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Francesca Carapella, Jin-Wook Chang, Sebastian Infante, Melissa Leistra, Arazi Lubis, and Alexandros P. Vardoulakis

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Financial Stability Implications of CBDC[1]

Francesca Carapella, Jin-Wook Chang, Sebastian Infante,

Melissa Leistra, Arazi Lubis, and Alexandros P. Vardoulakis

Board of Governors of the Federal Reserve System

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Abstract

A Central Bank Digital Currency (CBDC) is a form of digital money that is denominated in the national unit of account and constitutes a direct liability of the central bank. We examine the financial stability risks and benefits of issuing a CBDC under different design options. Our analysis is based on lessons derived from historical case studies as well as on an analytical framework that allows us to characterize the mechanisms through which a CBDC can affect financial stability. We further discuss various policy tools that can be employed to mitigate financial stability risks.

Keywords: CBDC, financial stability, runs, stablecoins, central bank liabilities, regulation.

JEL classification: E40, E50, G01, G21, G23, G28

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1. Introduction

A Central Bank Digital Currency (CBDC) is a form of digital money that is denominated in the national unit of account, constitutes a direct liability of the central bank, and can be distinguished from other central bank liabilities.[2] A CBDC could alter the financial and payments ecosystem in far-reaching ways. Whether these changes make the financial system more stable or more fragile will depend on how CBDC is designed and how the financial system adjusts to its implementation.[3]

This paper examines the financial stability implications of a CBDC under different design options and discusses policy tools that can be employed to mitigate financial stability risks. As discussed in more detail below, while a CBDC could in concept be held or transferred by any party, our analysis generally follows the four broad design recommendations provided by the Federal Reserve's 2022 discussion paper: (i) privacy protected; (ii) intermediated; (iii) widely transferable; and (iv) identity verified.[4] This paper does not more generally analyze tradeoffs related to CBDC policy and design choices outside of the financial stability lens.

We examine three broad ways in which a CBDC may affect financial stability.[5] First, a CBDC may increase the financial sector's vulnerability to destabilizing runs. By offering a safer asset, relative to private liabilities of the financial sector, a CBDC may present an attractive option for depositors and investors to fly to during times of stress. Some nonbank institutions, such as

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[2] Most central banks already provide digital liabilities in the form of reserve balances, which are mainly accessible to banks. Common definitions of CBDC do not attempt to determine on which dimensions CBDC could or should vary from other digital central bank monies. There are many potential design and policy choice variations. See for example, CMPI 2018 https://www.bis.org/cpmi/publ/d174.pdf

[3] The Federal Reserve has made no decisions on whether to issue a central bank digital currency and does not intend to proceed with issuance of a CBDC without clear support from the executive branch and from Congress, in the form of a specific authorizing law (Federal Reserve Board, 2022).

[4] Board of Governors of the Federal Reserve System (2022), "Money and Payments: The US Dollar in the Age of Digital Transformation," *Discussion Paper*, January 2022.

[5] This paper focuses on financial stability risks from a CBDC during times of stress rather than on the potential effect of a CBDC on bank deposits and credit provision during normal times.

prime money funds, might suffer larger or more frequent runs in the presence of a CBDC. Policy tools, such as CBDC remuneration and quantity limits on CBDC holdings, have the potential to mitigate such run risks, complementing traditional central bank tools for emergency liquidity assistance. Tiered remuneration—whereby remuneration decreases as CBDC holdings increase and can be adjusted during times of stress—could be combined with a hard quantity limit on individual holdings. The holding limit could be chosen to prevent severe and widespread runs to CBDC, while payments in CBDC continue to be possible. The calibration of holding limits is an important but difficult task. Given the uncertainty about the demand for CBDC, setting holding limits may involve a process of trial and error.

Second, a CBDC may weaken financial stability by reducing the ability of banks to extend credit during times of stress. We study a stress scenario in which the presence of a CBDC causes a withdrawal of deposits from banks, forcing them to use less desirable funding sources despite not necessarily precipitating a crisis. Using various estimates from the literature, we find that funding costs and, in turn, the rates charged to borrowers, may increase by 50 to 250 basis points in stress times. We roughly estimate that such higher borrowing rates may result in a decrease of about 1 to 5 percent in C&I lending.

Third, to the extent a CBDC is made more broadly available than other digital central bank liabilities, it could make the financial system more stable by providing a perfectly safe asset to nonbanks, foreign institutions, or others that might use it to enhance their liquidity management. Beyond its effect on the traditional financial system, a CBDC could improve financial stability in the digital asset ecosystem. Stablecoins with direct access to a digital central bank liability would be better able to prevent or manage runs.

Our analysis proceeds as follows. Section 2 presents case studies that share similar financial stability concerns as the ones raised for CBDC. Section 3 discusses specific mechanisms that have been highlighted in economic research through which a CBDC may affect financial stability. Section 4 analyzes the various tools to mitigate financial stability risks introduced by a CBDC and their implementation challenges.[6]

2. Lessons from case studies

Because a CBDC offers a safe asset to run to in times of crisis, a key financial stability concern about its introduction is that it may increase the vulnerability of institutions and markets that depend on short-term, runnable debt. Flight-to-safety concerns are not unique to CBDC and have been raised in several relatively recent examples both in the US and abroad. We review these cases to infer lessons that are relevant for thinking about the potential destabilizing effects of a flight-to-CBDC in times of crisis.

First, we review similar concerns introduced by potential requests for accounts at the Federal Reserve by state-chartered narrow banking institutions, planning to pass through part of the interest rates they would earn on their reserve holdings to their depositors. Second, we examine the similarities between a flight-to-CBDC and a flight-to-ON RRP (the Federal Reserve's Overnight Reverse Repurchase Facility), as an example of a central-bank liability available to eligible non-depository institutions, and consider whether such facility has contributed to the run on prime Money Market Funds (MMFs) during the COVID-19 crisis in March 2020.[7] Third, we analyze the recent episodes of traditional bank runs, including the run on Greek banks during the European

[6] See Carapella and Flemming (2020), and Infante et al. (2022) for detailed literature reviews.
[7] The ON RRP is a supplementary monetary policy tool that supports interest rate control by providing a floor in overnight money market rates to eligible investors.

sovereign debt crisis and banking stress of March 2023, when depositors at commercial banks attempted to withdraw their funds to hold them as central bank money.

2.1Pass-Through Investment Entities

Pass-Through Investment Entities ("PTIEs"), a type of “narrow bank,” were contemplated in a 2019 request for comment by the Federal Reserve Board. The request for comment explained that such institutions potentially could seek to be granted master accounts at the Federal Reserve and to be eligible for receiving interest on reserves balances (IORB).[8] Their business model would be to invest a significant fraction of, or all, their total deposits in reserve balances with the Fed in order to pass through the interest that they earn on reserve balances to their depositors. The Federal Reserve Board’s previous consideration of potential PTIEs provides the most direct comparison with the flight-to-safety concerns introduced by a CBDC.

PTIEs, if established and deemed eligible institutions would be businesses operating on narrow profit margins and, because their investments would be in perfectly safe assets, they have sought to be exempted from prudential regulation and paying insurance deposit premiums. As a result, there are no restrictions, in principle, on how big PTIEs can grow. To mitigate the potential risks arising from the attractiveness of a nearly unlimited safe asset in times of stress, among other reasons, the Board issued an Advanced Notice of Proposed Rulemaking (ANPR) to request public comment whether it should propose changes to Regulation D, such as on how to define PTIEs and

[8] With the elimination of reserve requirements during the pandemic, there is now only one rate of remuneration, referred to as interest on reserve balances (IORB) instead of an interest rate on excess reserves (IOER)..

on potentially paying them a lower rate than IORB, including possibly zero or tiered rates for different levels of balances held by PTIEs.[9]

Lessons for CBDC

No PTIEs have been established so far, which would have provided insights into how they would change the financial ecosystem. That said, we can already draw important lessons for CBDC. The appeal of PTIEs during times of stress would accrue both from the safety of their assets and the potential interest rate paid to their depositors. Paying a lower or zero rate of interest on reserve holdings of PTIEs—potentially above a certain threshold of holdings as contemplated by the ANPR—would lower the interest that PTIEs could offer depositors and potentially mitigate the incentives to run to PTIEs in times of stress. This contemplated proposal to amend Regulation D shares similar characteristics to tiered CBDC-remuneration to mitigate a flight-to-CBDC, which is a policy tool we explore later in this paper.

