Central Bank Digital Currency and Banking Choices

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Abstract

To what extent would a central bank digital currency (CBDC) compete with bank deposits? To answer this question, we develop and estimate a structural model where each household chooses a financial institution to deposit their digital money. Households value the interest paid on digital money, the possibility of obtaining complementary financial products, and the access to in-branch services. We find that a non-interest-bearing CBDC that does not provide complementary financial products or a broad branch network is unlikely to substantially crowd out bank deposits. Imposing a large limit on CBDC holdings is sufficient to mitigate the potential crowding out.

JEL Classification: E50, E58

Keywords: Central Bank Digital Currency; CBDC Designs; Micro-level Deposit Demand Estimation; Banking Competition

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1 Introduction

Many central banks are considering issuing a retail central bank digital currency (CBDC), a digital form of central bank money that is available to the general public and can be used for retail transactions.[1] By offering the public the option to hold the digital money in a CBDC instead of bank deposits, the CBDC would directly compete with bank deposits in the market for digital money. As a consequence, there are concerns that a CBDC could substantially crowd out bank deposits, which may undermine financial stability by raising the funding cost and reducing the profitability of the banking sector. However, little is known about the degree to which bank deposits and CBDC are substitutes.

The key to quantifying the potential demand for CBDC and its crowding-out effect is to understand how a CBDC would differ from bank deposits. This paper highlights two key differentiating features between a CBDC and bank deposits: (i) commercial banks, unlike central banks, provide products complementary to deposits, such as mortgages and credit cards;[2] (ii) most banks have extensive branch networks for in-person services.

We focus on these features because households have strong preferences for obtaining complementary financial products from their deposit banks and for conveniently accessing in-person services at physical locations (bank branches). According to Canadian household survey data 2010–2017, 56% of mortgage borrowers and 45% of credit card holders choose the same bank for their deposits and each respective product. Moreover, both urban and rural households prefer banks with branches closer to their residences. Around 60% of depositors reported that they had visited their branches at least once in the past month. Depositors prefer using bank branches for non-transaction related services, such as obtaining customer service and support and making complaints, to other methods such as online and mobile banking. Similar survey evidence is found for the US. Based on a 2022 survey of more than 2290 US consumers by PYMNTS and Amount, 45% of US consumers would prefer to get all their banking products from the same financial institution and 71% of this group say their

[1] According to the 2021 Bank for International Settlements (BIS) survey, 90% of the central banks are engaging in CBDC work and 62% are conducting experiments or proofs of concept. The survey respondents include 81 central banks that represent close to 76% of the world's population and 94% of global economic output (Kosse and Mattei, 2022). The Bahamas, Eastern Caribbean Central Bank, Jamaica, and Nigeria have already launched retail CBDCs. There are 21 countries that have already started their pilots, including China, India, Singapore, South Korea, and Sweden.

[2] We focus on the complementarity between deposits and other financial products within the same bank that is enjoyed by consumers, which differs from the complementarity between credit lines and deposits that is enjoyed by banks in Piazzesi and Schneider (2020) or the complementarity between print and online newspapers in Gentzkow (2007). The complementarity in our paper could reflect the convenience of managing the different products in the same bank, the ease of making bill payments from the deposit account, or the better deals from bundling different products at the same bank.

preference is driven by the ease and convenience of bundling accounts with one bank.[3]

To incorporate these two features, we develop a structural model where households obtain utility from holding their endowed liquid assets in physical cash and digital money. Before a CBDC is introduced, the only available digital money is demand deposits provided by private banks. A household first opens an account at one of the private banks, considering the varying deposit rates, complementary financial products, and branch network offered by each institution. Then it allocates its liquid assets between cash and demand deposits. Banks set deposit rates to compete for deposits. We estimate the model primitives, which include households' preference parameters for different attributes (e.g., deposit rate, complementarity, and branch network) and banks' marginal costs. These model primitives are assumed to be unchanged after CBDC issuance.

We exploit a unique Canadian household survey dataset that contains detailed product-level information on individual households' bank choices to estimate households' preferences for obtaining complementary financial products from their deposit banks. Specifically, we estimate how likely a household is going to bundle another financial product with their deposit bank. Furthermore, by combining detailed bank branch location data with households' residential locations from the household survey, we construct household-specific measures of local branch networks. This not only allows us to precisely estimate households' preferences for branch access, but also enables us to examine how differences in branch network affect urban and rural households.

After estimating the model primitives, we introduce a CBDC in counterfactual analyses, modeled as a new product with attributes exogenously chosen by the central bank. A household chooses to deposit its digital money in either an existing bank or the CBDC based on the product attributes and the household's idiosyncratic tastes for the products.[4] Because of the rich heterogeneity in households' idiosyncratic tastes, some households would switch to holding the CBDC, reducing the number of bank depositors (extensive margin). At the same time, the CBDC tends to make the deposit demand more elastic with respect to the deposit rate as households now have more choices. To remain competitive, banks respond by raising their deposit rates, which increases the deposits held by each depositor (intensive margin). In equilibrium, the effect of the CBDC on the extensive margin tends to dominate that on the intensive margin, resulting in fewer bank deposits. Therefore, the CBDC tends to crowd out bank deposits.

The magnitude of the crowding out depends on the design of the CBDC. In our baseline

[3]For more details, the report can be found from the website: https://www.pymnts.com/news/banking/2022/45-of-us-consumers-want-banking-bundles/.

[4]We also study the extension where each household can hold both CBDC and deposits.

design, the CBDC is non-interest-bearing and does not offer complementary products.[5] We also vary the service location network from having no service location to an extensive network that includes all bank branches and Canada Post offices.[6] In addition, we investigate the effects of holding limits (caps on the amount of CBDC an individual can hold), which are being considered by central banks including the European Central Bank (ECB) and the Bank of England.

The main findings are as follows. First, a non-interest-bearing CBDC that provides no complementarity nor service locations would have a negligible impact, crowding out banks' demand deposits by around 1%. Even if the CBDC has all Canada Post offices as service locations, the crowding out on demand deposits is less than 7%. Only with an extensive service location network that includes both Canada Post offices and all bank branches – exceeding the branch network of any single bank – could the CBDC reduce the demand deposits by around 12%. Under this extensive network design, if it is also designed to achieve an average level of complementarity that banks provide, then it can crowd out 28% of demand deposits.

Second, a large limit on CBDC holdings can substantially reduce crowding out, while having a relatively small effect on the depositors' welfare. By solving the model for a range of different limits, we find that even a holding limit of 25,000 Canadian dollars, which is much higher than the limit of 3,000 euros considered by the ECB (Panetta, 2022), would reduce the CBDC holdings by half, regardless of the service location network. Under this limit, only 10% of households are constrained but they would like to hold a large amount of the CBDC if there were no limit. Therefore, the effect of the holding limit on aggregate CBDC holdings is substantial. In contrast, the impact on depositors' welfare gains is much smaller precisely because only 10% of households are affected. This suggests policymakers can reduce the crowding out while making CBDC attractive to most households.

Third, the impacts of a CBDC on both banks and households are heterogeneous. Banks with higher market shares tend to respond more to the introduction of a CBDC, raising

[5] Since the central bank is unlikely to make loans to the public, if a household chooses the CBDC for their digital money, they still need to go to a private bank for a mortgage loan or a credit card. Nevertheless, we also consider the design where the CBDC provides a certain degree of complementarity through a mobile app that enables functions such as easy pay-off of debt.

[6] These counterfactual location choices are motivated by the policy discussions on whether a central bank should directly deliver the CBDC to the public (i.e., single-tier system) or partner with the private sector (i.e., two-tier system). The 2022 BIS survey shows that 87% of central banks engaged in retail CBDC work are considering a two-tier system that involves a role for the private sector (Kosse and Mattei, 2023). We highlight the implications of the delivery arrangement on service locations. While a single-tier system is likely to imply no service location for the CBDC, a two-tier system would imply a network of CBDC service locations similar to those of the private sector providers.

deposit rates by more and losing fewer deposits.[7] Households in rural areas would benefit more from a CBDC than urban households even if the CBDC does not have service locations. This is because rural areas tend to be relatively underserved by bank branches.

This paper complements the growing theoretical literature that studies the effects of a CBDC on banking (e.g., Andolfatto, 2021; Garratt, Yu and Zhu, 2022; Chang et al., 2023; Chiu et al., 2023; Keister and Sanches, 2023).[8] This literature typically assumes that the CBDC is a perfect substitute for bank deposits.[9] Most papers in this stream also have limited discussions on the designs of the CBDC, focusing mainly on the interest rate. In contrast, we use rich micro-level data to estimate households' preferences over product characteristics such as branch networks and complementarity with other financial products, and use these preferences to predict the effect of a CBDC on banking under different designs.[10]

This paper contributes to the empirical literature on CBDC, which is scarce at this point due to the lack of data. To address this issue, our approach is to develop a structural model and estimate the households' preferences for product attributes using the data on existing products that are close substitutes for a potential CBDC. The estimated model is then used to conduct counterfactual analysis on the CBDC. Our approach is therefore related to Huynh et al. (2020), Li (2023), Whited, Wu and Xiao (2023), Lambert et al. (2024), and Nocciola and Zamora-Pérez (2024), who use different structural models to study CBDC. Our contribution is to show the importance of the service locations, and the complementarity between deposits and other financial products from the consumers' point of view by developing a model that

[7]Similarly, Whited, Wu and Xiao (2023) find that when the banking sector is more concentrated, banks lose fewer deposits to a one dollar increase in CBDC. Garratt, Yu and Zhu (2022) find that the large bank raises its deposit rate by more in response to a higher CBDC interest rate. With the household-level data, we can also study the heterogeneous impact of a CBDC on households.

[8]Existing theoretical literature also studies the effects of a CBDC on financial stability (e.g., Brunnermeier and Niepelt, 2019; Skeie, 2019; Schilling, Fernández-Villaverde and Uhlig, 2020; Fernández-Villaverde et al., 2021; Williamson, 2021; Ahnert et al., 2023), monetary policy (e.g., Bordo and Levin, 2017; Jiang and Zhu, 2021; Davoodalhosseini, 2022; Abad, Nuño and Thomas, 2023; Niepelt, 2024), macroeconomic volatility (e.g., Barrdear and Kumhof, 2022; George, Xie and Alba, 2022; Minesso, Mehl and Stracca, 2022; Assenmacher, Bitter and Ristiniemi, 2023), payment competition (Liu, Reshidi and Rivadeneyra, 2023; Cong and Mayer, 2024), and welfare (e.g., Piazzesi and Schneider, 2020; Assenmacher et al., 2021; Williamson, 2022). For policy discussions on the implications of CBDC issuance, see Engert and Fung (2017), Berentsen and Schar (2018), Mancini-Griffoli et al. (2018), Meaning et al. (2018), Davoodalhosseini, Rivadeneyra and Zhu (2020), García et al. (2020), Gross and Letizia (2023), Claessens et al. (2024), etc.

[9]Garratt, Yu and Zhu (2022) consider a large bank and a small bank that differ in both deposit rates and convenience values in their theoretical analysis, but they still maintain the perfect substitution assumption in the sense that CBDC demand would be zero if its interest rate and convenience value combined is lower.

[10]While there are a few papers studying the non-price design features of a CBDC, such as anonymity (Garratt and Lee, 2021; Agur, Ari and Dell'Ariccia, 2022; Ahnert, Hoffmann and Monnet, 2022; Cheng and Izumi, 2023; Chiu and Monnet, 2023; Tinn, 2024; Capponi, Lee and Zhu, 2025) and expiry date on offline CBDC balances (Kahn, van Oordt and Zhu, 2021), we are the first to quantify the impact of the CBDC designs in terms of the network of service locations and the complementarity.

can be applied to household-level data on banking choices.[11]

Another approach is to conduct surveys or experiments to directly ask people about their intention to adopt a hypothetical CBDC. For example, surveys have been conducted in the Netherlands (Bijlsma et al., 2021), Austria (Abramova et al., 2022), and by the ECB (Kantar Public, 2022). In the absence of a CBDC or a concrete design for CBDC, this survey approach is challenging because the results rely heavily on consumers' understanding of a hypothetical CBDC. Choi et al. (2022) use a discrete choice experiment approach, where each respondent is asked to choose between a pair of hypothetical payment methods (constructed by varying the values of nine product attributes). Again, the accuracy of the results relies on consumers' understanding of the description of each hypothetical payment instrument. In contrast, our approach uses households' preferences that are revealed from their choices and does not rely on their ability to understand descriptions of hypothetical products.

The rest of the paper is organized as follows. Section 2 presents the model without a CBDC, which is used for estimating households' preferences using data on existing products. Section 3 discusses identification and estimation of this model. Section 4 presents our data sources and estimation results. Section 5 shows the counterfactual analyses for CBDC using the estimated model. Section 6 considers several extensions. Section 7 concludes.

2 Model

The model consists of two types of agents: households indexed by $i \in \mathcal{I}$ and banks indexed by $j \in \mathcal{J}$. A household first chooses a bank to open a deposit account and decides on the deposit holding. Throughout the paper, we focus on demand deposits, as they face direct competition from the CBDC. Thus, any mention of "deposits" refers to "demand deposits" unless stated otherwise. After choosing a deposit bank, the household may need to choose a bank for other financial products. To capture the complementarity between deposits and financial products, we allow the household to get extra utility if it chooses financial products provided by its deposit bank. The household problem generates the demand for deposits. Banks take the deposit demand as given and engage in Bertrand competition with differentiated products in the deposit market. A bank sets its deposit rate to maximize profits. We focus on the deposit market where a CBDC will have a direct impact and abstract from banks' lending decisions

[11] This paper also adds to the literature that uses structural models to study the deposit market (e.g., Dick, 2008; Ho and Ishii, 2011; Egan, Hortaçsu and Matvos, 2017; Abrams, 2019; Aguirregabiria, Clark and Wang, 2019; Wang et al., 2020; Xiao, 2020; Albertazzi et al., 2022), the lending market (e.g., Buchak et al., 2018; Crawford, Pavanini and Schivardi, 2018; Allen, Clark and Houde, 2019; Benetton, 2021), and the crypto market (e.g., Benetton and Compiani, 2024). Our paper relates to studies of the deposit market, which often rely on aggregate bank-level data and do not consider the bundling of financial products within banks. We show that household-level data can offer new insights in this line of research.

and how the complementarity affects the loan demand. We discuss the household's problem in Section 2.1 and the bank's problem, along with the implications of the aforementioned abstraction in Section 2.2.

2.1 Household's Problem

Household i is endowed with w_i liquid asset balances, which they would like to hold in both the physical form (cash) and the digital form. For now, there is no CBDC and bank deposits are the only available digital liquid asset. We introduce a CBDC in Section 5. To hold deposits, the household first opens an account at a bank selected from its choice set $\mathcal{J}_i \subseteq \mathcal{J}$. Conditional on choosing deposit bank j, the household optimally allocates w_i between cash and deposits. After this,[12] the household may need to obtain a financial product $k \in \mathcal{K}$, such as a mortgage loan or a credit card, with an exogenous probability ω^k. To obtain each product $k \in \mathcal{K}$, the household needs to choose a bank n from its choice set $\mathcal{J}_i^k \subseteq \mathcal{J}^k$. To capture complementarities between deposits and other financial products within the same bank, we allow the household to enjoy extra utility if it obtains the financial product from its deposit bank.

The household's utility from opening a deposit account at bank j is

$$V_{i,j}^f = \theta V_{i,j}^b + \phi \sum_{k \in \mathcal{K}} \omega^k \mathbb{E} V_{i,j}^k + \boldsymbol{X}_{i,j} \boldsymbol{\beta}^f + \eta_j^f + \varepsilon_{i,j}^f, \tag{1}$$

where $V_{i,j}^b$ is the utility from holding the optimal portfolio of cash and deposits at bank j, and $\omega^k \mathbb{E} V_{i,j}^k$ is the expected utility from obtaining the financial product k, which equals the probability of needing the financial product, ω^k, multiplied by the expected value from the financial product, $\mathbb{E} V_{i,j}^k$. We assume that when the household first chooses the deposit bank, it does not know its idiosyncratic tastes for other financial products yet. Therefore, it considers the expected value from each product. The parameters, θ and ϕ, capture the importance of the utility from liquidity holding and from complementary financial products, respectively. The vector $\boldsymbol{X}_{i,j}$ contains the branch network measures of bank j that are specific to household i's local area, and $\boldsymbol{\beta}^f$ consists of the preference parameters for each branch network measure. Lastly, η_j^f is the bank fixed effect that captures unobserved heterogeneity in the quality of bank services, and $\varepsilon_{i,j}^f$ is the idiosyncratic taste of the household for bank j.

