CBDC with $i_e > \hat{i}_r$. Solid blue line: without CBDC. Red dash line: with CBDC but banks cannot use CBDC to meet reserve requirement. Black dotted line: with CBDC and banks can hold CBDC to meet reserve requirement.

B.2 Cournot Deposit Market

We again focus on the case where the CBDC is effective, which occurs only if i_r is not too big.

If the reserve requirement binds, then i_d and i_ℓ in the equilibrium with a CBDC are determined by

$$\begin{aligned} i_d &= i_e, \\ \mathbf{L}_d(i_\ell) &= (1-\chi)\hat{\mathbf{D}}(i_e). \end{aligned}$$

This regime occurs if i_ℓ that solves the above equations satisfies $i_\ell > i_r$, which implies that i_r is sufficiently small. Notice that i_d and i_ℓ are not affected by i_r and the pass-through from i_r to both rates is muted, i.e., both rates are dictated by the CBDC rate. This is different from the case under perfect competition in the deposit market where the pass-through to i_ℓ is strengthened by the CBDC. Because banks have market power, they do not pass through the increase in i_r to either the deposit or the loan market. Instead, they just get more profit.

If the reserve requirement is slack, then $i_d = i_e$ and $L = \mathbf{L}_d(i_r)$. In this regime, the amount of checkable deposits, $\hat{\mathbf{D}}(i_e)$, is larger than $L/(1-\chi)$. Banks hold the difference in reserves. A higher i_r does not affect the deposit rate but increases the loan rate one-for-one. As a result, banks make fewer loans and hold more reserves.

The dashed red curves in Figure 10 show the pass-through of i_r. When i_r is low, introducing a CBDC raises the interest rate on checkable deposits, raising the deposit quantity (relative to the case without a CBDC). This leads to more loans and a lower loan rate compared to the equilibrium with no CBDC. Moreover, the pass-through of i_r to the economy is completely muted for low i_r, i.e., both the rates and the quantities do not change with i_r. As i_r increases, the reserve requirement becomes slack. As a result, the loan rate increases with i_r and the loan quantity decreases with i_r. But the deposit rates and deposit quantity stay unchanged. As i_r increases further, the CBDC becomes ineffective. Banks offer interest rate higher than the CBDC rate and passes increases in i_r to the interest rate on checkable rates and deposit quantity increases as well. Notice that when the bank has market power on the deposit market, the quantity of checkable deposits changes continuously with i_r.

We now summarize the results obtained so far. If there is no CBDC, the pass-through of i_r depends on whether the reserve requirement is binding and the market