2.2 ON RRP, Bank Deposits, and MMFs

Another arrangement that has been compared to CBDC for its property of being a potential safe haven during crisis times, is the Overnight Reverse Repo Facility (ON RRP). The Federal Reserve introduced ON RRP in 2014 to support its control of short-term interest rates by allowing eligible non-bank participants in the short-term funding markets to earn interest on repurchase agreements (repos) with the Federal Reserve. The set of such eligible counterparties is broad and includes Money Market Funds (MMFs), Primary Dealers, and Government Sponsored Enterprises (GSEs).

[9] The Advanced Notice of Proposed Rulemaking (ANPR) was published in Federal Register Vol. 84, No. 48 on Tuesday, March 12, 2019 (Federal Register :: Regulation D: Reserve Requirements of Depository Institutions). The Board had not determined whether any or all potential PTIEs might be eligible institutions.

Although the ON RRP is a monetary policy tool, its potential destabilizing effects were highlighted early on.[10] In theory, there are two channels through which access to ON RRP could potentially affect financial stability.

The first channel operates through bank depositors who may run on their banks and move funds into government MMFs during a flight-to-safety episode.[11] Large institutional entities have funds that they choose to keep in their banks or to invest in short-term instruments, balancing their needs for immediate liquidity, credit risk management, and potential returns. In stress, the incentive to move bank account balances that are above deposit insurance thresholds to secured investments increases. Government MMFs receive many of these investments. Without access to ON RRP, government MMFs would invest these additional funds into government assets, such as Treasury securities, which would put downward pressure on their yields, mitigating the incentive to run. Further, MMFs may take actions to limit additional inflows when the Treasury yield falls significantly. With access to an elastic ON RRP, instead, MMFs could absorb more liquidity without suppressing short-term rates. As a result, access to ON RRP could exacerbate potential runs from banks to MMFs.

The second channel operates through nonbank institutions, such as MMFs, that may substitute away from lending to financial or non-financial firms towards the ON RRP. MMFs, both government and other types, must also keep cash on hand for liquidity risk management. Subsequently, they are large cash lenders in repo markets, substantial buyers of commercial paper, and otherwise lend in short-term funding markets. A migration of such funds to ON RRP could

[10] See, for example, Frost et al. (2015).

[11] Government MMFs are defined as MMFs that invest 99.5% or more of their total assets in very liquid investments, namely, cash, government securities, and/or repurchase agreements that are collateralized fully with government securities.

amplify a crisis by reducing multiple sources of short-term funding for financial and non-financial firms. The financial stability risks of both channels are higher under full allotment, that is, if the facility is uncapped on aggregate, or if a cap is sufficiently large.[12] To mitigate these risks, the ON RRP imposes individual caps, while the size of the System Open Market Account (SOMA) portfolio also imposes an implicit aggregate limit. For example, the initial limit on the amount each counterparty could invest was set to $30 billion, it was raised to $80 billion in March 2021, and then to $160 billion in September 2021.[13]

Stress events since the introduction of ON RRP are instructive for considering these channels and potential lessons for a CBDC. As shown in Figure 1, the ON RRP take-up spiked in March-April 2020 at the outbreak of the COVID-19 pandemic. However, flows to the ON RRP during that stress episode were limited overall, and take-up quickly normalized to levels close to zero. At the same time, deposits, including uninsured ones, increased at a fast rate.[14] Similarly, there is limited evidence that the ON RRP contributed to the banking stress of March of 2023. While some regional and small banks suffered a contraction in their deposit base, ON RRP take up declined in the first week following the onset of the crisis. These episodes indicate that there is little evidence to date for the first channel, described above through which ON RRP had destabilizing effects.[15]

[12] A full allotment facility is limited by the overall size of the Federal Reserve's balance sheet. In the highly unlikely event that the ON RRP demand exceeds the amount of available securities, awards will be made at the rate at which this size limit was achieved (the stop-out rate), with all propositions below this rate awarded in full and all propositions equal to this rate awarded on a pro rata basis. See https://www.newyorkfed.org/markets/rrp_faq.

[13] Initially the facility also had an exogenously set aggregate limit of 300bn, which was removed in December 2015. Before its removal, the aggregate cap was reached once in September 2014.

[14] The increase in take-up that started occurring in March 2021 is not related to flight-to-safety episodes and, thus, not relevant for financial stability.

[15] See Logan (2021) for a similar conclusion. We should note, however, that the March 2020 episode was primarily a liquidity event that found banks with strong capital and liquidity position. Movement from bank deposits to ON RRP amid stress driven by concerns about bank credit quality might look different.

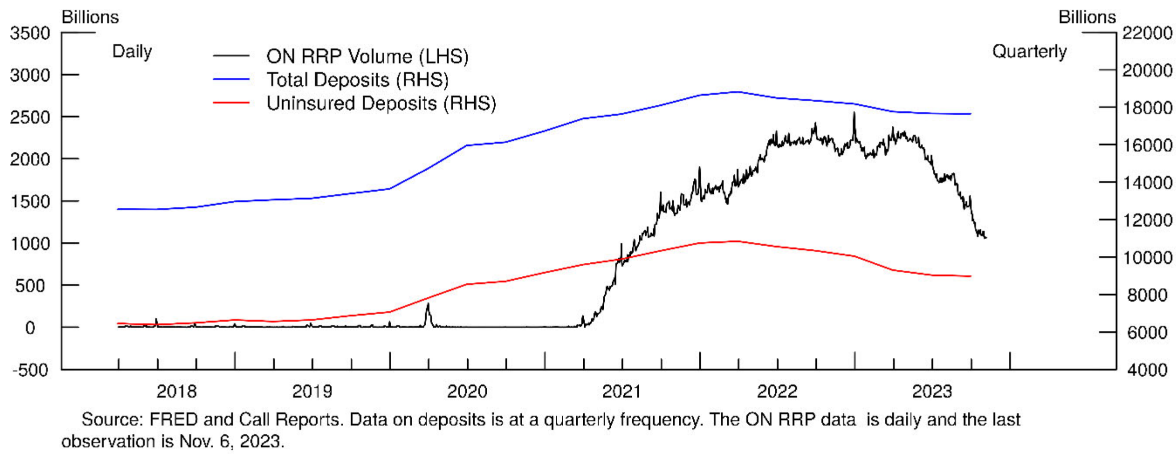

Figure 1: ON RRP and Deposit Flows

The second channel briefly emerged during the COVID episode but was not quantitatively strong nor persistent. As shown in the left panel of Figure 2, prime MMFs' holdings of certificate of deposits (CDs) and commercial paper (CP) fell while ON RRP take-up briefly increased along with Treasury holdings. Quickly, ON RRP take-up returned to previous levels while Treasury growth continued. The right panel of Figure 2 shows a similar pattern for government MMFs.

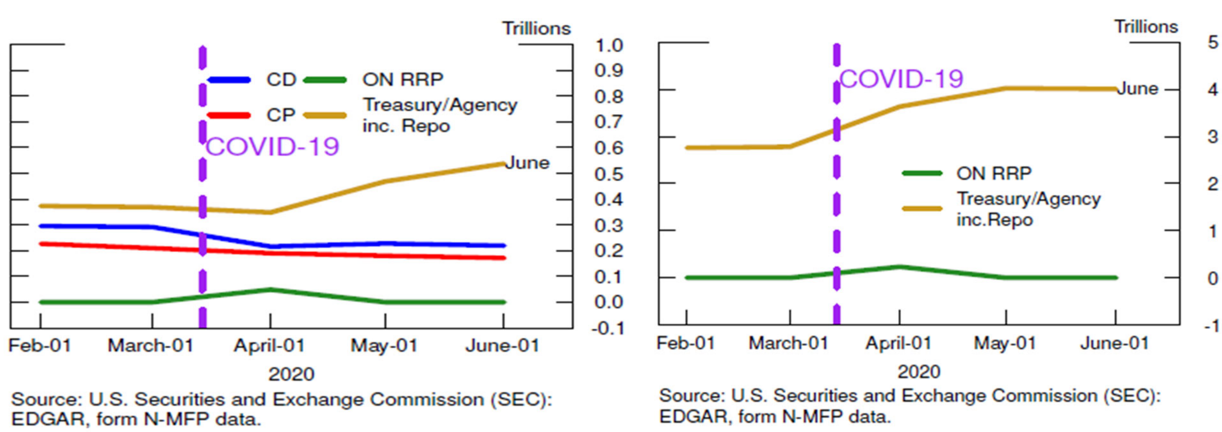

Figure 2: MMFs Exposures

One possible explanation why the second channel, described above, was relatively weak was because there were liquid and safe alternatives, namely Treasuries, yielding a higher rate. While the ON RRP rate and the yield on four-week Treasury bills fell after the COVID-19 shock, Treasury bill yields traded relatively higher than the ON RRP rate, and Treasuries could absorb the extra demand for safety (Figure 3). It is conceivable that the second channel could have been stronger if the supply of Treasuries could not satiate the demand for safety, pushing Treasury yields down, potentially to negative territory, and making ON RRP more attractive.