Household i chooses a bank from its choice set $\mathcal{J}_i$ to maximize $V_{i,j}^f$. Assuming $\varepsilon_{i,j}^f$ follows

[12] This timing assumption is supported by the Canadian household survey data from 2010–2017, where around 80% of the mortgage borrowers take out a mortgage after getting the deposit account. The median household takes out a mortgage 8 years after having the deposit account.

a type-I extreme value distribution and is independent across banks, the probability of choosing bank $j \in \mathcal{J}_i$ has the standard logit form:

$$\mathbb{P}(j_i^* = j | r_j, \boldsymbol{r}_{-j}) = \frac{\exp\left(\theta V_{i,j}^b + \phi \sum_{k \in \mathcal{K}} \omega^k \mathbb{E} V_{i,j}^k + \boldsymbol{X}_{i,j} \boldsymbol{\beta}^f + \eta_j^f\right)}{\sum_{m \in \mathcal{J}_i} \exp\left(\theta V_{i,m}^b + \phi \sum_{k \in \mathcal{K}} \omega^k \mathbb{E} V_{i,j}^k + \boldsymbol{X}_{i,m} \boldsymbol{\beta}^f + \eta_m^f\right)}, \tag{2}$$

where j_i^* denotes the optimal choice, r_j is the deposit rate of bank j, and $\boldsymbol{r}_{-j}$ is the vector of deposit rates set by banks other than j. We next discuss $V_{i,j}^b$ and $\mathbb{E}V_{i,j}^k$ in detail.

Value from Liquid Asset Portfolios. Household i obtains utility from holding $c_{i,j}$ in cash and $d_{i,j}$ in deposits at bank j:

$$\ln \left[c_{i,j}^{\sigma} + \left(u_{i,j}^b d_{i,j}\right)^{\sigma}\right]^{1/\sigma}, \tag{3}$$

where $\sigma \in (0,1)$ controls the level of substitution between physical and digital liquid assets and $u_{i,j}^b$ captures the value of deposits relative to cash. The latter depends on the after-tax deposit rate $r_{i,j}$, branch network measures $\boldsymbol{X}_{i,j}$, household characteristics $\boldsymbol{Z}_i$, bank fixed effect η_j^b, a deposit-specific constant ζ^b, and a household's idiosyncratic taste for deposits ε_i^b:

$$u_{i,j}^b = \exp\left(\alpha^b r_{i,j} + \boldsymbol{X}_{i,j} \boldsymbol{\beta}^b + \boldsymbol{Z}_i \boldsymbol{\gamma}^b + \eta_j^b + \zeta^b + \varepsilon_i^b\right), \tag{4}$$

where the parameters α^b and $\boldsymbol{\beta}^b$ measure how much the households value the respective bank-specific characteristics. The parameter vector $\boldsymbol{\gamma}^b$ captures the effects of household characteristics on $u_{i,j}^b$. The household's value from the optimal portfolio at bank j is

$$V_{i,j}^b = \max_{c_{i,j}, d_{i,j}} \ln \left[c_{i,j}^{\sigma} + \left(u_{i,j}^b d_{i,j}\right)^{\sigma}\right]^{1/\sigma} \quad \text{st} \quad c_{i,j} + d_{i,j} = w_i. \tag{5}$$

After substituting for the optimal $d_{i,j}$ and $c_{i,j}$, one can obtain

$$V_{i,j}^b = \frac{1-\sigma}{\sigma} \ln \left[1 + \left(u_{i,j}^b\right)^{\frac{\sigma}{1-\sigma}}\right] + \ln w_i. \tag{6}$$

Moreover, household i's optimal deposit holding is

$$d_{i,j}(r_j) = \frac{(u_{i,j}^b)^{\sigma/(1-\sigma)}}{1 + (u_{i,j}^b)^{\sigma/(1-\sigma)}} w_i. \tag{7}$$

Therefore, household i's expected demand for deposits at bank j is $d_{i,j}(r_j)$ multiplied by the choice probability (2).

Value from Financial Products. If household i needs a financial product $k \in \mathcal{K}$, it will choose a bank n from its choice set $\mathcal{J}_i^k$. If the deposit bank is j, the utility of obtaining the financial product from bank n is

$$U_{i,n}^k(j) = \kappa^k \mathbb{1}(n = j) + \boldsymbol{X}_{i,n}\boldsymbol{\beta}^k + \eta_n^k + \varepsilon_{i,n}^k, \tag{8}$$

where κ^k captures the complementarity between deposits and the financial product k. All else being equal, a household prefers to obtain the product k from its deposit bank if $\kappa^k > 0$. This complementarity could reflect the convenience in managing different products at the same bank, or potentially better deals offered by banks, for instance.[13] The vector $\boldsymbol{X}_{i,n}$ consists of the bank branch network measures, η_n^k is the bank fixed effect, and $\varepsilon_{i,n}^k$ is an idiosyncratic taste that follows the type-I extreme value distribution. We assume that $\varepsilon_{i,n}^k$ is independent across financial products and banks, and is independent of all other idiosyncratic tastes in the model.[14] The parameter $\boldsymbol{\beta}^k$ reflects the importance of the branch network measures in the bank choice for product k. Let $\mathbb{E}V_{i,j}^k$ denote the expected value from product k if the deposit bank is j:

$$\mathbb{E}V_{i,j}^k = \mathbb{E}[\max_{n \in \mathcal{J}_i^k} \ U_{i,n}^k(j)], \tag{9}$$

where the expectation is taken with respect to $\varepsilon_{i,n}^k$. It can be shown that $\mathbb{E}V_{i,j}^k$ has the following closed-form expression:

$$\mathbb{E}V_{i,j}^k = \ln\left(\sum_{n \in \mathcal{J}_i^k} \exp\left(\kappa^k \mathbb{1}(n = j) + \boldsymbol{X}_{i,n}\boldsymbol{\beta}^k + \eta_n^k\right)\right) + C, \tag{10}$$

where C is a known constant. If $\kappa^k = 0$ for all $k \in \mathcal{K}$, the expected value from each financial product is independent of the deposit bank and thus would not affect the deposit bank choice.

[13] Literature has shown that banks and BigTech platforms use payment information to adjust their monitoring intensity (Mester, Nakamura and Renault, 2007) and credit provision (Ouyang, 2023), and to offer better payment services (Chiu and Koeppl, 2022). Similarly, banks may use information from households' deposit accounts to give them better deals for other products. However, better deals are not necessary for households to prefer their deposit banks. They may get worse deals from their deposit banks but still prefer their deposit banks due to convenience.

[14] This assumption greatly simplifies the estimation of the model. If $\varepsilon_{i,n}^k$ were correlated with $\varepsilon_{i,j}^f$, households might prefer obtaining financial products from their deposit bank not because these products are complementary, but because they have a strong preference for their deposit bank. As will be discussed in Section 4.2, the estimate for the preference for complementarity κ^k is robust to the correlated consumer tastes measured by the bank fixed effects interacted with various household characteristics.

2.2 Banks' Problem

Aggregating across the households' individual deposit demand, we obtain the deposit demand for each bank j:

$$D_j(r_j, \boldsymbol{r}_{-j}) = \sum_{i \in \mathcal{I}} \mathbb{P}(j_i^* = j | r_j, \boldsymbol{r}_{-j}) d_{i,j}(r_j), \tag{11}$$

where $\mathbb{P}(j_i^* = j | r_j, \boldsymbol{r}_{-j})$ is defined by (2) and $d_{i,j}$ is defined by (7). We assume banks invest in assets with an exogenous return r_j^l.[15] Let mc_j denote bank j's marginal cost. Bank j takes the deposit rates of other banks, $\boldsymbol{r}_{-j}$, as given and chooses a deposit rate r_j to maximize its profit:

$$\pi_j(r_j, \boldsymbol{r}_{-j}) = (r_j^l - r_j - mc_j) D_j(r_j, \boldsymbol{r}_{-j}). \tag{12}$$

Let $\boldsymbol{r^*} = (r_1^*, r_2^*, \cdots, r_J^*)$ denote the equilibrium deposit rates. They satisfy the set of first-order conditions of banks:

$$r_j^l - r_j^* - mc_j = \left[\frac{\partial D_j(r_j^*, \boldsymbol{r^*}_{-j})}{\partial r_j^*} \frac{1}{D_j(r_j^*, \boldsymbol{r^*}_{-j})} \right]^{-1}, \ \forall j, \tag{13}$$

where the left-hand side is the markup and the right-hand side is the inverse semi-elasticity of deposit demand. One can show that this semi-elasticity can be written as:

$$\begin{aligned} \frac{\partial D_j(r_j, \boldsymbol{r}_{-j})}{\partial r_j} \frac{1}{D_j(r_j, \boldsymbol{r}_{-j})} = & \sum_i \frac{\mathbf{P}_{i,j} d_{i,j}(r_j)}{D_j(r_j, \boldsymbol{r}_{-j})} \left[\theta \alpha^b (1 - \tau_i) \frac{d_{i,j}(r_j)}{w_i} \right] (1 - \mathbf{P}_{i,j}) \\ & + \sum_i \frac{\mathbf{P}_{i,j} d_{i,j}(r_j)}{D_j(r_j, \boldsymbol{r}_{-j})} \left[\frac{\alpha^b (1 - \tau_i) \sigma}{1 - \sigma} \left(1 - \frac{d_{i,j}(r_j)}{w_i} \right) \right], \end{aligned} \tag{14}$$

where $\mathbf{P}_{i,j} \equiv \mathbb{P}(j_i^* = j | r_j, \boldsymbol{r}_{-j})$ and $\mathbf{P}_{i,j} d_{i,j}(r_j) / D_j(r_j, \boldsymbol{r}_{-j})$ can be viewed as the weight on household i. Once a CBDC is introduced, a household can choose to hold its digital money in either the CBDC or an incumbent bank. This tends to reduce the probability of choosing any existing bank and makes the deposit demand more elastic.

[15] We abstract from modeling how the loan supply is affected by a CBDC or how the loan demand is affected by the complementarity with deposits. These simplifications do not affect the estimation of the households' demand side or how a CBDC affects the deposit demand. They only affect the equilibrium loan rate, which in turn changes the magnitude of banks' endogenous responses in deposit rates. We find that the change in equilibrium deposits is not very sensitive to the magnitude of the endogenous rate responses. As a result, abstracting from the loan side is unlikely to substantially change our results on the crowding-out effects of the CBDC.

3 Identification and Estimation

The demand side of the model has four sets of unknown parameters: parameters in the value from the liquid asset portfolio, $(\alpha^b, \boldsymbol{\beta}^b, \boldsymbol{\gamma}^b, \boldsymbol{\eta}^b, \zeta^b, \sigma)$; parameters in the bank choice for a financial product $k \in \mathcal{K}$, $(\kappa^k, \boldsymbol{\beta}^k, \boldsymbol{\eta}^k)$; the probabilities of needing each financial product k, ω^k; and the weights on different components in the utility for the deposit bank $(\theta, \phi, \boldsymbol{\beta}^f, \boldsymbol{\eta}^f)$. Here, $\boldsymbol{\eta}^b = \left\{\eta_j^b\right\}_{j\in\mathcal{J}}, \boldsymbol{\eta}^k = \left\{\eta_j^k\right\}_{j\in\mathcal{J}^k}, \boldsymbol{\eta}^f = \left\{\eta_j^f\right\}_{j\in\mathcal{J}}$ are the vectors of fixed effects for all banks in the portfolio allocation decision, the bank choice for financial product k, and the bank choice for the deposit account, respectively. The supply side has one set of unknown parameters, i.e., each bank's marginal cost, mc_j.

Suppose we observe an independent sample of households. For each household $i \in \mathcal{I}$, we observe a vector $\left(\mathcal{J}_i, j_i^*, c_i^*, d_i^*, \tau_i, \left\{\mathcal{J}_i^k\right\}_{k\in\mathcal{K}}, \left\{n_{i,k}^*\right\}_{k\in\mathcal{K}}, \left\{\boldsymbol{X}_{i,j}\right\}_{j\in\mathcal{J}}, \boldsymbol{Z}_i\right)$, where c_i^* and d_i^* are household i's cash and deposit holdings at its chosen deposit bank j_i^*, and $n_{i,k}^*$ is its chosen bank for financial product k. For each bank j, we observe (r_j, r_j^l), which implies that we observe the after-tax deposit rate $r_{i,j} = (1-\tau_i)r_j$ for all i and j. This section studies how to identify and estimate the unknown parameters of the model with the above information. We focus our discussion on the demand side of the model. Once we obtain the demand-side parameters, we can identify $D_j(r_j, \boldsymbol{r}_{-j})$ and use banks' first-order conditions (13) to identify the marginal cost, mc_j. If r_j^l is not observed, then (13) identifies the net return on assets, $r_j^l - mc_j$, which is sufficient for our counterfactual analysis.

3.1 Identification

Identification of the demand-side parameters involves three steps. First, we use households' portfolio allocations to identify the preference parameters in the value from liquid asset portfolios. Second, we use households' bank choices for financial products to identify the preference parameter for complementarity and other preference parameters in the value from financial products. Lastly, we combine these two sets of parameters with households' deposit bank choices to identify the preference parameters in the deposit bank choice. We discuss each step in turn below.

Parameters in the Value from Liquid Asset Portfolios

Use optimal deposit balance (7) and the budget constraint to obtain

$$\ln\frac{d_i^*}{c_i^*} = \frac{\sigma}{1-\sigma}\left(\alpha^b r_{i,j_i^*} + \boldsymbol{X}_{i,j_i^*}\boldsymbol{\beta}^b + \boldsymbol{Z}_i\boldsymbol{\gamma}^b + \eta_{j_i^*}^b + \zeta^b + \varepsilon_i^b\right), \tag{15}$$

where d_i^* and c_i^* denote the observed deposit and cash holdings at the chosen bank j_i^*, respectively. This is a linear regression model, so the coefficients and residuals are in general identifiable if explanatory variables have sufficient variation (i.e., the design matrix is invertible). As can be seen from (15), we cannot separately identify σ and the other parameters because they enter into the linear regression model in a multiplicative fashion. If we increase $\sigma/(1-\sigma)$ and decrease all the other parameters by the same factor, the predicted portfolio will stay unchanged. Therefore, we can only identify $\tilde{\upsilon} = \sigma\upsilon/(1-\sigma)$ for every $\upsilon \in \{\alpha^b, \boldsymbol{\beta}^b, \boldsymbol{\gamma}^b, \boldsymbol{\eta}^b, \zeta^b, \varepsilon_i^b\}$. Nevertheless, as will be shown later in this section, this is sufficient for most of our counterfactual analyses.[16]

The deposit rate r_{i,j_i^*} is household- and bank-specific because we multiply the net interest rate by one minus the marginal tax rate on household income as the interest earned on savings is taxed at the same marginal rate as income. Most importantly, our household-level data on deposit holdings, together with nationally set deposit rates, imply that simultaneity is unlikely. This largely alleviates the need for an instrumental variables approach, in contrast to much of the existing literature that uses bank-level data. Additionally, we include bank and year fixed effects to partly control for unobserved demand shocks. As discussed in Section 4.2, we estimate the model using ordinary least squares and demonstrate that our results are robust to using an instrument drawn from the literature that uses bank-level data.

Parameters in the Value from Financial Products

If a household needs a financial product k (i.e., mortgage loan, credit card, guaranteed investment certificate), it selects a bank n from its choice set to maximize its utility, taking its deposit bank as given, i.e., it solves $\max_{n \in \mathcal{J}_i^k} U_{i,n}^k(j_i^*)$. Since the idiosyncratic taste $\varepsilon_{i,n}^k$ is i.i.d. and follows the type-I extreme value distribution, the household's probability of choosing a bank $n \in \mathcal{J}_i^k$ is

$$\mathbb{P}(n_{i,k}^* = n) = \frac{\exp\left(\kappa^k \mathbb{1}(n = j_i^*) + \boldsymbol{X}_{i,n}\boldsymbol{\beta}^k + \eta_n^k\right)}{\sum_{m \in \mathcal{J}_i^k} \exp\left(\kappa^k \mathbb{1}(m = j_i^*) + \boldsymbol{X}_{i,m}\boldsymbol{\beta}^k + \eta_m^k\right)}. \tag{16}$$

We identify the parameters $(\kappa^k, \boldsymbol{\beta}^k, \boldsymbol{\eta}^k)$ by matching the conditional choice probabilities for each product k predicted by (16) with those implied by the data.

The parameter κ^k captures household preference for complementarity, the utility that the household gains from obtaining the financial product k from its deposit bank j_i^*. Identifying κ^k requires observing both the deposit bank and the bank chosen for product k for each

[16] Only the counterfactual analysis on CBDC holding limits depends on the value of σ. For these counterfactuals, we show that our results are robust to a wide range of σ values.

household. Intuitively, if everything else being equal, households are more (less) likely to choose their deposit bank for product k, then we can infer that κ^k is positive (negative). The magnitude of κ^k reflects the extent to which households use the same bank for deposits and other financial products.