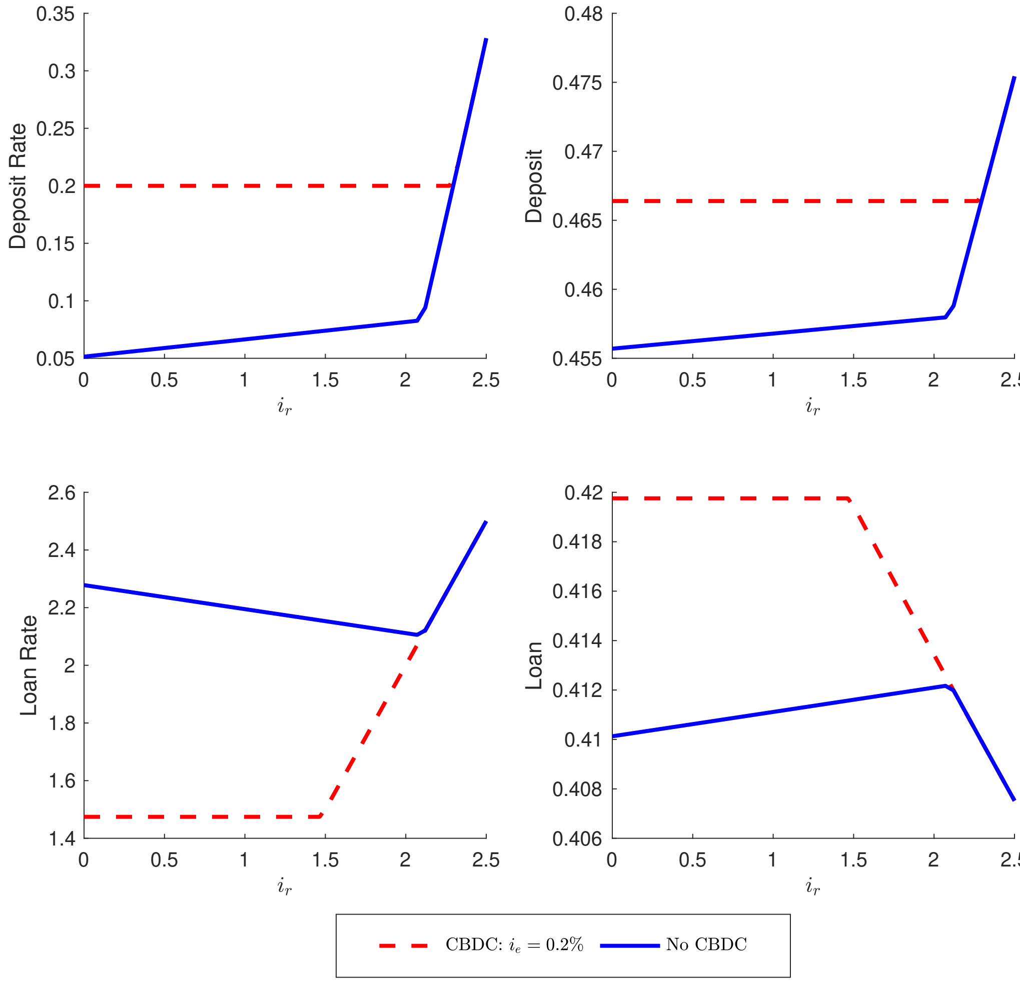

Figure 10: Pass-Through of i_r with Cournot Deposit Market (Banks Cannot Hold CBDC)

structure of the banking sector. If it is binding, a higher i_r increases i_d and decreases i_ℓ. The pass-through is less than perfect, i.e., 1% change in i_r leads to less than 1% change (in absolute value) in i_d and i_ℓ. If the reserve requirement is not binding, i_r increases both i_d and i_ℓ. The pass-through of i_r to i_ℓ is perfect, while the pass-through to i_d can be perfect or imperfect depending on whether the deposit market is perfectly competitive or not.

Introducing the CBDC weakens the pass-through of i_r to i_d regardless of the market structure of the banking sector (the CBDC rate while effective dictates the deposit rate). Its effect on the pass-through from i_r to i_ℓ depends on the market structure. If the deposit market is perfectly competitive, the CBDC strengthens the pass-through from i_r to i_ℓ if the reserve requirement is not binding, i.e., an increase in i_r decreases i_ℓ by more. But if the deposit market is imperfectly competitive, the CBDC weakens the pass-through from i_r to i_ℓ.

C Pass-through of the Interest Rate on CBDC

We now study the pass-through of the CBDC rate, and how it depends on the interest rate on reserves, i_r. We will first analyze the case where the deposit market is competitive, and then the case where the deposit market features Cournot competition.

C.1 Competitive Deposit Market

The CBDC is effective only if $i_e > i_r$, which is the case that we focus on. If the reserve requirement binds,

$$\frac{\partial i_d}{\partial i_e} = 1, \tag{20}$$

$$\frac{\partial i_\ell}{\partial i_e} = 1/(1-\chi) > 1. \tag{21}$$

There is a perfect pass-through from i_e to i_d, reflecting the fact that banks have to match the CBDC rate. The pass-through from i_e to i_ℓ is larger than 1 if $\chi > 0$. Because banks can lend only $1-\chi$ if they get 1 additional unit of checkable deposits, they need to increase the lending rate by $1/(1-\chi)$% if the deposit rate increases by 1%. Notice that if i_r is higher, the CBDC stays ineffective for a wider range of i_e. As a result, the pass-through of i_e is muted for a wider range of i_e

Figure 11 shows the pass-through of i_e under $i_r = 0$ (the solid blue) and $i_r > 0$ (the dashed red) if the banking sector is perfectly competitive. In both cases, a higher i_e does not affect the equilibrium if i_e is small because the CBDC is not effective. But if i_e is sufficiently large, A higher i_e increases i_d and i_ℓ. As a result, it reduces the quantity of checkable deposits and loans. Note that if i_r is higher, the pass-through of i_e stays at 0 for a larger range of i_e as discussed above. Interestingly, if $i_r > 0$ the deposit quantity jumps down if i_e exceeds i_r. This is because the banks hold excess reserves under i_r. If i_e exceeds i_r, holding excess reserves becomes not profitable because the banks have to match the CBDC rate. Therefore, banks cut all the excess reserves and reduce deposit creation and households instead hold more CBDC.

C.2 Cournot Deposit Market

If <u>the reserve requirement binds</u>, the pass-through of i_e is

$$\begin{aligned}
\frac{\partial i_d}{\partial i_e} &= 1, \\
\frac{\partial i_\ell}{\partial i_e} &= (1-\chi) f'\left(\hat{\mathbf{D}}(i_e)(1-\chi)\right)\hat{\mathbf{D}}'(i_e).
\end{aligned}$$

If <u>the reserve requirement is slack</u>, the pass-through is

$$\frac{\partial i_d}{\partial i_e} = 1, \ \frac{\partial i_\ell}{\partial i_e} = 0.$$

In this case, the CBDC rate dictates the deposit rate and the interest rate on reserves dictates the lending rate.