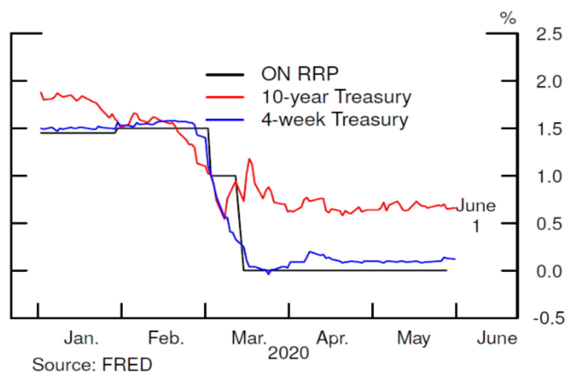

Figure 3: ON RRP and Treasury yields

The key drivers of the run on prime MMFs were the COVID-19 shock, the liquidity transformation activities performed by prime MMFs, and the adverse effect of existing regulations such as gates tied to a fund's liquidity position.[16] The ON RRP may have facilitated a modest portion of the outflows from prime MMFs and inflows towards government MMFs, but other factors may also have contributed to or rather facilitated the run. In particular, the switching costs for investors to move their funds out of prime MMF to other vehicles have been found to be important factors for run intensity.[17] For example, fund families with relatively higher

[16] See Li et al. (2021).
[17] See Cipriani and La Spada (2020).

specialization in government MMFs saw greater outflows from their prime MMFs into their government funds, both for institutional and retail investors.

Lessons for CBDC

There are at least three lessons helpful for thinking about financial stability risks from a CBDC. First, addressing the source of funding risks at the institutional level may be effective at mitigating financial stability concerns from a flight-to-safety. Prime MMFs experienced severe runs but strong capital and liquidity positions of banks were likely the reasons why confidence in large banks was never seriously shaken and large uninsured depositors did not move their funds from large banks to government MMFs with access to the ON RRP. While the stress episode of March 2023 does suggest that some smaller and less creditworthy banks are subject to depositor runs, the role of the ON RRP in attracting them is limited.[18]

Second, the rate of remuneration on CBDC during crisis is crucial. As discussed above, ON RRP take-up likely was limited during the pandemic because the ON RRP rate was set to zero, making it less attractive relative to other safe alternatives. Because some potential CBDC design features may offer benefits to holders that are not provided by other money market instruments and ON RRP balances, the remuneration rate on a CBDC may need to be considerably lower than in normal times to discourage a flight-to-safety during a crisis. Holding limits on CBDC may also be useful.

Third, as suggested by the experience of prime MMF during March 2020, low switching costs may facilitate run episodes on banks and other institutions investing in money-market instruments. One distinct difference between CBDC and ON RRP is that the former, if introduced,

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[18]The Federal Reserve issued an after-action report on bank and supervision shortcomings follow the failure of SVB. See https://www.federalreserve.gov/publications/files/svb-review-20230428.pdf.

would be designed as a settlement asset and this is not the function of the latter. The potential features of CBDC or its supporting infrastructure that could make it attractive, such as enabling fast payments, facilitating interoperability, and provision of wider access to digital central bank money, could dramatically reduce the switching costs from both deposits and money-market instruments and lead to much faster runs.

2.3 Recent Episodes of Traditional Bank Runs

Recently, there have been limited cases of traditional banking panics that could have had systemic-wide implications. Two salient examples are the run on the Greek banking system during the European sovereign debt crisis and the banking stress in March 2023 in the United States. These episodes provide a good example of how a run may materialize at a slow pace, with high switching costs from bank deposits to other alternative stores of value, including physical currency; or in a matter of a days when switching costs are low and depositors are connected to one another. The first example suggests that imposing switching costs from deposits to CBDC may slow the pace of a run, but it cannot eliminate them altogether. The second example suggests that reduced switching costs and fast convertibility offered by a CBDC may have the potential to further exacerbate runs.

The Greek case materialized amid concerns over "Grexit", as Greek bank deposits fell by just over 30% from 2010-2012 and by a further 25% from 2014-2016. In this instance, the deposit run off was slow moving. Most Greek residents had to rely on domestic banks or physical banknotes to store their liquid wealth and to make and receive payments, while only larger firms and wealthier individuals already had or could easily establish bank accounts in other countries.[19]

[19] See, for example, Artavanis et al. (2019).

Figure 4 plots the withdrawal of deposits along with the spikes in cash holdings. Note that after the imposition of capital controls in June 2015, demand deposits started mechanically increasing and available cash started mechanically falling.

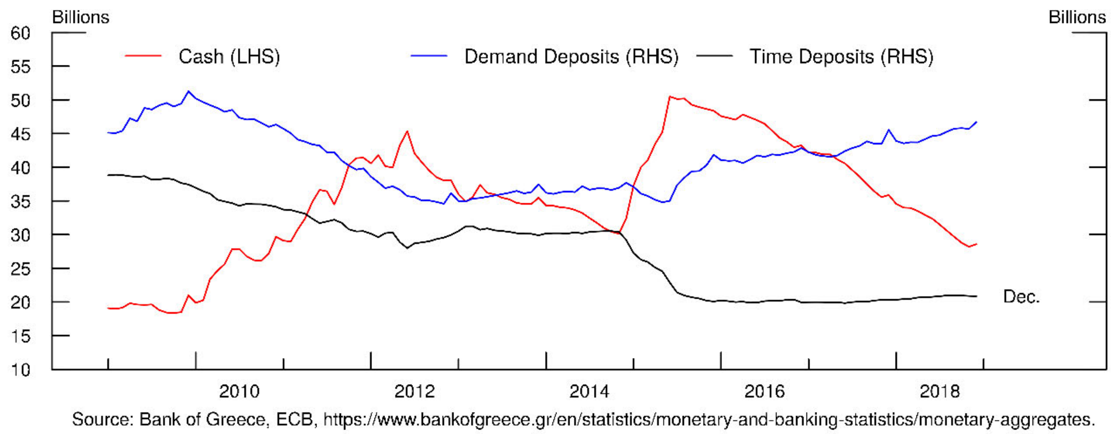

Figure 4: Cash and Deposit Holdings during Greek Crisis

While interest paid on deposits may have been a reason why retail depositors kept their money at Greek banks, another important factor governing the slow exodus of deposits from banks was likely high switching costs. Withdrawing funds deposited at a bank to hold physical currency had considerable switching costs. In fact, storing cash in a security box at a bank was expensive, while individuals who withdrew large amounts of cash were a common target of house robberies and individual assaults. An additional switching cost from bank deposits to cash was the length of time needed to obtain physical currency from a bank. Depositors had to call their banks several days in advance so that the bank could bring in the required cash.

The more recent case of the banking stress of March 2023 shows a dramatically different environment, which resulted in deposit runs that were extraordinarily fast and large. Rose (2023) documents that the runs on Silicon Valley Bank (SVB) and Signature Bank materialized in a matter of one or two days. In contrast to the Greek stress, confidence in other U.S. banks remained strong. Depositors willingly transferred deposits to other banks, which they were able to do quickly. Sectoral or other interconnectedness of the banks' depositors facilitated a particularly rapid and coordinated withdrawal. While the concentration of uninsured depositors was a particularly salient issue during this bank run episode, it underscores how the availability of a safe store of value with seamless and immediate convertibility can quickly destabilize banks. The introduction of CBDC mighty similarly accelerate runs through any removal of payments frictions its transfer system entails and, perhaps more uniquely, through provision of a safe alternative that is not dependent on continued confidence in the wider banking sector.

Lessons for CBDC

While the parallels with the potential effects of a CBDC are imperfect, the Greek and March 2023 episodes illustrate how switching costs impact runs. In both cases, conditions prompted a desire to run from banks that were deemed illiquid or in danger of being insolvent. In the case of Greek banks, depositors that faced low switching costs to readily available alternatives left those banks quickly. Individuals who faced high switching costs still migrated from deposits to those other alternatives, but more slowly. Slower runs can give policy makers sufficient time to act to prevent undesirable outcomes. The case of March 2023 is a cautionary tale of how low switching costs and ease of convertibility can exacerbate incentives to run, and how bank runs can materialize from one day to the next. A CBDC has the potential to substantially reduce switching costs and withdrawal times compared to redeeming in physical currency. As a result, runs on uninsured or very large deposits at banks or other financial institutions may materialize in a very short time leaving little scope for policy intervention.

3. Mechanisms

In this section, we analyze the mechanisms through which a CBDC can affect financial stability, focusing on the following three broad topics:

1. How would a CBDC affect the run dynamics on financial institutions?
2. How would a CBDC affect the credit provision by banks in times of crisis?
3. How would a CBDC help address financial stability risks from stablecoins?