We assume that the idiosyncratic taste $\varepsilon_{i,n}^k$ is independent across banks and across the separate choices of financial products k. Additionally, the idiosyncratic tastes $\varepsilon_{i,n}^k$ are assumed to be independent from the idiosyncratic taste for deposit bank $\varepsilon_{i,j}$. The dependence between the two choice problems comes only from the parameter κ^k. With these assumptions, the parameters $(\kappa^k, \boldsymbol{\beta}^k, \boldsymbol{\eta}^k)$ can be identified and estimated separately from the deposit bank choice. We use the parameters to calculate the expected value for each choice of deposit bank $\mathbb{E}V_{i,j}^k$, which has a closed-form solution shown in (10).

Parameters in Deposit Bank Choice

To identify the parameters $(\theta, \phi, \boldsymbol{\beta}^f, \boldsymbol{\eta}^f)$ in (2), we first need to compute $\sum_{k\in\mathcal{K}} \omega^k \mathbb{E}V_{i,j}^k$ and $V_{i,j}^b$. The expected value, $\mathbb{E}V_{i,j}^k$, can be calculated using (10) because all the involved parameters are identified in the previous step. The exogenous probability ω^k of needing a financial product k is calibrated using the fraction of households that have obtained the financial product k. The term $V_{i,j}^b$ is defined by (6) and it affects deposit bank choices only through

$$\frac{1-\sigma}{\sigma} \ln\left[1 + (u_{i,j}^b)^{\sigma/(1-\sigma)}\right], \tag{17}$$

because $\ln w_i$ is the same for all banks. As discussed earlier, σ cannot be separately identified from θ in (2), so we estimate the combined parameter $\tilde{\theta} = (1-\sigma)\theta/\sigma$, which is sufficient for most of our counterfactual analyses. Since $(1-\sigma)/\sigma$ is part of the estimated parameter, we only need to calculate $\tilde{V}_{i,j}^b = \ln[1 + (u_{i,j}^b)^{\sigma/(1-\sigma)}]$, which will enter the deposit bank choice problem. Online Appendix OA shows more details on how $\tilde{V}_{i,j}^b$ and $\mathbb{E}V_{i,j}^k$ are calculated using the estimated parameters.

To proceed, define $\tilde{V}_{i,j}^b = \ln[1 + (u_{i,j}^b)^{\sigma/(1-\sigma)}]$ and $\tilde{\theta} = (1-\sigma)\theta/\sigma$. We can then rewrite the choice probability (2) as

$$\mathbb{P}(j_i^* = j | r_j, \boldsymbol{r}_{-j}) = \frac{\exp\left(\tilde{\theta}\tilde{V}_{i,j}^b + \phi \sum_{k\in\mathcal{K}} \omega^k \mathbb{E}V_{i,j}^k + \boldsymbol{X}_{i,j}\boldsymbol{\beta}^f + \eta_j^f\right)}{\sum_{m\in\mathcal{J}_i} \exp\left(\tilde{\theta}\tilde{V}_{i,m}^b + \phi \sum_{k\in\mathcal{K}} \omega^k \mathbb{E}V_{i,m}^k + \boldsymbol{X}_{i,m}\boldsymbol{\beta}^f + \eta_m^f\right)}. \tag{18}$$

Then, $(\tilde{\theta}, \phi, \boldsymbol{\beta}^f, \boldsymbol{\eta}^f)$ is identified by matching the conditional choice probabilities of deposit banks predicted by (18) with those implied by data.

For identification, all independent variables need to have sufficient cross-bank variation, as household choices depend on the relative differences in attributes across banks. The parameters $\tilde{\theta}$ and ϕ are identifiable because both $\tilde{V}_{i,j}^b$ and $\mathbb{E}V_{i,j}^k$ are functions of bank characteristics. In particular, $\tilde{V}_{i,j}^b$ varies across banks largely due to the differences in deposit rates, which enter through $u_{i,j}^b$. The expected value $\mathbb{E}V_{i,j}^k$ depends not only on the complementarity parameter κ^k, but also on the branch network and bank fixed effects, as shown in Online Appendix OA.2.

With household-level data on residence locations and branch locations, the branch network measures in this paper are not only bank-specific, but also household-specific. As a result, even though bank fixed effects are included, the parameter vector $\boldsymbol{\beta}^f$ remains identifiable due to the rich variation in household locations. More specifically, since households reside in different locations, they face different travel distances to the nearest branches of each bank and have different numbers of nearby branches.[17]

3.2 Estimation

The estimation strategy closely follows the identification strategy. The estimation of the demand side involves three steps. First, we apply ordinary least squares to (15) to estimate $\tilde{\upsilon} = \frac{\sigma\upsilon}{1-\sigma}$ for $\upsilon \in \{\alpha^b, \boldsymbol{\beta}^b, \boldsymbol{\gamma}^b, \boldsymbol{\eta}^b, \zeta^b, \varepsilon_i^b\}$. Second, because we observe the individual household's bank choices for deposits and for each product k, we can apply maximum likelihood estimation (MLE) to (16) to estimate $(\kappa^k, \boldsymbol{\beta}^k, \boldsymbol{\eta}^k)$. The estimator is defined as

$$(\hat{\kappa}^k, \hat{\boldsymbol{\beta}}^k, \hat{\boldsymbol{\eta}}^k) = \arg\max_{\kappa,\boldsymbol{\beta},\boldsymbol{\eta}} \sum_{i\in\mathcal{I}} \ln \frac{\exp\left(\kappa \mathbb{1}(n_{i,k}^* = j_i^*) + \boldsymbol{X}_{i,n_{i,k}^*}\boldsymbol{\beta} + \eta_{n_{i,k}^*}\right)}{\sum_{m\in\mathcal{J}_i^k} \exp\left(\kappa\mathbb{1}(m = j_i^*) + \boldsymbol{X}_{i,m}\boldsymbol{\beta} + \eta_m\right)}.$$

Third, we estimate $\tilde{V}_{i,j}^b$ and $\mathbb{E}V_{i,n}^k$ using the estimates from the first two steps. Let $\widehat{\tilde{V}_{i,j}^b}$ and $\widehat{\mathbb{E}V_{i,n}^k}$ denote the resulting estimators. We can then apply MLE to (18) to estimate $(\tilde{\theta}, \phi, \boldsymbol{\beta}^f, \boldsymbol{\eta}^f)$ and the estimator is defined as

$$(\hat{\tilde{\theta}}, \hat{\phi}, \hat{\boldsymbol{\beta}}^f, \hat{\boldsymbol{\eta}}^f) = \arg\max_{\theta,\phi,\beta,\boldsymbol{\eta}} \sum_{i\in\mathcal{I}} \ln \frac{\exp\left(\theta\widehat{\tilde{V}_{i,j_i^*}^b} + \phi\sum_{k\in\mathcal{K}}\omega^k\widehat{\mathbb{E}V_{i,j_i^*}^k} + \boldsymbol{X}_{i,j_i^*}\boldsymbol{\beta} + \eta_{j_i^*}\right)}{\sum_{m\in\mathcal{J}_i}\exp\left(\theta\widehat{\tilde{V}_{i,m}^b} + \phi\sum_{k\in\mathcal{K}}\omega^k\widehat{\mathbb{E}V_{i,m}^k} + \boldsymbol{X}_{i,m}\boldsymbol{\beta} + \eta_m\right)}.$$

With the estimates of all the demand-side parameters, we can obtain bank j's deposit demand as a function of the deposit rates, $D_j(r_j, \boldsymbol{r}_{-j})$. Then the estimates of banks' marginal

[17] Note that $\tilde{V}_{i,j}^b$ and $\mathbb{E}V_{i,j}^k$ are non-linear functions of the branch network and bank fixed effects, so they do not absorb all the variation in those variables for the deposit bank choice, allowing $\boldsymbol{\beta}^f$ and η_j^f to remain identifiable.

costs are obtained from (13) once we replace $D_j(r_j, \boldsymbol{r}_{-j})$ by their estimates.

4 Data and Estimation Results

Section 4.1 provides a detailed discussion on the data used for estimating the model. Section 4.2 then presents the estimation results for the households' preferences on the demand side and banks' marginal costs on the supply side.

4.1 Data

Estimating the model requires (1) information on households, including their bank choices for different financial products, allocations of liquid assets, residential locations, and other demographic characteristics, and (2) information on banks, such as their interest rates and branch locations. We obtain this information by combining three main data sources, i.e., the Canadian Financial Monitor (CFM) household survey, the Financial Consumer Agency of Canada (FCAC) data on branch locations, and CANNEX data on interest rates.

The CFM household survey is a syndicated survey run by Ipsos. A unique feature of the data is that they contain information on a household's deposit bank and its bank choices for other financial products, including mortgage loans, credit cards, and guaranteed investment certificates (GICs).[18] For each product, we observe household choices across a diverse set of banks and credit unions, which we collectively refer to as banks for convenience.[19] This allows us to estimate the preference parameter for complementarity for each of these financial products – if a bank is chosen as a deposit bank, how likely a household will choose it for another financial product.

The data also contain information on a household's allocation of liquid assets, defined as the sum of cash and demand deposits. Cash is measured by the sum of cash in the wallet and precautionary holdings of cash. Demand deposits are measured by the sum of chequing, chequing/saving, and saving account balances. In our sample, a median household holds around 5% of its liquid assets in cash (\$195 in cash and \$3,500 in demand deposits).[20] More-

[18] More than 70% of households go to one bank for demand deposits, as shown in Table A1 in Appendix A.2. The fraction of households that have a single mortgage bank, credit card issuer, and GIC issuer is 98%, 42%, and 78%, respectively. For households that have multiple deposit banks, we use their main financial institution where they have the largest deposit balance. Similarly, we assume their main mortgage bank, credit card issuer, and GIC issuer are the ones with the largest remaining mortgage payment, the highest current balance, or the highest GIC balance, respectively.

[19] More precisely, we observe 20 deposit-taking banks in total. For other financial products, we observe a few additional institutions. For example, in addition to the banks available for deposits, households can also choose American Express and Capital One for credit cards.

[20] Approximately 99% of households hold demand deposits worth less than \$100K and thus are fully covered

over, the data record each household's residential location by postal code, which provides relatively precise geographic information. In many cases, postal codes uniquely identify as small as a condominium building or a group of houses in a suburb, as noted by Perez-Saiz and Xiao (2022). We use the sample period of 2010–2017 because the survey questions on cash are consistent throughout this period.

The FCAC data contain addresses of all existing branches of banks and credit unions in 2019. They also record all branch closures between 2005 and 2020. We combine the two sets of information to construct bank branch locations in years other than 2019. Together with households' locations, we calculate the (great-circle) distance from each household to each branch location, allowing us to construct the accessible branch network for each household. Based on this distance measure, we construct the choice set of each household by assuming that a household considers all available banks that have a branch within a certain distance from its residence. Since the travel cost is different between urban and rural areas, we assume that an urban household considers all banks with a branch within 15 kilometers of its residence and a rural household considers banks with a branch within 50 kilometers.[21] We measure a bank's branch network using the distance from a household to the nearest branch of the bank, and the number of the bank's branches located within the household's choice set.[22] Table 1 shows summary statistics on the number of branches and banks available to each household based on the constructed choice set. Accessibility of banks and branches varies greatly across provinces and regions. In particular, urban households can access more banks and branches than rural households.

CANNEX provides bank-level interest rates of demand deposits and mortgage loans.[23] We observe the rates on demand deposits for the big five banks, National Bank, and Laurentian Bank from 2010 to 2017. In our sample, 70% of households choose the big five banks and National Bank as their main financial institutions. We assume the deposit rates of the other banks are equal to the average rates of the big five banks and National Bank. We did

by deposit insurance. Therefore, there is not enough variation in the data to allow us to estimate households' preferences towards safety, which is another differentiating feature between a CBDC and bank deposits.

[21]The estimation and counterfactual results are robust to alternative choice set definitions – such as 10 km, as in Allen, Clark and Houde (2019), or 30 km for urban households, and 30 km or 70 km for rural households.

[22]For online banks, we include a separate fixed effect to account for their unobservable branch presence. For estimation, we assume online banks have no physical branches and assign a distance of 15 km for urban households and 50 km for rural ones. The results are robust to this assumption due to the presence of the fixed effect. For example, we used 50 km or 100 km uniformly across all households and obtained nearly identical estimates.

[23]Cross-bank variation in these rates are shown in Figure A3 in Appendix A.3. These rates are at the national level, as we do not observe branch-level interest rates in Canada. In fact, none of the major institutions post different deposit rates by province. Therefore, banks in our model compete in the national deposit market rather than the local market around a household's residential location.

Table 1: Number of Branches and Banks in the Choice Sets of Urban and Rural Households

(a) Number of Branches

	Urban 15 km					Rural 50 km				
	Min	Median	Max	Mean	Obs	Min	Median	Max	Mean	Obs
Alberta	3	260	297	212	1077	3	92	361	143	183
British Columbia	4	280	592	310	1528	1	48	717	181	157
Manitoba	3	128	132	112	430	1	33	152	60	127
New Brunswick	1	23	46	23	261	.	.	.	.	0
Newfoundland	3	46	47	33	129	1	12	55	21	75
Nova Scotia	4	78	83	51	324	7	70	140	73	152
Ontario	3	350	1286	586	3872	1	322	1738	538	697
Prince Edward Island	10	19	23	17	38	8	46	69	49	27
Quebec	3	895	979	589	2236	5	328	1230	540	422
Saskatchewan	5	39	55	37	292	1	15	64	22	129

(b) Number of Banks

	Urban 15 km					Rural 50 km				
	Min	Median	Max	Mean	Obs	Min	Median	Max	Mean	Obs
Alberta	2	10	11	9	1077	1	6	11	6	183
British Columbia	1	11	14	10	1528	1	6	14	6	157
Manitoba	3	10	11	9	430	1	4	11	4	127
New Brunswick	1	7	8	5	261	.	.	.	.	0
Newfoundland	2	7	7	5	129	1	3	7	3	75
Nova Scotia	1	6	7	5	324	1	5	7	4	152
Ontario	2	8	12	8	3872	1	8	12	7	697
Prince Edward Island	5	6	6	5	38	2	6	7	5	27
Quebec	1	9	12	8	2236	1	8	12	7	422
Saskatchewan	4	8	10	8	292	1	3	10	3	129

Data sources: CFM 2017, FCAC 2017

Note: The upper (lower) panel shows the summary statistics for the number of branches (banks) that are within 15 km of urban households' locations and 50 km of rural households' locations in each province. "Rural area" is defined as the second digit of the Canadian postal code being zero. Online banks are excluded in this table.

not use Laurentian Bank for imputation because it is a small bank that mostly operates in Quebec and offers much higher rates than the big five banks and National Bank. Alternative imputation methods yield very similar results.[24] Since households care about the after-tax interest income, we calculate the after-tax interest rates by combining the bank-level deposit rates with household income information from the CFM data and the federal and provincial

[24]For example, including Laurentian Bank for imputation leads to similar estimates. We also tried using the average spread between GIC and demand deposit rates for the big five banks and National Bank to impute deposit rates for seven additional banks with available short-term GIC rates but unobserved demand deposit rates. As shown in Table OB4 in Online Appendix OB, adding the cross-bank variation from those seven banks has a negligible impact on the deposit rate coefficient.

income tax rates from the Government of Canada website.

We use mortgage rates to measure the exogenous return on assets r_j^l. As discussed in Section 3, $r_j^l - mc_j$ is identified from (13) and is sufficient for counterfactual analysis. The level of r_j^l does not affect the counterfactual analysis and is only used as a sanity check for the estimated marginal costs. For the mortgage rate, we consider the 5-year closed mortgages, which are the most popular product in Canada. The mortgage rates are available for the big five banks and National Bank, and the average mortgage rate of these six banks is used for mortgage loans at other banks. Summary statistics of some key variables are shown in Table A2 of Appendix A.3.

4.2 Estimation Results

Following the discussion in Section 3.1, we estimate the demand parameters in three separate steps: (1) portfolio allocation choice; (2) bank choices for mortgage loans, credit cards, and GICs; and (3) deposit bank choice taking into account the utilities from holding a portfolio of liquid assets and from obtaining complementary financial products. We first discuss the results from each step in order and then discuss the estimates of banks' marginal costs.

Table 2 shows the estimated parameters for the deposit rates and the branch network measures (i.e., $\tilde{\alpha}^b$, $\tilde{\boldsymbol{\beta}}^b$) in the value from liquid asset portfolios. The parameters for the household characteristics, bank fixed effects, and the deposit-specific constant (i.e., $\tilde{\boldsymbol{\gamma}}^b$, $\tilde{\boldsymbol{\eta}}^b$, $\tilde{\zeta}^b$) are shown in Table OB2 in Online Appendix OB. We include year fixed effects to absorb unobserved aggregate shocks.[25] We need to exploit the cross-bank variation in the deposit rates, so we do not include a fixed effect for each bank. Instead, we include indicators for different groups of banks, i.e., big five banks, small banks, online banks, the Desjardins credit union, and other big credit unions.