Figure 12 shows the pass-through of i_e if the deposit market is imperfectly competitive. The blue solid curve is under $i_r = 0$ and the red dashed curve is under $i_r > 0$. If $i_r = 0$, the CBDC rate does not have an effect on the interest rate on checkable deposits if it is low but has a perfect pass-through to the interest rate on checkable deposits if it is sufficiently large. This raises households' demand for checkable deposits, which leads to higher deposit quantity. Because bank has more funding from deposits, they lend out more, lending to a drop in the loan rates. Therefore, the pass-through from the CBDC raet to the loan rate is negative until i_e reaches a threshold where banks' profits reach 0. Then banks behave as if they are perfectly competitive. Then the pass-through from the CBDC rate to the loan rate is positive.

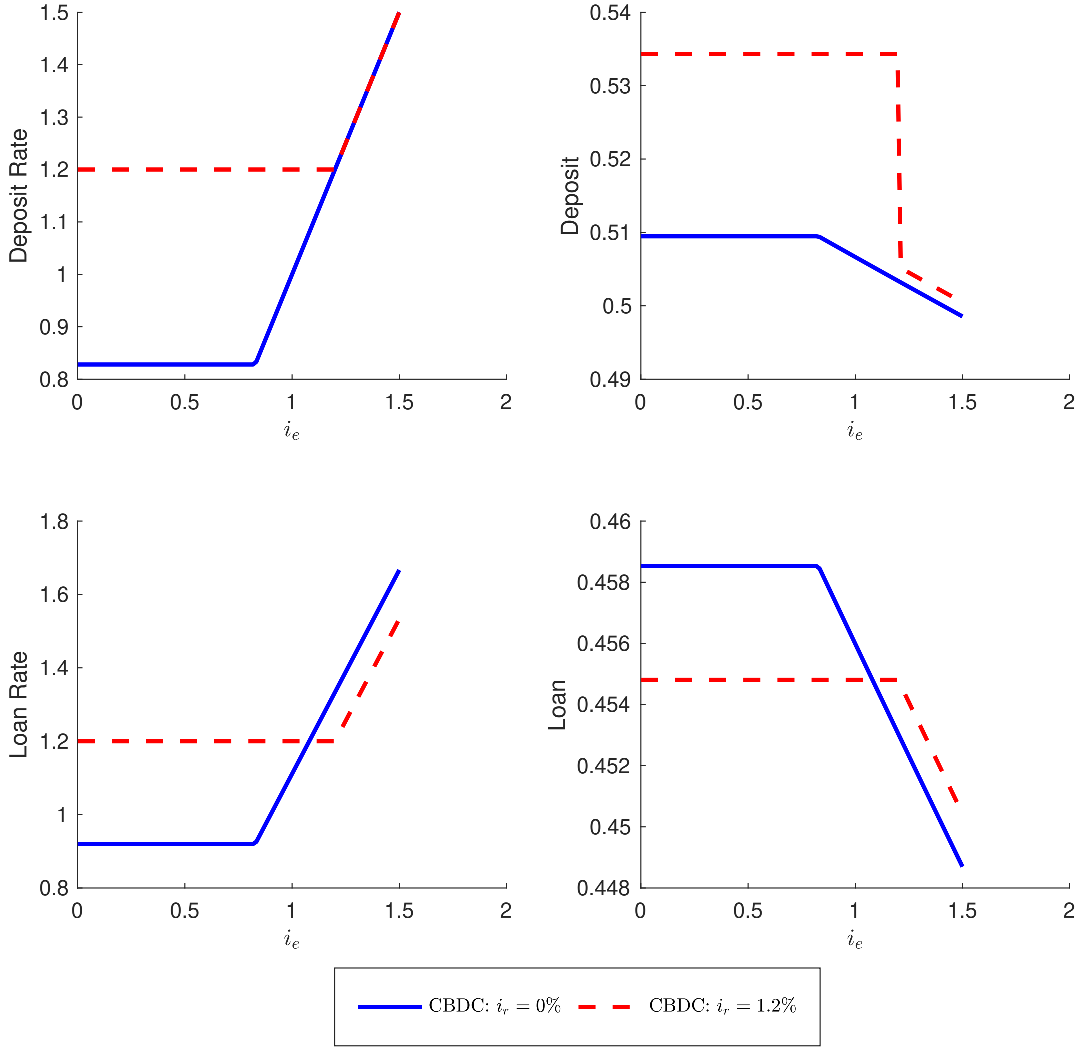

Figure 11: Pass-Through of i_e with Competitive Deposit Market (Banks Cannot Hold CBDC)

Notes. Solid blue line: $i_r = 0$. Red dashed line: $i_r = 1.2\%$.