While investigating these questions, we discuss both the negative and positive implications of a CBDC for financial stability. We discuss separately the positive effects of CDBC on stablecoins, as the digital nature of CBDC could bring additional benefits for them.

The design choices for a CBDC matter for its properties as a safe haven asset in times of crisis. We follow the four design recommendations provided by the Federal Reserve's discussion paper: (i) privacy protected; (ii) intermediated; (iii) widely transferable; and (iv) identity verified.[20] Apart from these characteristics, we consider a CBDC that could be, in principle, held by any institution or individual, and that can be interest-bearing.[21] Throughout our analysis we assume that an intermediated CBDC can be held directly by institutions or indirectly by individuals through wallets provided by institutions or segregated accounts at custodial institutions.[22]

[20] Board of Governors of the Federal Reserve System (2022), "Money and Payments: The US Dollar in the Age of Digital Transformation," *Discussion Paper*, January 2022.
[21] Access restrictions, holding or transaction limits, and the level of CBDC remuneration are important policy tools—rather than rigid design choices. Such tools can mitigate potential effects of a CBDC on financial stability and will be examined in Section 4.
[22] In our analysis a CBDC is a liability of the central bank that is distributed/allocated/transferred to the public with the help of institutions rather than via direct individual accounts at the central banks without restriction on the type of entities allowed to hold it. We do not judge whether the set of institutions that may hold it directly for themselves or intermediate it for others differs from current statutory limitations on provision of Reserve Bank accounts and services.

3.1 How would a CBDC affect the run dynamics on traditional financial institutions?

Financial institutions that fund illiquid assets with liabilities redeemable on demand at par are said to engage in liquidity transformation and are exposed to the risk of runs. To analyze the effect of the introduction of a CBDC on such run risk, we consider a stylized model which embodies the following elements:

- Financial institutions are funded by runnable liabilities.
- The runnable liabilities can have money-like attributes and provide payment services besides their role as a store of value.
- On the asset side, financial institutions hold both safe/liquid and risky/illiquid assets.
- Concerns about negative returns on the risky assets can result in self-fulfilling runs whereby holders of runnable liabilities withdraw their funds out of fear that others will do the same.

The model description and analytical results we derive can be found in the Appendix. The model is a modified version of the bank run model in Goldstein and Pauzner (2005).[23]

We examine various channels through which a CBDC can affect run risk at financial institutions that engage in liquidity transformation. We should note that not all channels are equally

[23] Ahnert et al. (2023) also study the effect of CBDC on bank run risk using a similar bank run model. They examine how banks may respond to higher CBDC remuneration by increasing deposit rates, which yields ambiguous effects as banks are able to mitigate run incentives for low enough levels of CBDC remuneration. This mechanism is absent in our model because all bank revenues are distributed to deposits, as in Goldstein and Pauzner (2005), and there is no room for the bank to adjust its profits and deposit rate to mitigate run incentives. Instead, our model focuses on the role of liquidity transformation and payment services of deposits on run risk, which are elements absent in Ahnert et al. and which matter, as we show, for the implication of remunerated CBDC on run risk. See also Schilling et al. (2023) for a nominal bank run model to examine the trade-off introduced by CBDC between bank runs and price stability.

important for every institution, and we provide examples of institutions for which each channel is relevant.

Channel 1: A CBDC provides an attractive option for flight-to-safety

The level of run risk at financial institutions does depends on the degree of liquidity transformation, as measured by the asset share of liquid assets, and on the availability and desirability of an outside option to run to. For example, large uninsured depositors or investors at prime MMFs may redeem their deposits or shares, respectively, and place them in government MMFs, while small retail depositors could also choose to redeem their bank deposits in currency. A CBDC may offer a more attractive alternative, which could intensify the risk of runs at financial institutions.

The attractiveness of CBDC as a safe haven does not only accrue from the safety inherent in a CBDC, but also from other important characteristics, such as the payment services offered by a CBDC, the low cost of switching to and from CBDC, and the interest rate that the central bank may choose to pay on CBDC holdings. For example, large uninsured depositors may find it more convenient to hold CBDC during a crisis compared to transferring deposits to an alternative bank or investing funds in government MMFs, given that switching costs to CBDC could be smaller and that the CBDC could be used directly for transactions. Both benefits can be considerable. The few available studies on the subject suggest that switching costs for moving one's deposits to another bank are not negligible; a CBDC could effectively reduce such costs.[24] Moreover, the incremental benefit of using CBDC in transactions could be approximated by the difference

[24] Shy (2002) uses Finnish banking data with a simple calibration method. The estimated switching costs for moving one's deposits into another bank account for between 0% to 11% of the average balance a depositor maintains with the bank. Stenbacka and Takalo (2019) also use the same method with more recent Finnish deposit market data. Their estimated switching costs are approximately 50% higher than that of Shy (2002). Kim et al. (2003) use Norwegian banking industry data and estimate the magnitude and significance of switching costs. The point estimate of the average switching cost is 4.1%, about one-third of the market average interest rate on loans.

between 3-month Treasury bills and deposit rates, which may represent the relative convenience yield of the latter. This benefit depends on the level of rates, and in recent years has been around 80 basis points.[25] On top of these characteristics, an attractive CBDC remuneration can increase further the flight-to-CBDC incentives.

We can group these distinct incremental benefits—reduced switching costs, convenience from use in transactions, interest paid on CBDC—together in an aggregate incremental benefit and use the model described earlier to show how run incentives increase as the CBDC becomes a more desirable outside option. We consider three stylized financial institutions that could span the spectrum from prime MMFs, with currently high run risk, to bank-like institutions with currently sufficient liquid assets and low run risk: (i) an institution with high liquidity transformation, (ii) an institution with low liquidity transformation, and (iii) an institution with low liquidity transformation, the liabilities of which can be used as means of payment.

There are a couple of interesting takeaways from this analysis, the details of which can be found in the Appendix. First, not surprisingly, run risk is increasing the attractiveness of the CBDC as an outside option. Second, the incremental increase in run risk is higher for institutions with higher liquidity transformation because these firms hold fewer assets that are liquid in all stress events compared to their runnable liabilities. Third, the destabilizing effect of a CBDC is much smaller for institutions the liabilities of which are useful as means of payment. Taken together, our analysis suggests that the effect on run risk of bank-like institutions with low liquidity transformation is expected to be small. However, the introduction of CBDC may increase run risk at fragile arrangements, such as prime MMFs.

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[25] See Van den Heuvel (2019).

Channel 2: CBDC could affect institutions' reliance on wholesale funding

A CBDC may alter the composition of the liabilities of financial institutions in normal times, affecting both banks and nonbanks.

The introduction of a CBDC may result in a shift in bank liabilities from stable insured bank deposits to other funding sources which may be less stable, should depositors find it more convenient to hold CBDC.[26] Banks are subject to liquidity requirements such as the Liquidity Coverage Ratio (LCR), which broadly requires that a bank's high quality liquid assets (HQLA) are higher than the appropriately weighted runnable liabilities within a 30-days horizon. An increase in non-deposit liabilities may require additional HQLA—depending on existing buffers over the LCR minimum requirement—which would decrease bank profitability and increase the cost of intermediation (see section 2.2). But the effect on banks' run risk may be muted, especially if the composition of HQLA is tilted to short-term liquid instruments such as reserves.[27]

Nonbanks may find it more expensive to raise secured wholesale funding should investors find that CBDC offers a more attractive safe investment, inducing nonbanks to turn to other, potentially more fragile, sources of wholesale funding. The implications of this shift may not be prohibitively high during normal times. Yet, it can have an adverse effect on financial stability if institutions enter a crisis with a higher share of runnable liabilities.

A contrarian argument suggests that the introduction of a CBDC, especially if remunerated, has the potential to satiate the demand for safe assets and suppress convenience yields of private

[26] For example, Whited et al. (2022) show that banks can replace a large fraction of deposits with wholesale funding, making banks' funding costs more sensitive to changes in short-term rates.