The deposit rate has a significantly positive effect on the allocation of liquid assets. If the deposit rate increases by one percentage point, the deposit-to-cash ratio would increase by 52% from a median of around 20 to 30. The implied semi-elasticity of cash demand is 28, i.e. a one percentage point increase in post-tax deposit rate results in a 28% decrease in cash demand. This is higher than the estimates in the literature using data before 1995, which could be due to the increasing usage of digital payments.[26] The implied semi-elasticity

[25] The year and bank fixed effects can control for unobserved demand shocks to some extent. As discussed in Section 3.1, the use of household-level data on deposit holdings mitigates the concerns about simultaneous causality. Nonetheless, we also use banks' heterogeneous pass-through of policy rates to instrument for the deposit rate, following Egan, Hortaçsu and Matvos (2017), and obtain a similar estimate for $\tilde{\alpha}^b$, as shown in Table OB3 in Online Appendix OB. The counterfactual results are robust to using the IV estimates.

[26] For example, Attanasio, Guiso and Jappelli (2002) use Italian data from 1989 to 1995 to estimate cash demand elasticity and obtain 0.27 to 0.59. This implies a semi-elasticity of cash demand ranging from 6 to

Table 2: Estimated Parameters in Portfolio Allocation Choice

Dependent variable: Log of deposit-to-cash ratio	
Post-tax deposit rate	0.522***
	(0.193)
ln(Distance to branch)	0.004
	(0.010)
ln(Distance to branch) $\times$ Live in rural area	-0.053***
	(0.015)
ln(Number of branches + 1)	0.024***
	(0.008)
ln(Number of branches + 1) $\times$ Live in rural area	-0.026
	(0.017)
Observations	62,504

Robust standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Data sources: CFM 2010–2017, CANNEX 2010–2017, FCAC 2010–2017, Government of Canada website
Note: The table shows a subset of the estimated parameters from the OLS regression of the log of deposit-to-cash ratio on the post-tax deposit rates, bank branch network, grouped bank fixed effects, and household characteristics (including region and year fixed effects). The "Observations" shows the number of households in the CFM sample from 2010 to 2017.

of deposit demand, as will be discussed below, aligns with the recent literature on bank deposit demand estimation.[27] Overall, easier access to bank branches increases the deposit-to-cash ratio, which is consistent with the classic Baumol-Tobin model. Interestingly, the distance from the residence to the closest branch does not have a significant effect on an urban household's portfolio decisions. This could be because urban households can easily withdraw cash at branches close to their workplaces.

Table 3 shows the estimates for the preference parameter for complementarity κ^k and bank branch network $\boldsymbol{\beta}^k$ in the households' bank choices for credit cards, mortgage loans, and GICs. Bank fixed effects are included to absorb the cross-bank variation in prices of these financial products,[28] as well as the unobserved bank quality, which are shown in Table OB5 in Online Appendix OB. The estimated κ^k implies that households have a strong preference

14 given the average post-tax deposit rate of 4.2% during that period. Similarly, Mulligan and Sala-i-Martin (2000) estimate the elasticity of cash demand to be 0.5 using the 1989 Survey of Consumer Finance for US households, which implies a semi-elasticity of cash demand of 10 at a 5% annual interest rate.

[27]To compare the implied deposit demand elasticity with the literature, we need to use the choice probabilities obtained from the deposit bank choice estimation below to calculate each bank's deposit demand.

[28]We do not separately include the prices of these financial products in the estimation because when households choose their banks for deposits, they do not know the prices of the other financial products yet. This does not affect our estimates of the preference parameter for complementarity. As shown in Table OB7 in Online Appendix OB, adding the mortgage loan rates does not change the coefficient for the preference for complementarity, which is the key variable of interest here.

Table 3: Estimated Parameters from Bank Choices of Different Financial Products

	(1) Credit Card	(2) Mortgage	(3) GIC
Preference for Complementarity	2.351***	2.671***	2.916***
	(0.010)	(0.016)	(0.018)
ln(Distance to branch)	-0.117***	-0.123***	-0.156***
	(0.008)	(0.015)	(0.015)
ln(Distance to branch) × Live in rural area	0.003	-0.026	-0.055**
	(0.013)	(0.024)	(0.025)
ln(Number of branches + 1)	0.083***	0.132***	0.086***
	(0.007)	(0.014)	(0.014)
ln(Number of branches + 1) × Live in rural area	0.030**	0.044*	-0.026
	(0.014)	(0.026)	(0.026)
Observations	1,075,719	314,230	292,732
Number of choice sets	72,449	24,603	22,858

Robust standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Data sources: CFM 2010–2017, CANNEX 2010–2017, FCAC 2010–2017, Government of Canada website
Note: Each column in the table corresponds to a conditional logistic regression of the bank choice for a given financial product (i.e., credit card, mortgage loan, guaranteed investment certificate GIC) on the deposit bank indicator, branch network variables, and bank fixed effects. Only the estimated parameters for the deposit bank indicator and the branch network measures are presented in this table. The "Number of choice sets" denotes the number of households in the sample, while "Observations" represents the cumulative total of alternatives/banks within each household's choice set.

for getting the considered financial product from their deposit banks. This is not surprising because 45% of credit card holders get their credit cards from their deposit banks and more than half of mortgage borrowers borrow from their deposit banks, as shown in Table 4.[29] Other estimates in Table 3 show that households value the branch network when choosing these financial products.

Table 5 shows the estimated coefficients (i.e., $\tilde{\theta}, \phi, \boldsymbol{\beta}^f$) on the utility from liquid asset holdings, the sum of expected utilities from other financial products, and the branch networks, respectively, in the deposit bank choice problem. The estimated bank fixed effects $\boldsymbol{\eta}^f$ are shown in Table OB6 in Online Appendix OB. As seen in Table 5, the estimates of $\tilde{\theta}$ and ϕ indicate that households take into account the utility from liquidity holding and from

[29]One may be concerned that this estimate may simply reflect the correlation among a household's tastes over the deposit bank and the banks for other financial products, which would give different implications in counterfactual analysis. To partially address this concern, we consider setups that include interaction terms between bank fixed effects and household characteristics, which partly control for the correlated tastes. Our results are not affected by these interaction terms. As shown in Table OB8 in Online Appendix OB, including the bank fixed effects interacted with the old age indicator (i.e., $\geqslant$ 55 years old) only marginally reduces the estimate of κ. Similar evidence is found when interacting the bank fixed effects with other household characteristics, such as education and household income.

Table 4: Fraction of Households with Different Financial Products

	Have the product	Have the product from deposit bank
Credit Card	0.90	0.45
Mortgage	0.30	0.56
Guaranteed Investment Certificates	0.29	0.55

Data sources: CFM 2010–2017

Note: The table shows the fraction of households that have a credit card, a mortgage loan, or a guaranteed investment certificate (GIC) in the second column. Conditional on the households that have a given product, the last column shows the fraction of households that bundle the product with their deposit banks where they have deposit accounts.

Table 5: Estimated Parameters in Deposit Bank Choice

Variables	Estimates
Utility from liquidity holding	1.661***
	(0.179)
Sum of expected utilities from financial products	1.368***
	(0.038)
ln(Distance to branch)	-0.175***
	(0.008)
ln(Distance to branch) $\times$ Live in rural area	0.113***
	(0.015)
ln(Number of branches + 1)	0.439***
	(0.011)
ln(Number of branches + 1) $\times$ Live in rural area	0.229***
	(0.021)
Observations	674,536
Number of choice sets	62,504

Robust standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Data sources: CFM 2010–2017, CANNEX 2010–2017, FCAC 2010–2017, Government of Canada website

Note: The table shows a subset of the estimated parameters from a conditional logistic regression of the deposit bank choice on the utility from liquidity holding $\tilde{V}^b_{i,j}$, the sum of expected utilities from financial products $\sum_{k \in \mathcal{K}} \omega^k \mathbb{E} V^k_{i,j}$, the branch network measures, and grouped bank fixed effects. The "Number of choice sets" denotes the number of households in the sample, while "Observations" represents the cumulative total of alternatives/banks within each household's choice set.

complementarity with financial products when choosing their deposit banks.

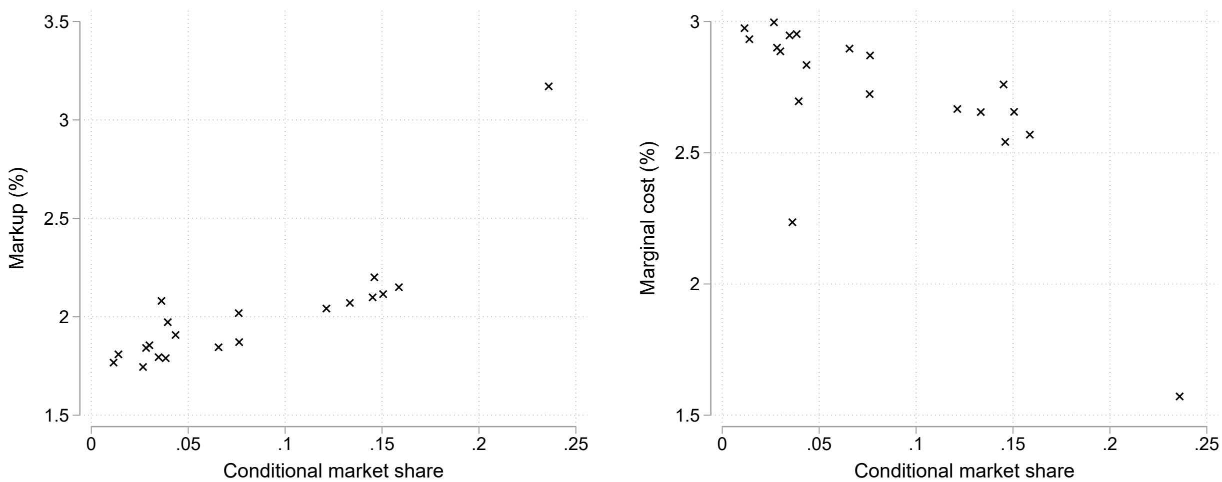
The branch network affects the choice probabilities of the deposit bank through one direct and two indirect channels. First, it directly affects the choice probabilities through the preference over the branch network, which is captured by $\boldsymbol{\beta}^f$. Second, it indirectly affects the choice probabilities through the value from liquid asset holdings and the value from complementary financial products. Through the direct channel, an increase in 1 km of the branch distance would reduce the choice probability by around 10% in urban areas. Adding a branch increases a bank's probability of being selected by about 14%. Rural households are more tolerant of distance, with a 1 km increase in distance barely reducing the likelihood of choosing a bank. However, given the low number of branches in rural areas, adding one branch would increase the choice probability by around 25%.

The finding that households value branches is consistent with data on branch usage. The CFM data show that more than 50% of households visited a branch in the month prior to the survey in 2017 (Figure A1 in Appendix A.1). According to the 2024 Mintel report, which surveyed over 2,000 banked internet users aged 18 and older, 77% of respondents visited a bank branch within the past 12 months. Withdrawing cash and obtaining customer service/support are among the important reasons for branch visits (Figure A2 in Appendix A.1).

Figure 1: Estimated Markup and Marginal Cost for Each Bank in 2017

(a) Markups

(b) Marginal Costs



Data sources: CFM 2010–2017, CANNEX 2010–2017, FCAC 2010–2017, Government of Canada website
Note: The figure plots the estimated markups and marginal costs of banks against their market shares in 2017. A bank's conditional market share refers to its market share conditional on its presence in the local markets, which is calculated using the estimated probabilities of choosing the bank averaged across all the local markets (around households' residences) that the bank operates in.

With the estimates of the demand side, we obtain the estimated markups, or equivalently, the inverse semi-elasticities of deposit demand. We then use (13) to obtain the supply-side parameters, i.e., banks' marginal costs. Figure 1 plots banks' markups and marginal costs against their market shares in the year 2017.[30] There is considerable heterogeneity in both market shares and markups, with the former ranging from around 1% to more than 20% and the latter ranging from 1.7% to around 3.2%. The markup estimates are comparable to findings in existing studies using the US data.[31] The estimated marginal costs range from 1.6% to 3.0%, with a mean of around 2.7% in 2017. The markups are positively correlated with market shares, while the marginal costs are negatively correlated with market shares. We next treat the demand-side parameters and the marginal costs of banks as fixed primitives and conduct counterfactuals to assess the effects of introducing a CBDC.

5 Counterfactual CBDC Issuance

This section evaluates what would have been the impact of introducing a CBDC in 2017 on the Canadian banking sector. We model the CBDC as a new product that is added to every household's choice set for digital money, as illustrated in Figure 2. Households can choose to hold either the CBDC or bank deposits but not both.[32] In most of the counterfactual analysis except for Section 5.1.2 that studies the impact of the complementarity, we assume the CBDC does not have complementarity with other financial products. The idea is that the central bank does not provide financial services other than payments. Therefore, a household who chooses to hold the CBDC has to obtain other financial products from a private bank. We then vary other design features such as interest rates, service locations and holding limits and study the aggregate and distributional effects of a CBDC.

To briefly discuss the method, we assume that the households' preference parameters and the banks' cost parameters remain unchanged after the CBDC issuance. For example, households value the CBDC service locations the same way they value bank branches. This is plausible because the important functions of branches discussed before, i.e. cash withdrawal and customer service/support, are also likely to matter for the CBDC. We can then use the estimated preference parameters and the exogenously chosen CBDC design attributes to obtain each household's utility from holding the CBDC.[33] This allows us to calculate the

[30]The market share of a bank is the average market share across all local markets served by the bank, where the bank's market share in a local market (around a household's residence) is measured using the estimated probability of the household choosing this bank.

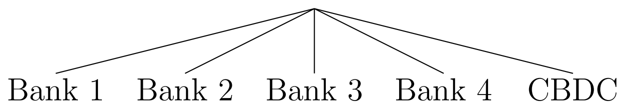
[31]The estimated markup or, equivalently, the inverse semi-elasticity of deposit demand aligns with the findings in the literature that uses US bank-level data to estimate the deposit demand. For example, the deposit demand elasticity is around 0.73, with an average deposit rate of 1.7% in Xiao (2020) and 0.56 at a deposit rate of 1% in Egan, Hortaçsu and Matvos (2017). This implies a markup of around 2.3% and 1.8%, respectively. Our estimated markup is around 2.0% on average across banks, which is similar to those found in the literature.

[32]In Section 6.2, we study an extension that allows a household to hold both the CBDC and deposits.

[33]To obtain the utility from the CBDC, we also need to make assumptions on the CBDC fixed effect that

new deposit demand faced by a bank, which in turn leads to a new equilibrium. More details can be found in Appendix B.

Figure 2: Choice Set for Holding Liquid Digital Assets after CBDC Issuance



Section 5.1 shows the aggregate effect of a CBDC. Section 5.2 shows how the effect differs across banks. Section 5.3 examines the holding limit policy and Section 5.4 discusses implications on consumer surplus.

5.1 Impact of CBDC on Aggregate Outcomes

This section shows aggregate impact of introducing a CBDC on the equilibrium outcomes, comparing the case without complementarity in Section 5.1.1 to one with complementarity in Section 5.1.2, while keeping everything else the same.

5.1.1 No Complementarity Between the CBDC and Financial Products

For the design of the CBDC, we consider all the combinations of two interest rates and four service location networks. The two interest rates we focus on are 0 and 10 basis points. The former is the consensus among many central banks,[34] while the latter is the average deposit rate during 2010–2017. The four service location networks are (1) no service location, in which case the CBDC is analogous to an online narrow bank; (2) all Canada Post offices; (3) all bank branches; (4) all bank branches and Canada Post offices.[35] In this exercise, we use the locations of all open Canada Post offices in 2021 obtained from the Canada Post Corporation. For now, there is no limit on CBDC holdings.

Figure 3 shows the aggregate CBDC share, the average change in deposit rates across banks, and the average percentage changes in bank deposits and profitability, under each design of the CBDC. There are two main findings. First, the network of CBDC service locations matters a lot for the take-up of the CBDC and its impact on banks. Second, the

captures the unobserved quality of the CBDC. In this section, we assume the CBDC fixed effect takes the value of the estimated fixed effect for the largest banks. We show the results using the worst fixed effect in Figure OC3 and OC4 in Online Appendix OC.

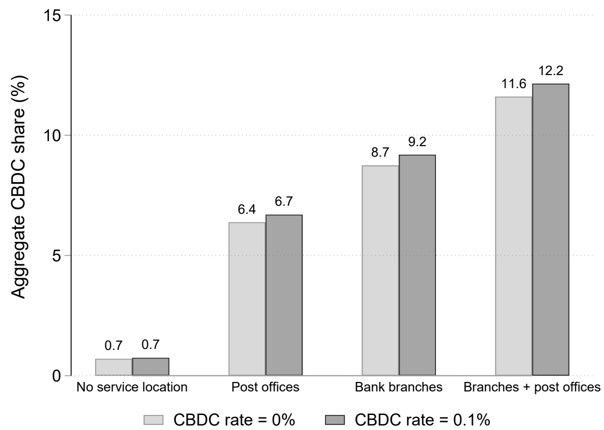
[34] For example, the ECB report on the digital euro (ECB, 2023) and the speech by Sir Jon Cunliffe on the digital pound (Cunliffe, 2023) both propose a non-interest-bearing CBDC.