If $i_r > 0$, the pass-through to deposit rate is largely unaffected. But the pass-through to the loan rate is weakened in the sense that if i_e is in an intermediate range, the pass-through of the CBDC rate to loan rate is 0. In this range, the reserve requirement becomes slack and i_r dictates the loan rate. Interestingly, the reserve requirement is slack if i_e is in some intermediate range. Because the pass-through to loan rate is weakened, the effect on loans is also weakened. Interestingly, the deposit quantity jumps down as i_e moves above i_r. Intuitively, if i_e is below i_r, it is profitable for banks to create deposits at rate i_e and invest them in excess reserves. But as soon as i_e moves from i_r, this strategy is not profitable and banks cut the excess reserves completely, leading to the drop in checkable deposits.

To sum up, the pass-through from i_e to i_d is perfect if i_e is not too small. The pass-through to i_d changes signs depending on whether the banks have positive profits, as shown in Chiu et al. (2023). If i_r increases, the pass-through from i_e to i_ℓ is weakened.

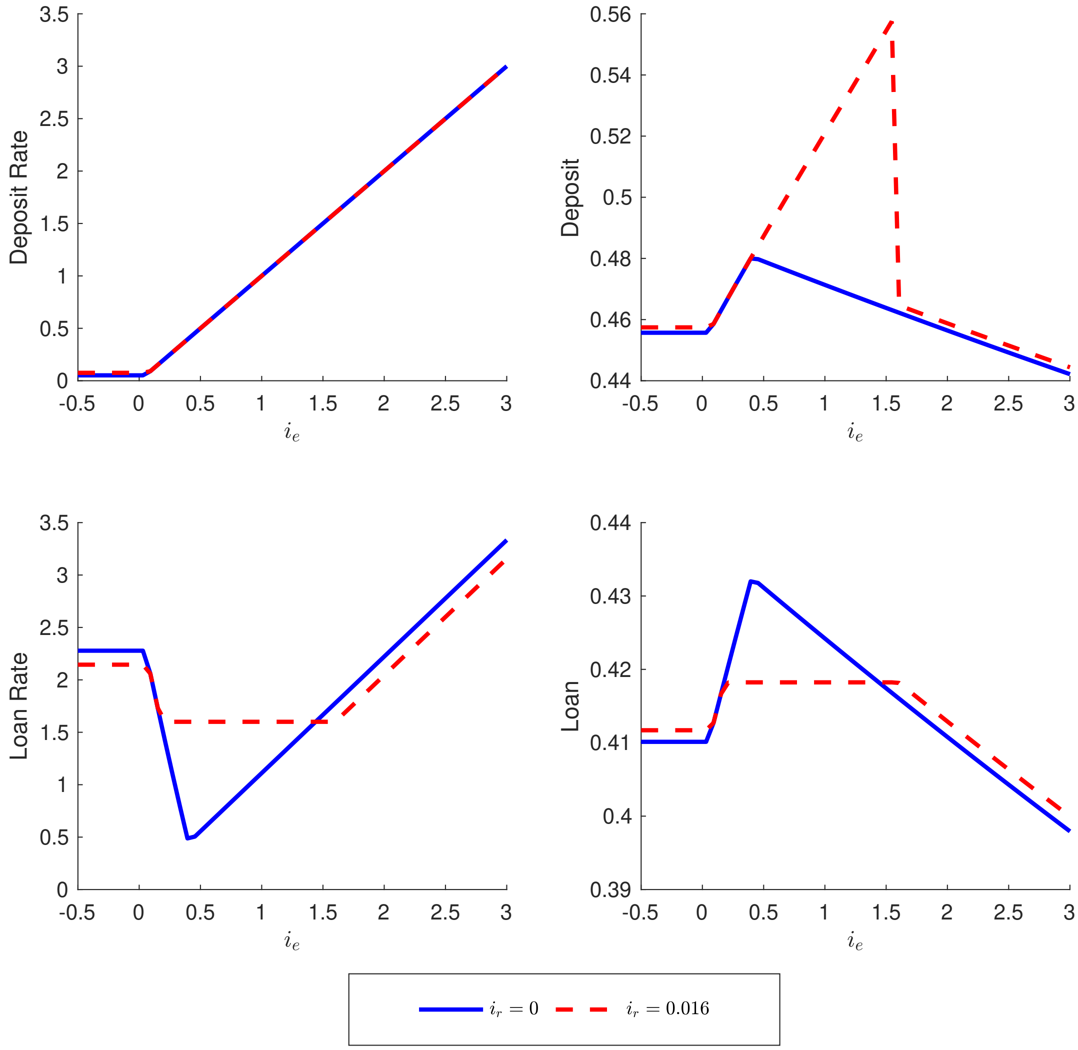

Figure 12: Pass-Through of i_e with Cournot Deposit Market (Banks Cannot Hold CBDC)