[27] We should note that the LCR weights for short-term liabilities were calibrated according to run-off rates absent a CBDC. The weights capture the haircuts applied to various short-term liabilities that enter the calculation of the LCR, determining the amount of HQLA needed to support a dollar of runnable liabilities. Should a CBDC render some short-term liabilities more prone to runs, adjustments to LCR calibration may be needed to neutralize the effect of a compositional change in institutions' liabilities on run risk and, thus, on financial stability.

short-term liabilities. As a result, incentives for financial and non-financial firms' potentially excessive reliance on short-term funding could be eliminated, enhancing financial stability. See Carlson et al. (2016) and Greenwood et al. (2016)_for a non-CBDC specific exposition of this argument. We should note that the ability of the central bank to satiate the demand for safe assets depends on how it sterilizes the issuance of CBDC. If CBDC issuance is accompanied by purchases of Treasury bills by the central bank, or by just replacing banks' reserves, then the net effect on the supply of publicly issued safe asset would be small, potentially close to zero.[28]

Channel 3: CBDC could enhance liquidity management at institutions

Although banks and certain nonbanks have access to central bank facilities, such as master accounts or the ON RRP, many other financial institutions do not. These institutions nonetheless may have large and variable dollar payment needs to manage for which they must rely on other institutions. A CBDC could widen access to a risk-free store of value and settlement asset and could enhance the ability of some financial institutions to manage their liquidity. If such widened access included foreign institutions and/or close interlinking with other central banks, CBDC could be a catalyst for cross-border and cross-currency liquidity risk management benefits. This potential benefit, however, does not appear unique to CBDC, but rather is a function of access to digital central bank liabilities and payment services more generally. Similarly, any negative tradeoffs attributed to expansion of allowable access would also be equally relevant to CBDC.

Using the same model described earlier, we can re-evaluate the effect of the introduction of a CBDC on run risk, considering that some of the CBDC benefits, such as remuneration and payment services, accrue to financial institutions holding it as a liquid asset in their portfolios. The

[28] This underscores the importance of how the central bank *recycles* CBDC inflows back to the economy. See Infante et al (2023) for a detailed discussion.

risk of runs may continue to increase with CBDC benefits, but it could be lower than it would have been if the institution did not hold CBDC, especially for institutions with low degree of liquidity transformation, because the institution's liquidity position also improves through the benefits offered by CBDC. In certain cases, the benefits offered by a CBDC may even dominate the adverse effect on run incentives and run risk may be lower compared to the case that the institution does not derive additional benefits from holding CBDC among its liquid assets.

Channel 4: CBDC could provide policymakers with valuable information during a run

CBDC could provide policy makers with valuable information that can be used to ameliorate undesirable outcomes stemming from a flight-to-safety. One potential example is related to the ability of the central bank to monitor the flow of funds into CBDC in real time. If such monitoring allowed policymakers to identify and resolve weak banks sooner, it could increase depositor confidence, making them less prone to running on the banks.[29]

3.2 How would a CBDC affect credit provision by banks in crisis?

As discussed earlier, a permanent shift of funds from deposits to CBDC may require banks to rely on riskier or more expensive wholesale funding markets to a greater extent than they currently do. A greater reliance on wholesale funding relative to deposits could increase the cost of funds to banks.[30] In turn, banks may increase their lending rates, affecting credit availability across the economy.[31] As a result, the introduction of a CBDC might restrict banks‘ ability to extend credit, resulting in either a reduction in overall credit or in disintermediation of the banking sector.[32] Such

[29] See Keister and Monnet (2022).
[30] Wholesale funding that is secured by HQLA is not necessarily a more costly source of funding for banks than deposits, as that depends on their relative convenience yields and the perceived safety of deposits, if uninsured.
[31] See Keister and Sanches (2022).
[32] The analysis below assumes that banks pass-through the increase in funding costs in times of stress from a flight-to-CBDC to borrowers. However, Chiu et al. (2022) show that if banks have market power in the deposit market, a

concerns may be more significant in a stress event. Banks that experience a loss of their deposits to CBDC during crisis have a set of options to substitute for lost funding. For example, they could resort to the discount window or turn to secured or unsecured wholesale funding markets. Banks could also decide to raise long-term debt or retain more of their earnings to boost their equity

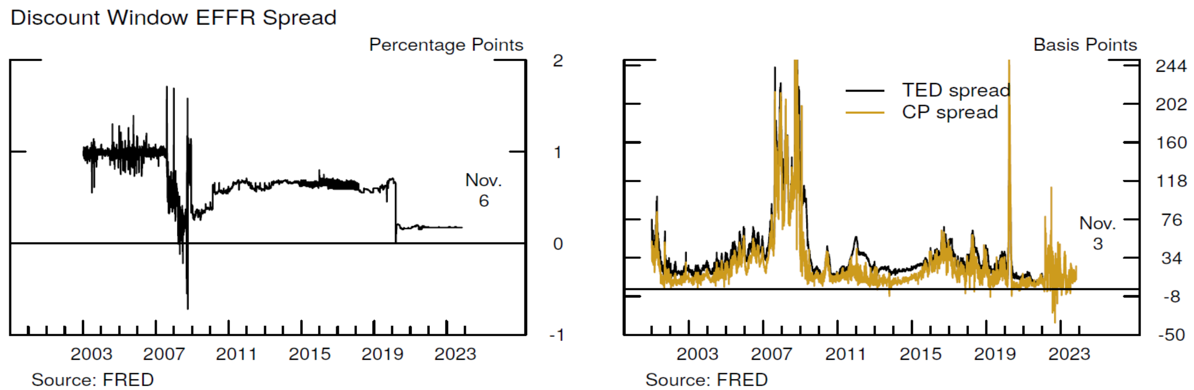

Figure 5: Borrowing Costs in Stress Times

funding, even though doing so might be costly or impossible during times of stress.[33] Figure 5 shows the incremental pecuniary cost of borrowing from the discount window or wholesale funding markets over short-term safe rates—left and right panel, respectively, over the past two decades. Both costs are not negligible, and we will consider them under different scenarios.

Consider a severe stress event that finds banks well capitalized and with adequate liquidity. As already mentioned above, we do not consider cases that banks are the source of the stress because the resulting drop in credit extension could be then better attributed to insufficient banking capital leading to a credit crunch, rather than to a CBDC. Moreover, credit extension may fall because of higher risk premia reflecting the lower growth prospects. What we are interested in is the

CBDC can enhance competition, expanding intermediation. We should note that their results may apply better to normal times rather than crisis, which is the focus herein.

[33] However, banks may not have earnings or be in a position to raise fresh equity, as was the case during the 2007-2009 financial crisis. In such circumstances, banks may need to deleverage, which significantly reduce credit supply. We do not examine this case, because the cause of deleveraging would arguably not be a CBDC but rather solvency concerns at banks, which is an important but separate issue.

incremental effect of a deposit flight-to-CBDC on credit extension. Thus, our estimates should not be regarded as capturing the total effect on credit extension during times of stress, but rather the incremental effect due to the introduction of a CBDC. We consider three possible scenarios.

- In the first scenario, banks borrow from the discount window at an extra cost of about 50 basis points, which is the conditional mean during crisis periods in the last two decades.
- In the second scenario, banks make up for their lost deposits with various types of wholesale funding, with an average additional cost of about 100 basis points.[34]
- In the third scenario, banks substitute lost deposit funding with unsecured wholesale funding, reaching an additional cost of funding of about 250 basis points, which is the upper end of the historical realization during the 2007-2009 financial crisis.

Table 1 reports the incremental effect of banks' increased cost of funding on the volume of bank lending due to a flight-to-CBDC in times of stress. Our focus is on the effect of a marginal loss of deposits to CBDC, which banks substitute with costlier funding. That is, if banks had to make up for a dollar of deposits directed to lending in times of stress with more expensive funding source, then they would borrow less and extend less credit to be able to charge a higher lending rate, compensating for the higher funding costs. Implicitly, we assume that banks would extend new credit in times of stress first using deposits, then using the discount window or wholesale funding. These cases span our scenarios. The situation might be different in the steady state whereby some lending would be supported by equity; thus, the effect of a marginal loss of deposits on credit supply would have to be weighted by their share in total funding sources.

[34] This estimate is based on Bassett and Rappoport (2022) who compute a comprehensive cost of short-term wholesale funding—as defined in the US implementation of the capital surcharge for globally systemically important banks—which includes: (1) secured funding transactions; (2) unsecured wholesale funding; (3) covered asset exchanges, (4) short positions, and (5) brokered deposits.

We assume that banks would pass-through the extra cost to borrowers rather than absorbing part or all of it, which would directly reduce their profitability. As such, the estimates for the decline in credit provision reported in Table 1 could be regarded as a lower bound.