[35] To ensure that a digital euro is inclusive, the ECB is considering using public entities, such as post offices, as service locations. See FAQs on the digital euro from the European Central Bank: https://www.ecb.europa.eu/euro/digital_euro/faqs/html/ecb.faq_digital_euro.en.html.

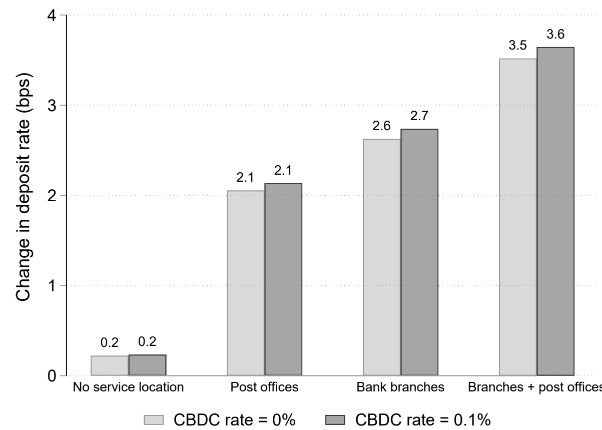
effect of the CBDC interest rate is limited unless it is significantly higher than the average deposit rate.

Figure 3: Impacts of CBDC Designs on Equilibrium Outcomes

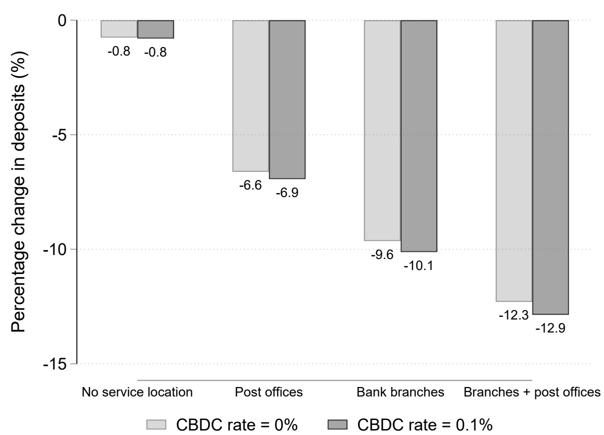
(a) Aggregate CBDC share



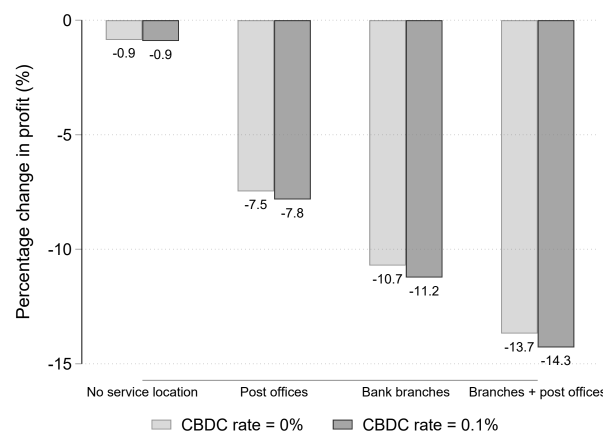
(b) Change in bank deposit rates



(c) Percentage change in deposits



(d) Percentage change in profits



Data sources: CFM 2017, FCAC 2017, Canada Post 2021, Government of Canada website

Note: This figure plots (a) the aggregate CBDC share calculated as the share of liquid assets allocated in equilibrium by households to the CBDC, (b) the average endogenous change in deposit rate (in basis points) across banks, (c) the average percentage drop in deposits across banks, and (d) the average percentage drop in profits across banks relative to the pre-CBDC equilibrium. In each graph, the given equilibrium outcome is plotted under four designs of service locations for CBDC (i.e., no service location, all Canada Post offices as service locations, all bank branches as service locations, and all bank branches plus Canada Post offices as service locations), combined with two different remuneration for CBDC: 0 and 10 basis points. In this figure, we use the fixed effect for the big five banks as the CBDC fixed effect. We show the results where CBDC fixed effect takes the estimated fixed effect of the small banks in Figure OC3 in Online Appendix OC.

Figure 3a shows the aggregate CBDC share under each design. If there is no service location, consumers barely adopt the CBDC. Only around 1% of total households' liquid assets are allocated to the CBDC, even if the CBDC pays an interest rate of 10 basis points. If all Canada Post offices provide in-person services for the CBDC, the aggregate CBDC share increases to about 6%. If the target market share of the CBDC is close to the current share of cash (4.5%), then providing CBDC services at the Canada Post offices is sufficient. When all bank branches provide services for the CBDC, the CBDC share increases to around 9%. The share increases further to about 12% under a more extensive network of service locations that includes all Canada Post offices and bank branches. This network is significantly better than that of any single bank, especially in rural areas.[36] Nevertheless, the CBDC adoption remains limited.

A 10 basis point interest on the CBDC slightly increases the adoption of the CBDC. However, if we raise its interest rate to 1.5% (15 times the average deposit rate), the market share of the CBDC can double, as shown in Figure OC1 in Online Appendix OC. We can also convert the value of service location network into equivalent interest rates. For example, the network of all Canada Post offices is worth 4% interest to the depositors, i.e. a CBDC with no service locations needs to pay 4% interest to obtain the same market share as a non-interest-bearing CBDC with all Canada Post offices as service locations.

Figure 3b plots the average change in deposit rates. In response to the CBDC issuance, banks tend to raise deposit rates to retain customers. The magnitude of the responses depends on the CBDC design. If the CBDC does not have service locations, the banks barely respond. However, if it offers an attractive network, the average deposit rate increases by 2 to 4 basis points, which is about 20 to 40 percent of the average deposit rate during 2010–2017.

Figure 3c shows the average percentage change in deposit quantity. The magnitude is similar to the market share of the CBDC shown in Figure 3a. Intuitively, since the market share of cash is small, the CBDC gains its market share mainly from deposits.[37] When the CBDC does not have any service network, it only crowds out demand deposits by around 1%. Even when all Canada Post offices are used as service locations, the crowding out on demand deposits is less than 7%. Only with the most extensive network could the CBDC reduce the demand deposits by slightly more than 10%. As discussed above, the most extensive network design would surpass the branch network of any existing bank, likely making it costly for the

[36] For example, the distance from an urban (rural) household to the nearest bank branch or the nearest Canada Post office is 1.2km and 1.6km (6.8km and 1.9km), respectively, while the distance from an urban (rural) household to the nearest branch of a big bank is 1.9km (19.4km).

[37] As shown in Figure OC2 in Online Appendix OC, the CBDC also crowds out cash, but to a lesser extent than deposits. This is because in our model, the CBDC is a closer substitute for deposits than cash.

central bank to implement. Moreover, the retail demand deposits in Canadian dollars (that a CBDC directly competes with) are around 35% of total Canadian dollar deposits based on the regulatory data of all federally chartered banks in 2017. Therefore, the crowding-out effect of the CBDC on bank deposits is likely to be manageable.

Finally, Figure 3d shows how the CBDC affects the average profit across banks. Similar to the other graphs, the impact of the CBDC increases as the network of service locations improves, while paying interest on the CBDC has limited effects if the rate is similar to the average deposit rate. The drop in profit results from two sources: (1) the decrease in the bank's markup, which is driven by the increase in the deposit rate shown in Figure 3b, and (2) the decrease in deposit quantity shown in Figure 3c. Note that the change in a bank's markup is equivalent to the change in its inverse semi-elasticity of deposit demand, as shown in (13). Introducing the CBDC tends to make banks' deposit demand more elastic, which induces banks to raise their deposit rates, leading to a drop in their markups.

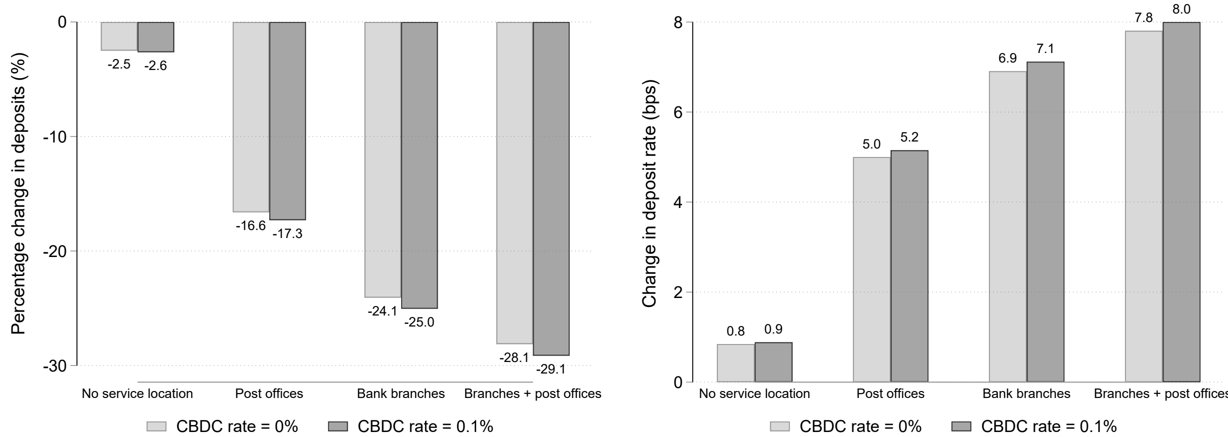
5.1.2 Complementarity Between the CBDC and Financial Products

In the baseline setup, the CBDC does not provide any complementarity with other financial products. However, it could be designed to allow households to benefit from complementarity by being interoperable with financial products provided by the private banks. For example, if the CBDC app enables easy repayment of mortgage and credit card debt at private banks, similar to an online banking app, households could still enjoy some complementarity while holding the CBDC. This design could have significant implications on the adoption of the CBDC and its crowding-out effect. However, implementing such interoperability can be costly to central banks in terms of engaging the private banks.

To study this scenario, we assume CBDC can be designed to provide the average expected value from complementary financial products that banks provide. Figure 4 shows the percentage change in deposits and the level change in bank deposit rates when CBDC inherits the average complementarity of banks in each choice set. The CBDC becomes more attractive since households can enjoy some positive spillovers between CBDC and other financial products offered by financial institutions. Therefore, CBDC has a larger crowding-out effect in Figure 4a compared to Figure 3c. Under the most extensive service network, deposits are crowded out by 28%, compared with 12% when CBDC provides no complementarity. Similarly, banks also have to respond more in deposit rates. Figure 4b shows that the rise in deposit rates more than doubled compared to Figure 3b. If CBDC provided the minimum expected value from complementary financial products offered by banks, then the CBDC adoption would be similar to the baseline case without complementarity. In the rest of Section 5, we assume CBDC provides no complementarity.

Figure 4: CBDC is Designed to Provide Certain Degree of Complementarity

(a) Percentage change in deposits (b) Change in bank deposit rates



Data sources: CFM 2017, FCAC 2017, Canada Post 2021, Government of Canada website
Note: This figure plots (a) the average percentage drop in deposits across banks and (b) the average endogenous change in deposit rate (in basis points) across banks, relative to the pre-CBDC equilibrium. In each graph, the given equilibrium outcome is plotted under four designs of service locations for CBDC (i.e., no service location, all Canada Post offices as service locations, all bank branches as service locations, and all bank branches plus Canada Post offices as service locations), combined with two different remuneration for CBDC: 0 and 10 basis points. In this figure, we use the fixed effect for the big five banks as the CBDC fixed effect.

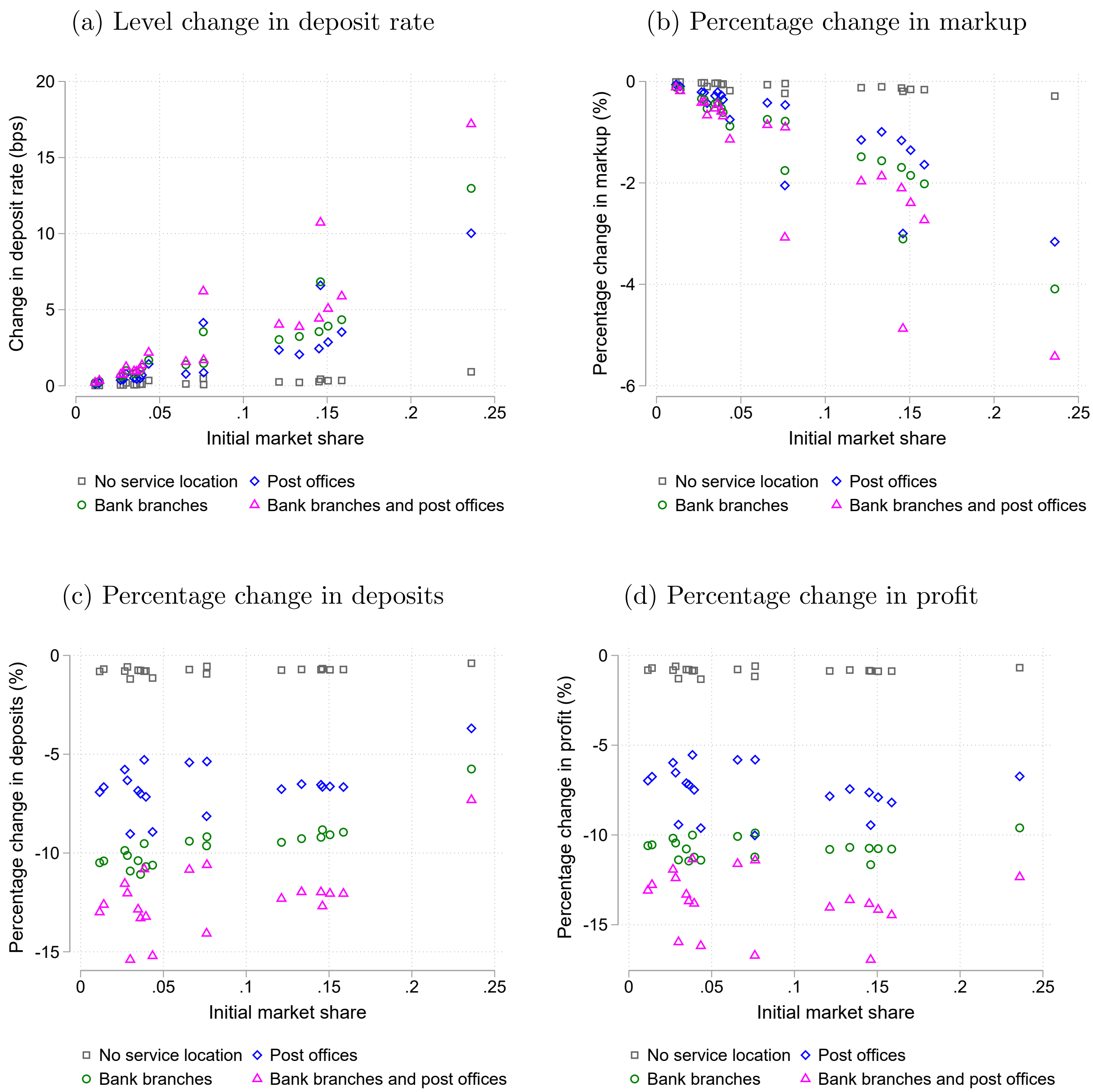
5.2 Heterogeneous Impact of CBDC on Banks

The impact of a CBDC can differ across banks and could in particular depend on banks' market power prior to the introduction of the CBDC. This section examines this heterogeneity. To measure a bank's market power, one can either use the market share of the bank or its markup. Both yield similar results because they are highly correlated, as shown in Figure 1a. Using the former measure, Figure 5 shows the results for a non-interest-bearing CBDC.

Figure 5a illustrates how the change in a bank's deposit rate varies with its pre-CBDC market power. Regardless of the design, banks with higher market power increases deposit rates by more in response to a CBDC. Intuitively, larger banks with higher market power are more affected by the CBDC, whereas smaller banks, which are already dominated by larger banks, would not respond as strongly.

Changes in deposit rates are more heterogeneous if the CBDC has a better service location network. Intuitively, banks with low market shares do not significantly increase deposit rates regardless of the CBDC's service location network because these banks have low markups. If the CBDC does not have any service location, banks with high market power enjoy a considerable competitive advantage due to their extensive branch networks. Consequently,

Figure 5: Impacts of CBDC on Banks with Different Initial Market Shares



Data sources: CFM 2017, FCAC 2017, Canada Post 2021, Government of Canada website

Note: This figure plots each bank's optimal response in deposit rates (in basis points), the percentage changes in markups, deposits, and profits for four different CBDC network designs (i.e., no service location, all Canada Post offices, all bank branches, both bank branches and Canada Post offices). The x-axis shows the bank's initial market share, calculated by averaging the estimated probabilities of households choosing the bank across all local markets (around households' residences) in which the bank operates. Here, we assume the CBDC is non-interest-bearing and has a fixed effect that is identical to that of the big five banks. We show the results where CBDC fixed effect takes the estimated fixed effect of the small banks in Figure OC4 in Online Appendix OC.

they do not significantly raise deposit rates either, resulting in relatively uniform responses to the CBDC. However, if the CBDC has many service locations, these banks face intensified competition and have to significantly raise deposit rates, resulting in relatively heterogeneous responses.

The change in markups, shown in Figure 5b, is more or less a mirrored image of Figure 5a because the markup depends negatively on the deposit rate. Perhaps more interestingly, Figure 5c shows that banks with more market power experience fewer deposit losses because they increase deposit rates by more. There is no apparent relationship between the percentage change in profit and the initial market share, as shown in Figure 5d. Banks with higher market shares tend to sacrifice more on markups but retain more deposits. These two effects largely offset each other.

5.3 Impact of Imposing Limits on CBDC Holdings

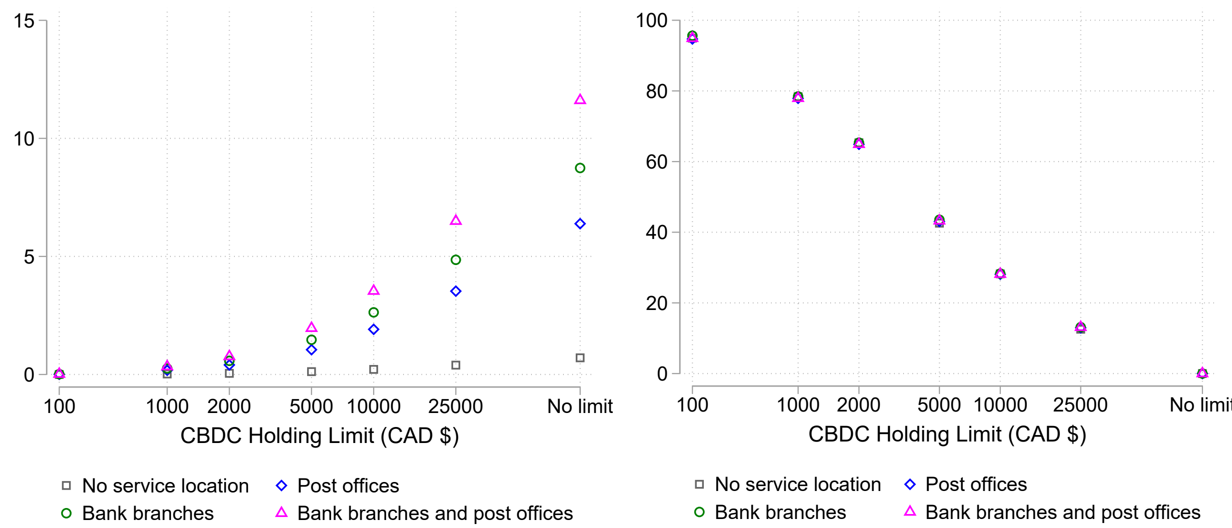
Recently, several central banks are considering imposing a limit on CBDC holdings. For example, the proposed digital euro legislation (European Commission, 2023) suggests that the ECB should establish a limit on CBDC holdings to avoid excessive crowding out. To study the effectiveness of this policy tool in the Canadian context, we use our estimated model and impose a constraint on how much CBDC a household can hold. We vary the limit from \$100 to \$25,000 and calculate the aggregate CBDC share and the percentage of households constrained by the limit in each case. This counterfactual analysis requires knowing the value of σ, which is not identifiable. To address this issue, we repeat our analysis for different values of σ, ranging from 0.1 to 0.9. The results are not sensitive to the value of σ. This section reports results under $\sigma = 0.5$ and additional results can be found in Figure OC5 in Online Appendix OC.

Figure 6a shows how the market share of a CBDC changes with the limit. As a benchmark, the right end of the x-axis shows the market share without any limit. Across all service location networks, even with a limit as high as \$25,000, the market share of the CBDC drops to less than half of its level without a limit. This implies that even with a very high limit, the reduction in CBDC holdings can still be substantial. If the limit is \$5,000, which is close to the 3,000-euro limit suggested by an ECB executive in a speech (Panetta, 2022), the CBDC would capture around 1% of the market, significantly lower than the market share of cash. If the goal is to achieve a CBDC market share similar to that of cash, the holding limit should be higher than \$65,000 if Canada Post offices are service locations, or at least \$35,000 if bank branches are service locations.

Figure 6b shows the fraction of households constrained by the limit. If the limit is \$25,000,

Figure 6: Imposing Different Limits on CBDC Holdings

(a) Aggregate CBDC share (b) Percentage of constrained households



Data sources: CFM 2017, FCAC 2017, Canada Post 2021, Government of Canada website
Note: This figure shows the aggregate CBDC share and the percentage of constrained households under different CBDC holding limits for four service location network designs (i.e., no service location, all Canada Post offices, all bank branches, both bank branches and Canada Post offices). The aggregate CBDC share is the share of households' total liquid assets allocated into the CBDC in equilibrium. The x-axis is displayed on a log scale for clarity. Here, we assume the CBDC is non-interest-bearing and has a fixed effect that is identical to that of the big five banks. The substitution parameter σ between cash and digital balance is assumed to be 0.5 here.

only slightly more than 10% of households are constrained. However, these households hold more than 50% of the total liquid assets, as shown in Figure OD8 in Online Appendix OD. As a result, the limit forces these households to hold much less CBDC than they wanted and thus greatly reduces the market share of the CBDC.

Our results suggest that a large holding limit is likely to be sufficient to avoid excessive crowding out without damaging the usefulness of the CBDC as a payment instrument.[38] A limit as high as $25,000 can keep the aggregate CBDC share under 5%, while only affecting a small fraction of households.

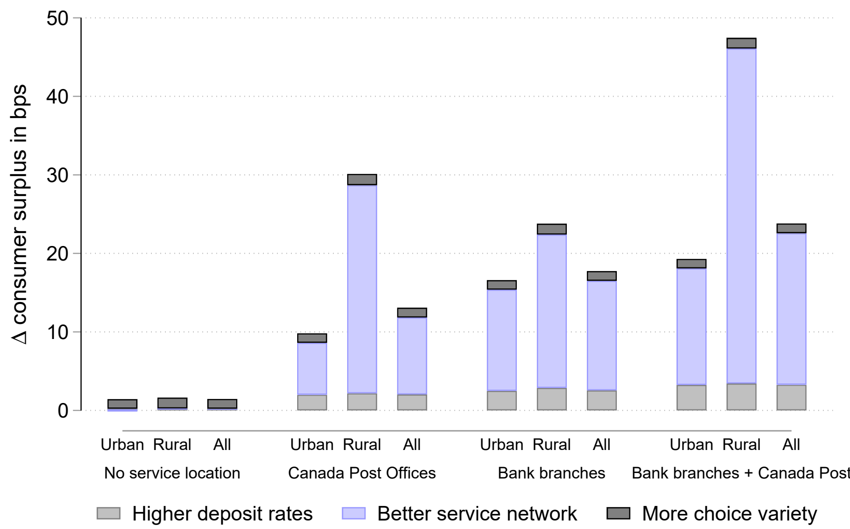
5.4 Change in Consumer Surplus

We measure the change in consumer surplus using the equivalent variation, that is, the increase in deposit rate required to compensate a household in an economy without a CBDC

[38]According to the 2018 Diary of Consumer Payment Choice in the US, above 99% of the transaction values are below 5,000 USD, which is far below a holding limit of 25,000 CAD.

to make their utility the same as in an economy with a CBDC.[39] Figure 7 shows the average change in consumer surplus across households under four designs of the CBDC service locations. In each case, we decompose the changes in consumer surplus into three components to study the contributing factors: (1) increased deposit rates induced by competition from the CBDC; (2) changes in the service location network; and (3) increased variety of choices due to the new product CBDC. We report results separately for urban, rural, and all households.

Figure 7: Decompose the Change in Consumer Surplus into Different Channels



Data sources: CFM 2017, FCAC 2017, Canada Post 2021, Government of Canada website
Note: This figure plots the changes in consumer surplus (in basis points) across four designs of CBDC service network: no service location, all Canada Post offices, all bank branches, or both branches and Canada Post offices. Within each service network design, each bar represents the average change in consumer surplus for urban, rural, or all households, respectively. The change in consumer surplus is decomposed into three different channels that drive the change: higher deposit rates, improvement in service network brought by the CBDC, and increase in choice variety due to the presence of the CBDC in the choice set. Here, we assume the CBDC is non-interest-bearing and has a fixed effect that is identical to that of the big five banks.

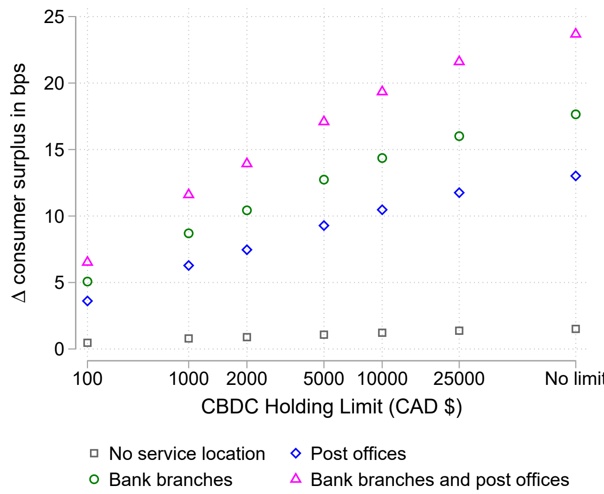
If the CBDC does not have service locations, deposit rates would barely change and thus almost all of the increase in consumer surplus is due to the introduction of a new product, which is very small. As the service location network becomes better, the increase in consumer surplus becomes larger. Specifically, if the CBDC only uses post offices as service locations, the consumer surplus increases by slightly over 10 basis points on average across all households. If it uses all bank branches, the increase is about 18 basis points. If it uses both bank branches and Canada Post offices, the gain can approach 25 basis points. In these cases, the service location network is the main contributor to the gain in consumer

[39] Here, "consumer" refers to a depositor instead of a borrower. Since we focus on the impact of a CBDC on the deposit market, we cannot discuss how a borrower's welfare is affected by the CBDC issuance.

surplus.

Rural households would benefit more from a CBDC that uses Canada Post offices as service locations than from one that uses bank branches. This is because post offices are more evenly distributed across the country compared to bank branches, which are more concentrated in urban areas. The average distance from a rural household to the nearest Canada Post office is around 1.9 km, while the distance to the nearest bank branch is considerably greater at 6.8 km. Therefore, including Canada Post offices as service locations may be useful for promoting financial inclusion.

Figure 8: Change in Consumer Surplus under Different Limits on CBDC Holdings



Data sources: CFM 2017, FCAC 2017, Canada Post 2021, Government of Canada website
Note: This figure shows the changes in consumer surplus (in basis points) across different CBDC holding limits (in Canadian dollars) for four service location network designs: no service location, all Canada Post offices, all bank branches, or both branches and Canada Post offices. In each case, the change in consumer surplus represents the average across all households. The x-axis is displayed on a log scale for clarity. Here, we assume the CBDC is non-interest-bearing and has a fixed effect that is identical to that of the big five banks. The substitution parameter σ between cash and digital balance is assumed to be 0.5 here.

Figure 8 shows how the holding limit affects the change in consumer surplus. When there is no limit, the results are identical to those shown in Figure 7, where, for instance, consumer surplus increases by around 25 basis points under the most extensive CBDC service network. Introducing a holding limit of \$25,000 reduces the gains in consumer surplus by less than 20%, which is much lower than the reduction in the CBDC market share (more than 50% as shown in Figure 6a). This suggests that although imposing a holding limit can substantially reduce the market share of the CBDC, its effect on the consumer surplus is relatively modest. One implication is that it may be better to design the CBDC as an attractive payment instrument and use holding limits to mitigate its crowding-out effect, rather than intentionally making the CBDC unappealing.

6 Extensions

This section studies three extensions. Section 6.1 allows households' preferences for branch network to vary by age. This enables us to examine a counterfactual scenario where all households value bank branches as little as the current young households. Section 5.1.2 allows the CBDC to provide some complementarity with other financial products. Section 6.2 extends the baseline model by allowing a household to hold both the CBDC and bank deposits.

6.1 Heterogeneous Tastes for Service Locations

Our baseline setup assumes that households of different ages value CBDC service locations or bank branches equally. However, younger generations, who tend to be more technologically savvy, may value bank branches less than older generations. We examine how accounting for these heterogeneous preferences might affect our quantitative results. Additionally, we analyze the impact of a CBDC in a future scenario where all households become as tech-savvy as today's young households, potentially reducing the importance of the service location network for the CBDC.

We first re-estimate the model and allow the preferences over bank branches to vary with age. The results are shown in Table OB9 in Online Appendix OB. As expected, older groups tend to have stronger preferences for branch network when choosing their deposit banks.[40] Using this new set of estimates, we find that accounting for the heterogeneous tastes for service locations has little effect on the aggregate CBDC adoption, as shown in Figure OC6 in Online Appendix OC.

However, if we apply the estimated preferences of the youngest households (under 35 years old) to all households, reflecting that in the foreseeable future, all households will be as tech-savvy as today's younger generation, the impact of CBDC service network is smaller, as shown in Figure OC7 in Online Appendix OC. Compared to Figure 3a, the aggregate CBDC share is higher when there is no service network and lower when there is an extensive network of service locations. Nevertheless, the crowding-out effect of CBDC remains limited.

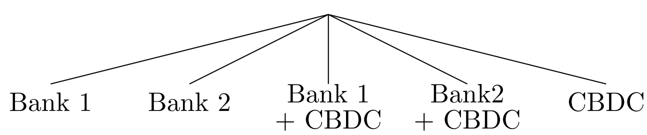
[40] We find the interaction terms between the branch network measures and the household age categories are less important for the bank choices for other financial products or in the allocation between cash and deposits.

6.2 Holding Both the CBDC and Deposits

Lastly, we allow a household to hold both the CBDC and bank deposits, in contrast to the baseline design where each household can hold only one. We find that even under this different model setup, the CBDC adoption and its crowding-out effect tend to be limited and they are even lower compared to those from the baseline setup.

Figure 9 illustrates the choice set of a household after a CBDC is introduced, assuming there are two banks in the choice set. As in the baseline, the household can still choose to hold only the CBDC or only a bank account at either of the two banks. However, two additional options are now available: (1) holding both the CBDC and a bank account at bank 1; (2) holding both the CBDC and a bank account at bank 2. This can be easily generalized to cases with more than two banks.

Figure 9: Household Choice Set Allowing for Holdings of Both Deposits and CBDC



A household chooses one option from their choice set after considering the utility for each option. We assume that when a household chooses to hold both the CBDC and a deposit account at a bank, it can benefit from the complementarity provided by the bank. In practice, this could be achieved if the bank upgrades their online banking app to support CBDC transfers and payments, making it just as easy to pay off credit card and mortgage debt from the deposit account as it would be with CBDC.[41]

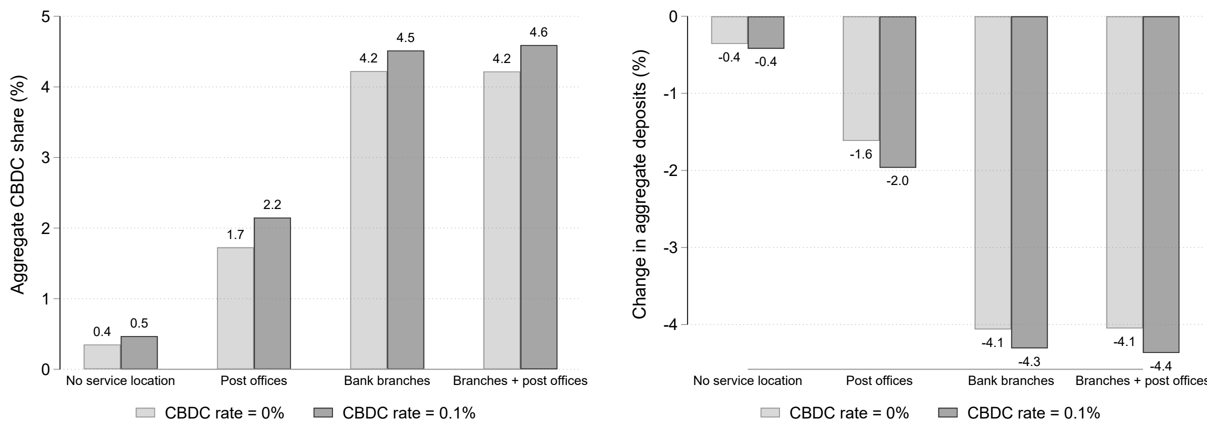
Similarly, we assume that if the household holds both the CBDC and a deposit account at a bank, it enjoys the better service location network of the two and obtains the higher value from liquidity holding between the two. The latter implies that the household holds all the digital balances in the digital money that provides the highest per-dollar value. More details can be found in Appendix C.