We examine the effects on different types of loans using estimates for the semi-elasticity of loan demand to interest rates from the literature.[35] Scenario two or a scenario in-between two and three are arguably the most likely ones, implying, for example, a decline in C&I loan provision between two and five percent in times of stress.[36]

Well-capitalized banks can be a source of stability by providing liquidity to struggling firms through the provision of lines of credit.[37] However, adverse effects on their willingness to provide such credit during a stress event, owing to higher funding costs from introducing a CBDC, could amplify a stress event. The combination of a potential flight-to-CBDC by depositors with a higher reliance on riskier wholesale funding may render the provision of credit lines unprofitable ex ante, resulting in lower liquidity insurance and instability during a crisis.[38]

	% Change in lending for deposits' flight-to -CBDC		
Type of credit	Scenario 1	Scenario 2	Scenario 3
Mortgage credit *Semi-elasticity of demand about 2.5* *(De Fusco and Paciorek, 2017)*	-1.25%	-2.50%	-6.25%
C&I loans *Semi-elasticity of demand about 2*	-1.00%	-2.00%	-5.00%

35 The semi-elasticity of loan demand to interest rates captures the percentage decline in loan demand for a one percentage point increase in interest rates; these elasticities are not exclusively derived for crisis periods.
36 The effect of deposit substitution on credit provision should be considerably lower in normal times. Considering an average TED spread of 30 basis points during normal times—spamming from 2010 to 2019—and a maximum deposits run-off rate of 40 percent, we obtain an increase in the average cost of funds of 12 basis point, which implies a decline of 0.30, 0.24, and 0.62 percent in mortgage credit, C&I loans, and consumer credit, respectively.
37 Li, Strahan, and Zhang (2020).
38 See, also, Piazzesi and Schneider (2022).

(Bassett et al., 2014)			
Consumer credit *Semi-elasticity of demand about 5.2* *(Gross and Souleles, 2002)*	-2.60%	-5.20%	-13.00%

Table 1: Decrease in Lending during Stress Times

3.3 How would a CBDC affect financial stability risks from stablecoins?

Despite aspirations to be potential alternatives to national currencies, cryptocurrencies like Bitcoin have exhibited extreme price volatility measured in dollars, which makes them ill-suited to become a medium of exchange or a consistent store of value. Stablecoins emerged to attempt to solve this problem. Stablecoins serve as relatively stable store of value within the crypto space, offer lower-cost entry and exit points to crypto markets, and are the main collateral asset for leveraged positions in the digital asset ecosystem.[39] However, stablecoins have been prone to runs, either because of their structure or because of doubts about their backing.[40]

A widely accessible CBDC might help to mitigate the instability introduced by stablecoins, as it could supplant relatively risky stablecoins or improve the quality of some stablecoins' reserve assets.[41] However, stablecoins that support use cases outside the scope of uses of CBDC—such as facilitating leveraged position in the digital asset ecosystem—would likely continue to develop, potentially outside the regulatory perimeter absent requirements and enforcement.

A CBDC may alternatively enhance financial stability by improving the quality of stablecoin reserve assets. If stablecoins were backed one-to-one by CBDC, they would not be as

[39] Gorton et al. (2022).
[40] See Azar et al. (2022) for a review of financial stability risks in the digital asset ecosystem, including stablecoins.
[41] See, among others, Gorton and Zhang (2021).

susceptible to runs, though CBDC would not mitigate issues arising from legal, custodial, or operational concerns.[42] Stablecoin issuers might then compete on technical innovation rather than on relative perceived capacity to redeem. The introduction of a CBDC to which stablecoin issuers had large-scale access thus could encourage the development of private stablecoins. Potentially, stablecoins arrangements may prefer CBDCs to other alternatives such as Treasury bills or even ON RRP or a master account at the Federal Reserve as a source of safe assets. If the design of a CBDC offered greater interoperability within the digital asset ecosystem than these alternatives, it could reduce transaction costs when moving between digital and traditional financial platforms and allow for more efficient settlement of digital transactions. Relatedly, depending on design choices related to information management, CBDC transaction records could be made publicly observable in real time, improving transparency of those stablecoins‘ reserves.

4. Policy tools to address financial stability concerns of CBDC

A variety of tools may be available to address the financial stability concerns associated with a potential disruptive flight to safety introduced by a CBDC in times of stress. All the tools proposed by academics and policy makers alike attempt to limit the desirability of CBDC during a crisis by reducing its appeal or availability as a store of value. We focus on two broad categories: (i) price tools, under which the central bank controls the remuneration on CBDC, and (ii) quantity tools of various types, including tools limiting the balances of CBDC that holders are allowed to maintain in their wallets/accounts. Such tools are integral to the design adopted by the central bank to issue, distribute, and implement policies pertaining to CBDC in accordance with achieving its mandate. Specifically, the tools discussed below could be implemented in a manner that is compatible with

[42] Consistent with earlier discussion of firm liquidity risk management, access to a CBDC, granting a master account at the Federal Reserve, or giving access to the ON RRP could all have similar implications for stablecoin stability.

the design choices for a CBDC recommended by the Federal Reserve's white paper and are feasible through two additional design choices: (a) remuneration, and (b) programmability.

Designing a CBDC to be remunerated enables the adoption of price tools to discourage a flight to safety in times of stress. Designing a CBDC to be programmable may provide built-in rules that constrain its use.[43] With respect to financial stability, a programmable CBDC potentially can overcome implementation hurdles associated with certain quantity tools as well as enable a novel category of tools.

Table 2 summarizes the set of tools examined in the remainder of this section, highlighting the effect of each tool on financial stability as well as possible undesirable side effects.

[43] Two natural components of the definition of programmable money are a digital form of money and a mechanism for specifying the automated behavior of that money through a computer program. See Lee (2021) for more details on programmable money.

Tool	Type of tool	Effect on run incentives	Potential Adverse Side effects
Tiered Remuneration	Price tool	Discourage flight-to-safety for moderate stress levels	Discourage use of CBDC as a medium of exchange during a crisis if not implemented properly
Access limits	Quantity tool	Reduce risk of runs originating from the entities on which the restrictions are placed	Harm the medium of exchange role of CBDC, increase the incentives for regulatory arbitrage
Transaction size limits	Quantity tool	Discourage flight-to-safety for moderate stress levels	Discourage use of CBDC as a medium of exchange if not implemented properly
Holding limits	Quantity tool	Prevent hoarding of CBDC above the limits in all instances	Ineffective if the limit is not chosen adequately for different entities; regulatory arbitrage; amplification of runs if set at aggregate level
Convertibility limits	Quantity tool	Stop a run if their implementation is unanticipated	Pre-emptive runs; multiple secondary markets for CBDC

Table 2: Tools to Mitigate Flight-to-CBDC

We study the ability of each potential tool to mitigate harmful runs on financial institutions during times of crisis. We highlight the possibility of calibrating these tools differently during normal times and crisis times to avoid restricting CBDC demand during normal times. No tool is individually superior to others, and each tool introduces trade-offs with respect to its costs, benefits, and ease of implementation.

Finally, we discuss the tools that the Federal Reserve could deploy to safeguard financial stability from a surge in demand for CBDC that can potentially disintermediate the financial system.

4.1 Price tools relevant for interest-bearing CBDC

The first category of tools addresses the financial stability concerns of a flight-to-CBDC by directly targeting the interest rate of a CBDC. We refer to such tools as price tools, which can be made state-contingent to more efficiently target flight-to-CBDC concerns in times of stress, while preserving the attractiveness of CBDC in normal times.

The simplest form of such tools is a single-tiered remuneration scheme, where the interest rate on CBDC holdings is the same irrespective of the amount of CBDC. According to this scheme, the interest rate on CBDC holdings needs to be sufficiently low to make CBDC relatively unappealing and to discourage a potential flight-to-safety in times of stress. Importantly, a CBDC would provide transaction services and other benefits, in addition to interest payments. As a result, dissuading a run to a CBDC may require a negative interest rate, potentially very low in some cases, highlighting how a CBDC design that did not include interest payments—that is, a zero percent interest rate on CBDC holdings—may not be sufficient to limit run risks. Significant or rapid rate changes, particularly into negative territory, may also discourage use of CBDC as a medium of exchange, which may further deter a flight-to-CBDC but may worsen welfare if CBDC payments are valuable in times of stress.

A more elaborate price tool is a two-tiered remuneration scheme, where CBDC holdings below a threshold, or in the first tier, are remunerated at a higher interest rate than those above the threshold, or in the second tier.[44] The interest rate differential between larger and smaller CBDC holdings aims to discourage large holdings of CBDC as a store of value in times of market stress while minimizing effects on its role as medium of exchange. In times of severe stress, sizeable negative rates may be required to prevent a flight-to-CBDC, regardless of tiering.[45] For moderate stress scenarios, however, two-tiered remuneration might reduce the likelihood of a flight-to-CBDC. This type of tiered renumeration would mimic the price elasticity of the demand for other safe haven assets. Hence, all else equal, the likelihood of a run on financial institutions induced by a flight-to-CBDC is lower.

When implementing a two-tiered remuneration scheme for CBDC, selecting the threshold separating the first from the second tier might be challenging. In fact, the choice of threshold by the central bank requires significant investment in gathering information about the interest-rate elasticities of the different entities and individuals holding CBDC. Institutional investors and retail depositors may have different needs for transactions, thus a universal threshold might be inadequate to deter runs for both types of investors while allowing them to use CBDC for transactions. Moreover, the potential financial stability benefits of CBDC described above, for example those related to improving the safety of the stablecoin industry, would be constrained by the imposition of such universal threshold. In these cases, a version of a tiered remuneration scheme based on voluntary remuneration targets (VRT) can provide a solution.[46]

[44] See Bindseil et al. (2021). Note that this remuneration scheme could be designed with multiple tiers.

[45] It is worthwhile to note that for depositors who can hold cash, a natural constraint on the remuneration rate for the second tier is given by the remuneration rate of their outside option, such as cash. Thus, lowering the remuneration rate on the second tier would be ineffective at discouraging the run if depositors want to run to cash and there are no other limits on their ability to do so. The introduction of a CBDC, however, is not relevant for this type of runs, which could occur even in absence of a CBDC. Moreover, note that cash may only be a viable outside option for low enough deposit balances.

[46] A VRT is a form of tiered remuneration where CBDC holders communicate to the central bank a target for their desired CBDC holdings and must pay a penalty should they miss it. Because holdings below the target are

Finally, it should be noted that even the simplest form of CBDC remuneration poses significant challenges for policy implementation. Accurate estimates of the elasticity of CBDC demand to its remuneration will depend on its uses, which, in turn, are intrinsically linked to its design features and to the evolution of the broader payment landscape.

4.2 Quantity tools relevant for interest-bearing and noninterest-bearing CBDCs

The second category of tools addresses the financial stability concerns of a flight-to-CBDC by placing scale restrictions on activities that users can undertake with a CBDC. We refer to such tools as quantity tools.

4.2.1 Access limits

Who may access CBDC is a key question that likely will be determined by the intended purpose of the CBDC along with other legal considerations not examined in this paper. Access policy choices will also directly shape who has an option to run into CBDC in stress. To the extent that withdrawals by specific entities are more likely to trigger a run on banks or other financial institutions, prohibiting those entities from holding CBDC would reduce risk of runs. For example, prohibiting institutional investors from holding CBDC would result in a reduced risk of banks and MMFs experiencing runs from large institutional deposits/investment.

4.2.2 Transaction size limits

Transaction size limits would constrain how much CBDC can be sent in a single payment. Such limits are common features of payment systems. In principle, there could be multiple, differentiated CBDC payment systems as is the case for balances in Reserve Bank accounts, where

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remunerated at the higher rate on the first tier while those above the target at the lower rate on the second tier, CBDC users have an incentive to choose a non-zero target. At the same time, the penalty for missing the target incentivizes users to set a target equal to their expected holdings. See Baughman and Carapella (2020, 2023).

transactions occur using multiple small and large value payment systems depending on the needs of the sending and receiving banks.[47] As in existing payment systems, a key rationale for potentially limiting the size of individual transactions using CBDC is to prevent or detect and to lessen the consequences of accidental or fraudulent transfers, or of cyber attacks.[48] An additional perspective on transaction size limits is that they can be in practice equivalent to access limits, yet less distortionary. If desired, reasonably small transaction size limits could allow individuals and commercial entities to use CBDC efficiently for a variety of consumer and commercial purposes while substantially reducing CBDC's usefulness for financial institutions' broader financial sector activities. Hence, financial institutions might be discouraged from holding large quantities of CBDC due to the inconvenience of using it in large amounts. Such a transaction size limit would be less distortionary than an access limit, as it would still be possible for financial institutions to hold, send, and receive CBDC making smaller payments: use would not be prevented, but simply impractical for large, financial market purposes. Nonetheless, transaction size limits would not affect the usefulness of CBDC as a store of value in times of stress and, thus, would likely not be useful to deter widespread runs in times of severe stress.

4.2.3 Holding limits

Holding limits are restrictions on the amount of CBDC that individuals or entities can hold or trade.[49] Similar to ON RRP caps discussed earlier, holding limits can be individual or aggregate.

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[47] For example, the Fedwire Funds Service has a transaction size limit of just below $10 billion and the default transaction limit for the FedNow Service is $100,000 with the option to adjust to up or down with a current ceiling of $500,000. Both Fedwire and FedNow are real-time gross settlement payment systems, but they differ in transaction size limits and other design features to better serve different primary use cases and their respective risk management needs. Similarly, the Reserve Banks also own and operate the National Settlement Service and ACH payments systems, which offer alternative settlement methods to meet user needs.

[48] For example, see Duffie and Younger (2019) and Rubenfeld (2019).

[49] See, for example, Bindseil (2020).

Aggregate limits are a cap on the stock of CBDC outstanding and could control the aggregate outflows from the financial system during times of crisis, thus mitigating the financial stability concerns from runs on financial institutions. They may, however, create incentives for pre-emptive runs as investors may fear that the aggregate limit is reached quickly and that they will not be able to fly to CBDC once the crisis is imminent. For example, an individual depositor may want to withdraw their deposits due to fears that the aggregate limit might be met through redemptions of other depositors, leaving them unable to obtain CBDC unless they withdraw first. By contrast, individual limits, placed at the level of wallet or physical individual/entity, can address run incentives more directly than aggregate limits, as they can be targeted to the typical size of activities of a given wallet/entity. Moreover, individual limits do not link individual run incentives to the probability that others might withdraw CBDC in sufficiently large amounts to meet the aggregate limit. Hence, individual limits would not induce incentives for coordination.

One approach to limit the desirability of CBDC as a safe haven without damaging its role in facilitating transactions would be to carefully calibrate individual holding limits. Such calibration poses challenges similar to the choice of remuneration thresholds for tiered remuneration. Given uncertain demand for CBDC beyond its role as safe haven, setting holdings limits may involve a process of trial and error. For example, the choice of holding limits for financial institutions could be informed by the experience of setting individual limits for other central bank facilities available to nonbanks, such as the ON RRP Facility. Similarly, the choice of holding limits for retail depositors could be set below the deposit insurance limit for bank deposits to minimize the role of CBDC as safe haven.

We should note that quantity limits could be combined with tiered remuneration to further improve outcomes in times of stress. As an example, suppose that the individual holding limit was sufficiently large and above the remuneration threshold separating the two remunerated tiers. CBDC holdings in the higher-remunerated tier could be unremunerated, while those in the lower-remunerated tier could be charged a penalty rate and those above the holding limit would not be allowed. This approach would allow users who would like to transact with CBDC to do so up to the holding limit, though at a cost when balances rose to the level of the lower-remunerated tier. Such costs would discourage transfers into CBDC above the lower-remunerated threshold and deter widespread runs, while allowing the CBDC to facilitate payments.[50]

4.2.4 Convertibility limits

Convertibility limits at the account holder level are restrictions that can be imposed on flows out of financial institutions and into CBDCs. Most simply, they are constructed as a velocity limit, constraining how much can be converted from one type of money to another in a given period of time. A cap on cash withdrawals from ATMs is an example of an existing convertibility limit. The potential drawback of convertibility limits is that they may lead to pre-emptive, slowly unfolding runs as investors may attempt to move funds out of their financial institutions within their convertibility limit. Hence, while convertibility limits might be effective at slowing down the pace of sudden, unanticipated flight-to-CBDC episodes, they may amplify runs triggered by noisy signals about the limit being met, thus contributing to a more prolonged surge in requests of withdrawals.

[50] Effectively, the higher-remunerated tier would be equivalent to an exemption threshold from negative remuneration rates on CBDC. This approach leverages the idea that quantity limits are economically equivalent to tiered remuneration, as the threshold separating the first remuneration tier from the second identifies the quantity of allowed balances held in an individual account or wallet, thus remunerated at a possibly zero net interest rate, while balances above the threshold are remunerated at a –100% rate, thus they're not allowed.

4.3 Implementation Hurdles and CBDC Programmability

Most of the tools described in this section, especially quantity limits, share concerns common to the effective implementation of most monetary and fiscal policies, but also raise some novel challenges.