Figure 10 shows that the aggregate CBDC share and the crowding-out effects on deposits are much smaller compared to the baseline results in Figure 3. This is because households prefer holding both the CBDC and the deposits to holding the CBDC alone and whenever they hold both, they tend to store their digital money in deposit accounts, which offer higher interest rates than the CBDC.

[41] While the analysis in Section 5.1.2 also assumes that CBDC can offer a certain degree of complementarity, the model setup differs because CBDC was treated as a stand-alone product with its own mobile app that can be designed to achieve some level of complementarity. In contrast, the CBDC here is more similar to a sub-product offered by the bank.

Figure 10: Allowing Households to Hold Both CBDC and Deposits

(a) Aggregate CBDC share (b) Percentage change in aggregate deposits



Data sources: CFM 2017, FCAC 2017, Canada Post 2021, Government of Canada website
Note: This figure plots the aggregate CBDC share and the percentage change in aggregate deposits in a different model setup when allowing households to hold both CBDC and deposits. In each graph, the given equilibrium outcome is plotted under four designs of branch network for CBDC (i.e., no service location, all Canada Post offices as service locations, all bank branches as service locations, and all bank branches plus all Canada Post offices as service locations), combined with two different remuneration for CBDC. Here, we assume the CBDC fixed effect is identical to that of the big five banks.

Notice that if a household holds both the CBDC and a deposit account at a small bank, it can enjoy the better branch network of the two. Therefore, if CBDC offers a good service location network, it benefits the small banks more than big banks because it improves the branch presence of small banks relative to the big banks. This would increase deposits at small banks and decrease deposits at large banks, reducing the concentration of the banking sector. This effect is larger if the CBDC has a better service location network. These results complement the theoretical findings in Garratt, Yu and Zhu (2022), who argue that the CBDC can level the playing field by improving the payment convenience of small banks.[42]

7 Conclusions

This paper brings two important aspects to the ongoing discussion on the impact of a CBDC on banks. First, banks provide financial products that are complementary to deposits, which cannot be provided by the central bank. Second, consumers value physical service locations.

[42]Sarkisyan (2024) finds similar evidence for the fast payment system (Pix) introduced by the Brazilian central bank, arguing that Pix improved the payment convenience of smaller banks, thereby reducing the competitive advantage of larger banks in terms of payment convenience.

We develop a structural model that incorporates both features and estimate the model using a unique Canadian dataset which contains information on households' bank choices for a rich set of financial products.

This framework allows us to address a range of questions related to a CBDC. First, we find that a non-interest-bearing CBDC that does not provide complementarity with financial products nor service locations would have a limited crowding-out effect on bank deposits, crowding out demand deposits by less than 1%. Only if the CBDC is designed to provide a certain degree of complementarity or an extensive service location network could it reduce the demand deposits by more than 10%. Second, a large limit on CBDC holdings can effectively reduce the crowding out while having a relatively modest effect on the depositors' welfare. Lastly, the impacts of a CBDC are heterogeneous across banks and households. In particular, we find that banks with higher market shares tend to raise deposit rates by more and lose fewer deposits as a result. Households in rural areas would benefit more from a CBDC due to the lack of access to banks in rural areas compared to urban areas.

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Appendix

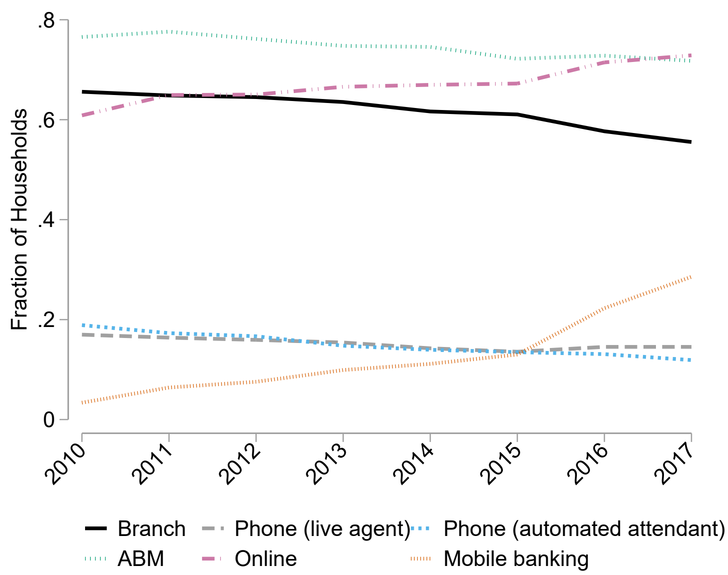
A Data

This section provides the supporting evidence from the data and shows the summary statistics for the main datasets used in this paper. Section A.1 shows the frequency of household branch visits and the types of services used. Section A.2 explains how we identify the main financial institution for a product when a household has multiple banks for that product. Section A.3 shows the summary statistics of the key variables and plots the bank-level interest rates.

A.1 Branch Usage Habits

Figure A1 shows that from the CFM data during 2010–2017, around 60% of the households reported that they visited their branches at least once in the past month. Households use branches, ABMs, and online banking more often than other channels. From 2010 to 2017, the branch usage frequency has declined slightly, but it still remained high in 2017.

Figure A1: Usage of Branches vs Other Channels over Time

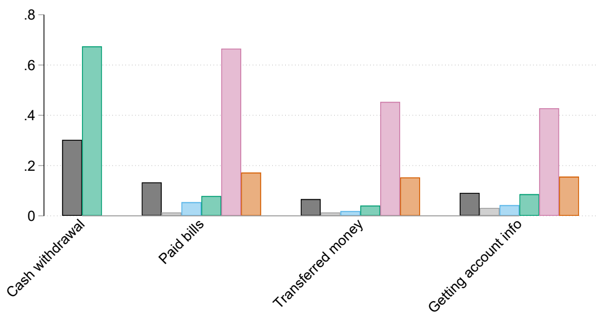


Data sources: CFM 2010–2017
Note: The y-axis refers to the fraction of households that used a given channel for banking services at least once in the past month. The x-axis shows the year in which the respondents reported the usage. Each line refers to a different method/channel used to obtain the banking services. The channels include branches (e.g., teller), phone (live agent), phone (automated attendant), ABM (automatic banking machine), online, or mobile banking.

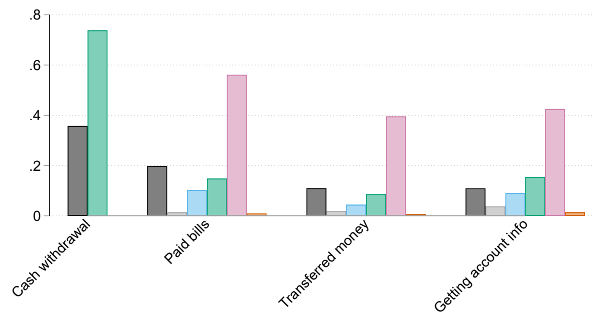
Figure A2 shows different types of services that households use each channel for. For transaction-related services, it can be seen that in 2017, around 30% of respondents still go to branches for cash withdrawals. For other service categories such as customer service/support, branch visit dominates the other channels. These patterns are very similar in 2017 and 2010, with only a slight decline in branch usage over time.

Figure A2: Usage of Branches vs Other Channels for Different Banking Services

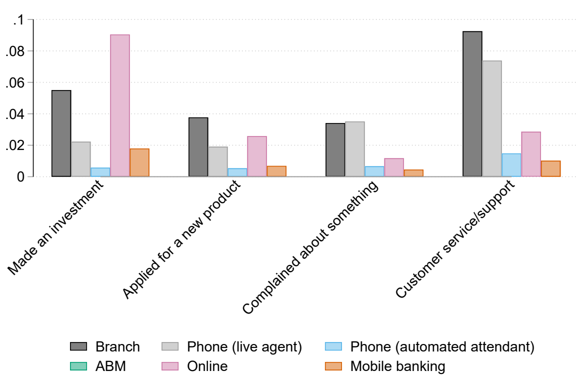
(a) Transaction-related services in 2017



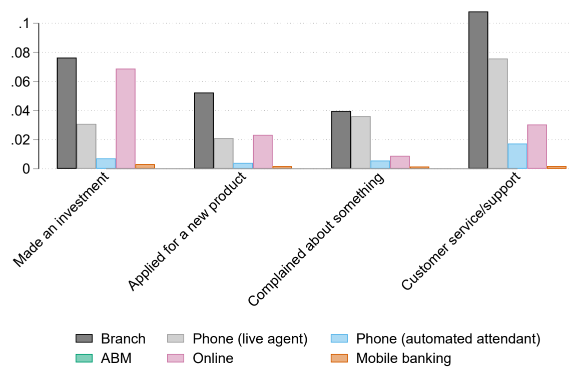
(b) Transaction-related services in 2010



(c) Other service categories in 2017



(d) Other service categories in 2010



Data sources: CFM 2010–2017
Note: This figure shows the fractions of households that need to use branches versus other channels (i.e., phone calls, ABM, online banking, mobile banking) for each service category in year 2010 and year 2017. The x-axis shows the service categories, ranging from cash withdrawal to customer service/support. The y-axis shows the fraction of households that used a given channel at least once in the past month in order to obtain the specific service indicated by the x-axis.

A.2 Main Financial Institution

This section shows the fraction of households with a single bank for each product, i.e., demand deposits, mortgage loans, credit cards, and guaranteed investment certificates (GICs). It also shows how we identify the main financial institution for a given product when a household has multiple banks for that product.

Table A1 shows that 73% of households go to a single bank for demand deposits. This fraction is 98% for mortgage loans, 42% for credit cards, and 78% for GICs. These numbers are even higher by looking at different household members (i.e., female household head, male household head, joint ownership) separately. For example, more than 85% of female household heads go to a single bank for their demand deposits, and the number is similar for male household heads.

Table A1: Number of Banks that Households Choose for Different Products

	Number of Banks			
	1	2	3	more than 3
Demand Deposits	0.73	0.23	0.04	0.00
Mortgage	0.98	0.02	0.00	0.00
Credit Card	0.42	0.31	0.17	0.11
Guaranteed Investment Certificates	0.78	0.16	0.03	0.02

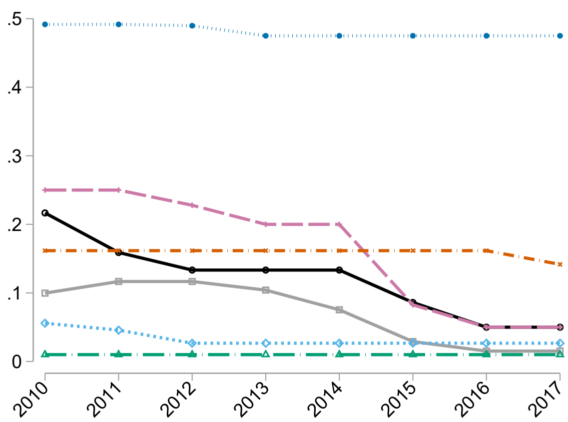
Data sources: CFM 2010–2017
Note: This table shows how many financial institutions that households go to for each product, i.e., demand deposits, mortgage loans, credit cards, and guaranteed investment certificates. Each column shows the fraction of households that go to 1, 2, 3, or more than 3 banks for a given product.

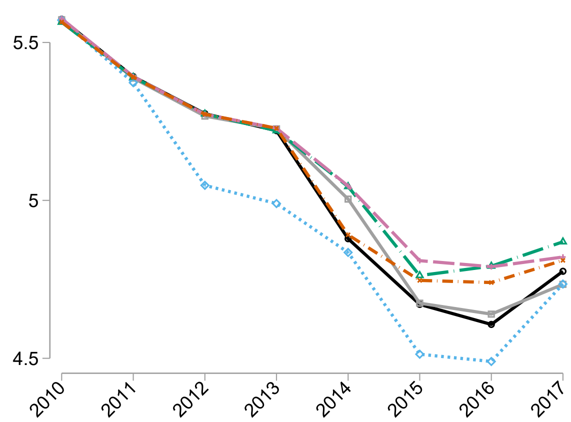
In our model and estimation, we assume each household only chooses one bank for each product. Therefore, if a household has multiple banks for a given product, we assume one of these banks is their main financial institution and is their chosen bank. More specifically, if a household has multiple banks for demand deposits, we assume their main financial institution is the one where they deposit the largest balance. Similarly, for households choosing multiple banks for the other financial products, we assume their main financial institutions for the mortgage loans, credit cards, and GICs are the ones with the largest remaining mortgage payment, the largest current outstanding balance, and the highest balance, respectively.

A.3 Summary Statistics

Figure A3 plots the demand deposit rates and the five-year closed mortgage rates for each bank over time from 2010 to 2017. Table A2 shows the summary statistics of some key variables.

Figure A3: Bank Interest Rates During 2010–2017





Data sources: CANNEX 2010–2017
Note: This figure shows the bank-level demand deposit rates and the five-year closed mortgage rates in percentage points during 2010 and 2017. The latter are used to measure the exogenous bank-specific returns on loans.

Table A2: Summary Statistics of Selected Variables

Variable	Obs	Mean	sd	Min	p25	p50	p75	Max
ln(deposit/cash)	66834	2.91	1.91	-4.76	1.67	2.97	4.16	12.43
Deposit rate (before tax)	66834	0.09	0.07	0.01	0.05	0.09	0.13	0.49
Deposit rate (after tax)	65162	0.06	0.05	0.00	0.03	0.06	0.08	0.34
Distance to the nearest branch	66834	5.17	8.08	0.01	0.92	1.81	5.24	50.00
Number of local branches	66834	21.96	32.39	0.00	2.00	9.00	28.00	296.00
Household head age	66834	55.07	15.48	18.00	44.00	57.00	66.00	106.00
Household income	65162	7.75	3.18	1.00	6.00	9.00	10.00	12.00
Household size	66834	2.15	1.14	1.00	1.00	2.00	3.00	8.00
Household head education	66413	3.67	1.35	1.00	2.00	4.00	5.00	6.00
Dislike investing in stock market	65950	6.04	2.95	1.00	4.00	6.00	9.00	10.00
Have difficulty in paying off debt	65835	3.39	2.88	1.00	1.00	2.00	5.00	10.00
Behind debt obligations in the past year	65078	0.06	0.23	.	.	.	.	.
Rent a home	65251	0.26	0.44	.	.	.	.	.
Household has a female head	66833	0.87	0.33	.	.	.	.	.
Live in rural area	66834	0.18	0.38	.	.	.	.	.
Big 5 indicator	66834	0.67	0.47	.	.	.	.	.
Small bank indicator	66834	0.05	0.21	.	.	.	.	.
Online bank indicator	66834	0.07	0.26	.	.	.	.	.
Desjardins credit union indicator	66834	0.09	0.28	.	.	.	.	.

Data sources: CFM 2010–2017, CANNEX 2010–2017, FCAC 2010–2017, Government of Canada website
Note: This table shows the summary statistics of the selected variables that are used in the estimation. The column "Obs" refers to the number of household-year observations in the estimation sample for the portfolio allocation choice.

B Introducing CBDC in Counterfactual Analysis

This section explains how we conduct the counterfactual analysis on CBDC. Section B.1 shows how we obtain the household's demand for a CBDC using the estimated demand-side preference parameters. Section B.2 explains how the CBDC issuance would affect banks' endogenous responses on the supply side. Section B.3 shows how we measure the aggregate asset holdings.

B.1 Household's Demand for CBDC

After a CBDC is introduced, we assume that each household's choice set would contain this new alternative. The household chooses to deposit their digital liquid assets in the CBDC or one of the existing banks by comparing the utility from each option. Based on (18), a household i's probability of depositing the digital money in the CBDC is

$$\mathbb{P}(j_i^* = cbdc | r_j, \boldsymbol{r}_{-j}) = \frac{\exp\left(\tilde{\theta}\tilde{V}^b_{i,cbdc} + \phi \sum_{k\in\mathcal{K}} \omega^k \mathbb{E}V^k_{i,cbdc} + \boldsymbol{X}_{i,cbdc}\boldsymbol{\beta}^f + \eta^f_{cbdc}\right)}{\sum_{m\in\mathcal{J}_i} \exp\left(\tilde{\theta}\tilde{V}^b_{i,m} + \phi \sum_{k\in\mathcal{K}} \omega^k \mathbb{E}V^k_{i,m} + \boldsymbol{X}_{i,m}\boldsymbol{\beta}^f + \eta^f_m\right)}, \tag{B1}$$

where the choice set $\mathcal{J}_i$ now also contains the CBDC and the subscript m refers to a bank or a CBDC. If a household chooses to deposit their digital money in the CBDC, then based on (7), the desired holding of the CBDC would be

$$d_{i,cbdc} = \frac{\left(u^b_{i,cbdc}\right)^{\frac{\sigma}{1-\sigma}}}{1 + \left(u^b_{i,cbdc}\right)^{\frac{\sigma}{1-\sigma}}} w_i, \tag{B2}$$

where $u^b_{i,cbdc} = \exp\left(\alpha^b r_{i,cbdc} + \boldsymbol{X}_{i,cbdc}\boldsymbol{\beta}^b + \eta^b_{cbdc} + \zeta^b + \varepsilon^b_i\right)$ is the per-dollar value from holding the digital balance in the CBDC. Therefore, each household's expected demand for CBDC is

$$\mathbb{P}(j_i^* = cbdc | r_j, \boldsymbol{r}_{-j}) d_{i,cbdc}, \tag{B3}$$

and summing over each household's CBDC demand would give the aggregate CBDC demand.

We assume the estimated preference parameters ($\tilde{\theta}$, ϕ, $\boldsymbol{\beta}^f$) are unchanged when the CBDC is introduced. The only unknown parameter in (B1) is the CBDC fixed effect η^f_{cbdc}. Intuitively, we do not know how consumers will value a product that is not yet offered. We consider a range of possibilities for the fixed effect of the CBDC, namely among the estimated fixed effects for the big five banks, the small banks, the online banks, and the regional credit unions. Below, we discuss how we obtain $\tilde{V}^b_{i,cbdc}$, $\mathbb{E}V^k_{i,cbdc}$, and $X_{i,cbdc}$ in (B1), as well as (B2). We also explain how we obtain (B1) and (B2) when there is a holding limit on the CBDC.

Value from Liquid Asset Portfolios (Without CBDC Holding Limit). We first obtain the utility from holding the portfolio of CBDC and cash, $\tilde{V}^b_{i,cbdc}$, using the estimates of the parameters $(\tilde{\alpha}^b, \tilde{\boldsymbol{\beta}}^b, \tilde{\boldsymbol{\eta}}^b, \tilde{\zeta}^b, \tilde{\varepsilon}^b_i)$:

$$\tilde{V}^b_{i,cbdc} = \ln\left[1 + \exp\left(\tilde{\alpha}^b r_{i,cbdc} + \boldsymbol{X}_{i,cbdc}\tilde{\boldsymbol{\beta}}^b + \tilde{\eta}^b_{cbdc} + \tilde{\zeta}^b + \tilde{\varepsilon}^b_i\right)\right], \tag{B4}$$

where r_{cbdc} is the CBDC rate and $r_{i,cbdc} = r_{cbdc}(1-\tau_i)$ is the post-tax CBDC rate. The vector $\boldsymbol{X}_{i,cbdc}$ consists of the branch network measures for CBDC. In the counterfactual analyses, we study different designs of CBDC in terms of the interest rate and the network of service locations. Assuming the preference parameters for attributes, $\tilde{\alpha}^b$ and $\tilde{\boldsymbol{\beta}}^b$, are unchanged after CBDC issuance, the remaining unknowns are the CBDC fixed effect, $\tilde{\eta}^b_{cbdc}$, and the unobserved idiosyncratic tastes for CBDC, $(\tilde{\zeta}^b + \tilde{\varepsilon}^b_i)$. As discussed above, we consider a range of CBDC fixed effects based on the estimated fixed effects η^f_j for different banks j. For the unobserved idiosyncratic tastes, we assume they are identical to those of bank deposits since they are both digital money.

Note that $\left(u^b_{i,cbdc}\right)^{\frac{\sigma}{1-\sigma}}$ is equivalent to the exponential term in (B4), so (B2) can be written as

$$d_{i,cbdc} = \frac{\exp\left(\tilde{\alpha}^b r_{i,cbdc} + \boldsymbol{X}_{i,cbdc}\tilde{\boldsymbol{\beta}}^b + \tilde{\eta}^b_{cbdc} + \tilde{\zeta}^b + \tilde{\varepsilon}^b_i\right)}{1 + \exp\left(\tilde{\alpha}^b r_{i,cbdc} + \boldsymbol{X}_{i,cbdc}\tilde{\boldsymbol{\beta}}^b + \tilde{\eta}^b_{cbdc} + \tilde{\zeta}^b + \tilde{\varepsilon}^b_i\right)} w_i, \tag{B5}$$

which can be calculated using the same method as discussed above.

Value from Liquid Asset Portfolios (With CBDC Holding Limit). Suppose a central bank would like to impose a limit $\bar{d}_{cbdc}$ on the holdings of the CBDC. If the desired holding of the CBDC exceeds this limit, then household i's CBDC holding is constrained at the limit $d_{i,cbdc} = \bar{d}_{cbdc}$ and they hold the rest of the liquid assets in cash $\bar{c}_{i,cbdc} = w_i - \bar{d}_{cbdc}$. In this case, the utility from liquidity holding is

$$\bar{V}^b_{i,cbdc} = \ln\left[\bar{c}^\sigma_{i,cbdc} + (u^b_{i,cbdc}\bar{d}_{cbdc})^\sigma\right]^{\frac{1}{\sigma}}, \tag{B6}$$

which can only be calculated once we know σ, unlike in the unconstrained case where we do not need to know the value of σ to calculate (B4). With the assumed value of σ, $\theta = \tilde{\theta}\frac{\sigma}{1-\sigma}$ can be calculated and the probability of choosing the CBDC is

$$\mathbb{P}(j^*_i = cbdc | r_j, \boldsymbol{r}_{-j}) = \frac{\exp\left(\theta\bar{V}^b_{i,cbdc} + \phi\sum_{k\in\mathcal{K}}\omega^k\mathbb{E}V^k_{i,cbdc} + \boldsymbol{X}_{i,cbdc}\boldsymbol{\beta}^f + \eta^f_{cbdc}\right)}{\sum_{m\in\mathcal{J}_i}\exp\left(\theta V^b_{i,m} + \phi\sum_{k\in\mathcal{K}}\omega^k\mathbb{E}V^k_{i,m} + \boldsymbol{X}_{i,m}\boldsymbol{\beta}^f + \eta^f_m\right)}, \tag{B7}$$

which tends to be lower relative to the unconstrained case due to the lower $\bar{V}^b_{i,cbdc}$ compared to $V^b_{i,cbdc} = \ln \left[c^\sigma_{i,cbdc} + (u^b_{i,cbdc} d_{i,cbdc})^\sigma\right]^{\frac{1}{\sigma}}$ when the holdings of cash and CBDC are optimal. We show that the results on CBDC holding limits are robust to different values of σ in Figure OC5 in Online Appendix OC.

Value from Financial Products. Based on (10), we obtain the expected value from obtaining the financial product $k \in \mathcal{K}$ when CBDC is chosen for depositing the digital money:

$$\mathbb{E}V^k_{i,cbdc} = \ln \left(\sum_{n \in \mathcal{J}^k_i} \exp\left(\kappa \mathbb{1}(n = cbdc) + \boldsymbol{X}_{i,n}\boldsymbol{\beta}^k + \eta^k_n\right) \right) + C. \tag{B8}$$

In the baseline analysis, we assume that households will not enjoy the extra utility κ if they choose the CBDC for their digital money, because they still need to obtain the financial product from some other bank. As a result, the expected value $\mathbb{E}V^k_{i,cbdc}$ would be lower compared to the case when they choose a bank to deposit their digital money. We use the estimated parameters $(\kappa, \boldsymbol{\beta}^k, \boldsymbol{\eta}^k)$ to calculate $\mathbb{E}V^k_{i,cbdc}$. The constant C does not matter for calculating the choice probability (B1) because it is the same for all choice alternatives.

Service Location Network for CBDC. As shown above, the service network for the CBDC indirectly affects the choice probability of the CBDC through the utility from liquidity holding and from the other financial products. In addition, we allow $\boldsymbol{X}_{i,cbdc}$ to directly affect the probability of choosing the CBDC since it reflects the convenience of getting in-person customer services for the CBDC. We look at different designs of the service location network $\boldsymbol{X}_{i,cbdc}$ for CBDC.

B.2 Banks' Endogenous Responses to CBDC

Introducing a CBDC would shift the demand for deposits at each bank. Upon issuance, the deposit demand for bank j would be reduced due to a lower probability of choosing bank j by each household i. A lower choice probability tends to make the deposit demand more elastic, according to (14), which would induce banks to raise their deposit rates to compete with CBDC.

We assume that banks' marginal costs estimated in Section 4.2 are unchanged by CBDC issuance. Therefore, the magnitude of deposit rate adjustments is only driven by the demand shift and the resulting change in the deposit demand elasticity. Using the estimated marginal costs and the banks' first-order conditions (13), we solve for the new equilibrium deposit rates in the presence of the CBDC. As we vary the design of the CBDC (i.e., $r_{cbdc}, \boldsymbol{X}_{i,cbdc}, \bar{d}_{cbdc}$), we can predict how banks adjust their deposit rates in response to the CBDC under each design.

B.3 Measuring Aggregate Asset Holdings

A higher new equilibrium deposit rate means that conditional on choosing a bank j, the household will allocate more of their endowed liquid assets into deposits than cash. In addition, it leads to a higher $\tilde{V}^b_{i,j}$, which raises the probability of choosing the bank j and lowers the probability of choosing the CBDC, compared to the case when there is no endogenous response in deposit rates.

The equilibrium aggregate CBDC holdings can be obtained using (B3) and the new equilibrium deposit rates:

$$d_{cbdc} = \sum_{i \in \mathcal{I}} \mathbb{P}(j^*_i = cbdc | r_j, \boldsymbol{r}_{-j}) d_{i,cbdc}(r_{cbdc}). \tag{B9}$$

Similarly, the new equilibrium aggregate deposit (D) and cash (C) holdings can be obtained using

$$D = \sum_{j \in \mathcal{J}_i \& j \neq cbdc} \sum_{i \in \mathcal{I}} \mathbb{P}(j^*_i = j | r_j, \boldsymbol{r}_{-j}) d_{i,j}(r_j), \tag{B10}$$

$$C = \sum_{j \in \mathcal{J}_i} \sum_{i \in \mathcal{I}} \mathbb{P}(j^*_i = j | r_j, \boldsymbol{r}_{-j}) c_{i,j}(r_j), \tag{B11}$$

where $\mathcal{J}_i$ contains both incumbent banks and the CBDC. The total liquid assets ($d_{cbdc}+D+C$) are assumed to be the same as the total liquid assets $\sum_i w_i$ before the CBDC issuance.

C Extension: Holding Both CBDC and Deposits

Under this model extension, if a household used to have $\mathcal{J}$ banks in the choice set, they will have $(2\mathcal{J} + 1)$ options after a CBDC is introduced. Compared to the baseline setup, the additional options include choosing a combination of the CBDC and one of the existing banks. The household's utility from choosing an option j is

$$V^f_{i,j} = \theta V^b_{i,j} + \phi \sum_{k \in \mathcal{K}} \omega^k \mathbb{E} V^k_{i,j} + \boldsymbol{X}_{i,j} \boldsymbol{\beta}^f + \eta^f_j + \varepsilon^f_{i,j}. \tag{C12}$$

If a household chooses an existing bank or the CBDC alone, (C12) is calculated based on the attributes of that specific bank or the CBDC. However, if a household chooses to hold a combination of bank deposits and the CBDC, we need to make assumptions on the attributes of this product bundle. In particular, we assume their expected value from other financial products $\mathbb{E}V_{i,j}^k$ takes on the higher value between the two, which is equivalent to the value they would receive if they chose the bank deposits alone. Similarly, we assume the branch network $X_{i,j}$ will take the value of the better option between the two, and the fixed effect η_j^f will also take the higher value of the two. Below, we explain how we calculate $V_{i,j}^b$ when j is the product bundle of bank deposits and the CBDC. We also discuss how $V_{i,j}^b$ changes when there is a holding limit on CBDC.

Value from Liquid Asset Portfolios (Without Holding Limit). If a household chooses a product bundle j that consists of both the CBDC and the deposits from bank h, we set the per dollar value to $u^* = \max(u_{i,h}, u_{i,cbdc})$. The household's value from liquidity holding is

$$V_{i,j}^b = \max_{c_{i,j},d_{i,j}} \ln \left[c_{i,j}^\sigma + (u^* d_{i,j})^\sigma\right]^{\frac{1}{\sigma}} \quad \text{st} \quad c_{i,j} + d_{i,j} = w_i,$$

where $d_{i,j}$ denotes the digital balance. If the per-dollar value of deposits $u_{i,h}$ is higher than $u_{i,cbdc}$, the household will store all the digital balance in deposits and vice versa. So the digital balance is

$$d_{i,j} = \begin{cases} \frac{u_{i,j}^{\frac{\sigma}{1-\sigma}}}{1+u_{i,j}^{\frac{\sigma}{1-\sigma}}} w_i & \text{if } u_{i,cbdc} \leqslant u_{i,j} \\ \\ \frac{u_{i,cbdc}^{\frac{\sigma}{1-\sigma}}}{1+u_{i,cbdc}^{\frac{\sigma}{1-\sigma}}} w_i & \text{if } u_{i,cbdc} > u_{i,j} \end{cases} \tag{C13}$$

and the cash balance in each case is $c_{i,j} = w_i - d_{i,j}$.

Value from Liquid Asset Portfolios (With Holding Limit). If there is a holding limit on CBDC, a household's utility from liquidity holding is

$$V_{i,j}^b = \max_{c_{i,j},d_{i,j}} \ln \left[c_{i,j}^\sigma + D_{i,j}^\sigma\right]^{\frac{1}{\sigma}} \quad \text{st} \quad c_{i,j} + d_{i,j} = w_i, \tag{C14}$$

where $D_{i,j}$ represents the total value from the digital balance when the product bundle j consists of both the CBDC and bank-h deposits:

$$D_{i,j} = \begin{cases} u_{i,cbdc}\bar{d}_{cbdc} + u_{i,h}(d_{i,j} - \bar{d}_{cbdc}) & \text{if } u_{i,cbdc} > u_{i,h} \ \&\ d_{i,j} > \bar{d}_{cbdc} \\ u_{i,cbdc} d_{i,cbdc} & \text{if } u_{i,cbdc} > u_{i,h} \ \&\ d_{i,j} \leqslant \bar{d}_{cbdc} \\ u_{i,h} d_{i,h} & \text{if } u_{i,cbdc} \leqslant u_{i,h} \end{cases} \tag{C15}$$

and $u_{i,h}$ refers to the per-dollar value of the bank-h deposits and $d_{i,j}$ refers to the digital balance. If $u_{i,cbdc} \leqslant u_{i,h}$, the household puts all digital balance in deposits, so $d_{i,j} = d_{i,h}$ and $D_{i,j} = u_{i,h}d_{i,h}$. If $u_{i,cbdc} > u_{i,j}$ & $d_{i,j} \leqslant \bar{d}_{cbdc}$, then the solution is also identical to the case without the holding limit and $d_{i,j} = d_{i,cbdc}$. However, if $u_{i,cbdc} > u_{i,j}$ & $d_{i,j} > \bar{d}_{cbdc}$, the utility from liquidity holding would be different. Specifically, divide the FOC wrt $c_{i,j}$ by the FOC wrt $d_{i,j}$ to get

$$\frac{c_{i,j}^{\sigma-1}}{(u_{i,cbdc}\bar{d}_{cbdc} + u_{i,h}(d_{i,j} - \bar{d}_{cbdc}))^{\sigma-1}u_{i,h}} = 1 \tag{C16}$$

Rearrange to get

$$c_{i,j} = u_{i,h}^{\frac{\sigma}{\sigma-1}}\bar{d}_{cbdc}\left(\frac{u_{i,cbdc}}{u_{i,h}} - 1\right) + u_{i,h}^{\frac{\sigma}{\sigma-1}}d_{i,j} \tag{C17}$$

Hence, the cash-to-digital balance ratio is:

$$\frac{c_{i,j}}{d_{i,j}} = u_{i,h}^{\frac{\sigma}{\sigma-1}}(\frac{u_{i,cbdc}}{u_{i,h}} - 1)\frac{\bar{d}_{cbdc}}{d_{i,j}} + u_{i,h}^{\frac{\sigma}{\sigma-1}} \tag{C18}$$

Substitute into the budget constraint and rearrange to get

$$d_{i,j} = \frac{u_{i,h}^{\frac{\sigma}{1-\sigma}}w_i - (\frac{u_{i,cbdc}}{u_{i,h}} - 1)\bar{d}_{cbdc}}{1 + u_{i,h}^{\frac{\sigma}{1-\sigma}}} \tag{C19}$$

Hence, the amount of cash holding is $c_{i,j} = w_i - d_{i,j}$ and the amount of deposit holding $d_{i,h}$ is $(d_{i,j} - \bar{d}_{cbdc})$.