The first is an inherent time-inconsistency problem of all policies that require commitment by policy makers to carry them through. For example, the central bank may have an incentive to increase CBDC quantity limits in the event of a developing run, in order to avoid damaging the transaction role of CBDC or disfavoring depositors without alternate options to store their wealth safely.[51] If the central bank lacks commitment or credibility to implement certain tools when opposing incentives are present, then investors may anticipate the policy change and their motives to run will be less affected by the quantity limit.[52]

Second, a potential drawback of some quantity tools is the possibility of encouraging the creation of secondary markets for CBDC, which might result in different prices quoted for CBDC and US dollars. If the Federal Reserve cannot ensure one-to-one convertibility of CBDC into other forms of central bank money, the parity among all forms of central bank money would depend on arbitrage. To the extent that price dislocations cannot be traded away in times of stress, there may be different prices for a dollar held in different forms of money. Consider the case of two individuals who would like to hold CBDC but one of them has already reached the holding limit. The two individuals could bypass the holding limit by creating another digital asset, for example a wrapped CBDC.[53] A wrapped CBDC would be a new token, issued by a smart contract that

[51] In this case the policy or the tool is defined to be time inconsistent (Kydland and Prescott, 1977).
[52] For an application to suspension of convertibility to prevent bank runs, see Ennis and Keister (2009).
[53] Wrapped tokens are a way to use cryptocurrencies on blockchains other than the blockchain on which they were originally built, thus proposing a solution to the problem of blockchain interoperability. Wrapped tokens are backed 1:1 by their underlying asset, which is stored in a digital vault.

retains custody of the actual CBDC until the wrapped CBDC is returned. Wrapped CBDC can then be traded in decentralized exchanges or in liquidity pools, where its role as a store of value would be as good as that of actual CBDC.[54] The reason is as follows. If wrapped CBDC was traded below the price at which actual CBDC is traded, then any individual—not facing a binding holding limit—could purchase it, return it to the smart contract to unlock the stored CBDC, thus realizing a profit equal to the difference in prices between the wrapped and actual CBDCs. Note that the actual CBDC is never owned by the individual with a binding quantity limit. Rather, this individual will hold a wrapped CBDC and hence there is no violation of individual quantity limits in terms of actual CBDC.[55]

More generally, all quantity tools could be potentially circumvented by designing securities to be issued and traded outside the purview of policy makers to mimic the forbidden CBDC trade. The issuance and trade of such securities may not be prevented unless policy makers have detailed information about the public's transaction behaviors and payment flows.[56] As a result, a secondary market for CBDC may arise, which might lessen the effectiveness of the quantity tools. Moreover, tools may be difficult to implement adequately. This is particularly true for quantity tools as they require a lot of information about the identity and the activity of CBDC users.

A CBDC designed with programmable features may introduce ways to potentially overcome some of these hurdles. For example, the problem of time-inconsistency can be addressed

[54] We implicitly assume that wrapped CBDC could be minted in distributed ledgers using smart contracts, as wrapped cryptocurrencies are currently minted, and that CBDC also could be traded on distributed ledgers or against tokenized assets that can themselves be traded on distributed ledgers and held in smart contracts. The central bank may find these arrangements desirable to enhance interoperability or to provide an alternative to private stablecoins.
[55] Note that the degree to which counterparty or other additional risks are entailed in this transaction will depend on its specific implementation.
[56] It is worthwhile to highlight that the solution to the problem of regulatory arbitrage requires the tools developed by the literature on (dynamic) mechanism design with hidden trades/actions. Despite this class of problems are hard to solve, policy makers should be aware that proper design of quantity tools should account for the possibility of hidden actions on the side of the agents.

by programming individual limits in CBDC together with costs embedded in the CBDC. While the introduction of such costs would not directly force commitment onto the central bank and policy makers, it would reduce the severity of their time-inconsistency problem by reducing the benefits of bypassing the limits.[57]

4.4 Ex-post tools to preserve financial stability

The tools described so far can be characterized as ex ante tools aimed to promote financial stability by discouraging activities that can endanger it ahead of any stress event. It is also worthwhile to highlight a wide set of ex post tools aimed to preserve financial stability once stress hits. Rather than being specific to the flight-to-safety concern arising from the introduction of CBDC, such tools belong to policy makers' machinery to respond to any financial crisis regardless of the event that triggers it. Discount window lending is an example of such a tool; in the event of a run that causes banks to be illiquid, access to the discount window provides ready access to funding and can therefore help avoid potential insolvency of an individual bank. In general, all the tools traditionally adopted by central banks for crisis response would be available after the introduction of CBDC. The economic mechanisms by which such tools would operate are similar to the mechanisms by which they act in a world without CBDC. The scope of such tools, however, might be broader, as the introduction of CBDC could bring along a new set of assets and operations that were not technologically feasible before.

[57] The literature has suggested additional features for CBDC programmability such as being eligible only for certain transactions during times of crisis, for example purchases of groceries, medical bills and similar goods or services, which would effectively make the CBDC useless to be transferred anywhere else and, therefore, to be hoarded. While not citing CBDC explicitly, see Andolfatto (2020) for an application to market freezes. Notice that this notion of programmability could be enabled within several layers of the CBDC architecture, such as the platform, coin/token, contract, and wallet level, all of which would be characterized by different trade-offs. See Lee (2021).

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A Appendix

We consider a simple bank run model akin to Goldstein and Pauzner (2005) extended to account for both liquid and illiquid asset holdings and payment services offered by deposits similar to Kashyap, Tsomocos, and Vardoulakis (2023).

Consider an economy with three time periods, $t = 0, 1, 2$, one bank, and a continuum of representative, risk-neutral, depositors of mass one. There is no time discount. The bank is fully funded with deposits D, normalized to one, while competition and free entry drive bank profits to zero such that all bank revenues are distributed to depositors similar to Goldstein-Pauzner. The bank invests the deposits in a portfolio of risky and safe assets. The risky asset requires one unit of investment at $t = 0$ and yields a payoff $R > 1$ with probability $\theta \sim U[0, 1]$ at $t = 2$; and zero otherwise. Following Golstein-Pauzner, the risky asset may also be illiquid, such that it yields $\xi < 1$ if liquidated early at $t = 1$ for realization of $\theta < \overline{\theta} < 1$; while it yields R if liquidated early for realization of $\theta \geq \overline{\theta}$. [58] The safe asset also requires an investment of one at $t = 0$, but it is both safe and liquid, such that it delivers a payoff of one at $t = 2$ and can also be liquidated for one at $t = 1$. Denote by ℓ the share of the safe asset in the bank's asset portfolio, which determines the degree of liquidity transformation. We will not derive ℓ endogenously but rather perform comparative statics on it to examine how run risk from a CBDC differs across banks with different levels of liquidity transformation. [59] Deposits carry a convenience yield from payment services at $t = 2$ equal to V, which depositors only reap if the bank survives.

Depositors receive at $t = 1$ a private noisy signal about the realization of θ given by $x_i = \theta + \varepsilon_i$, with $\varepsilon_i \overset{\text{iid}}{\sim} U[-\varepsilon, \varepsilon]$. Given the private signal, each individual depositor decides whether to keep or withdraw their deposits in a manner that we detail below. If depositors withdraw early they forfeit any claim on future bank revenues and just receive the face value of their deposits. If the individual depositor manages to withdraw their deposits successfully, then they can invest the proceeds in a CBDC that promises to repay $\bar{R} \geq 1$ with certainty at $t = 2$ plus a convenience yield equal to $\bar{V}$. If they keep their deposits at the bank, they receive the total payoff from bank investments distributed pro rata among remaining depositors, plus the convenience yield only when the bank is solvent.

Denote by $\lambda \in [0, 1]$ the portion of depositors that withdraw early. Depending on the level of λ, the number of illiquid assets the bank may need to liquidate could drive it to

[58] $\overline{\theta}$ is an exogenously assumed threshold that defines the region of fundamentals ($\theta \geq \overline{\theta}$) where individual depositor never choose to withdraw irrespective of their beliefs about others' action. For $\theta < \overline{\theta}$ individual actions may depend on beliefs about the actions of others.

[59] It would be interesting to introduce bank heterogeneity on different dimensions that could result in different equilibrium ℓ and study how the introduction of CBDC changes these equilibrium levels. We leave this for future work, and focus on the partial equilibrium effects of a CBDC.

insolvency at $t = 2$ or may even result in the bank running out of liquidity to serve all early withdrawals at $t = 1$. We derive these two thresholds for λ below. For the remainder of the analysis, we focus on the case $\theta < \overline{\theta}$. [60]

The available liquidity that the bank has at $t = 1$ after serving withdrawals is given by

$$L(\lambda) = \xi(1-\ell) + \ell - \lambda, \tag{A.1}$$

which implies that the bank runs out of liquidity for $\lambda > \bar{\lambda} = \xi(1-\ell) + \ell$ in which case withdrawing depositors receive their deposits only with some probability according to sequential servicing.

For $\lambda \leq \bar{\lambda}$ the bank has enough liquidity to serve early withdrawals, but doing so may result in lower revenues at $t = 2$. Given that the illiquid asset are liquidated at a discount, we assume that the bank will first use the liquid assets to serve early withdrawals. But after $\lambda > \ell$ it will also liquidate a portion of the illiquid assets equal to $y = [\lambda - \ell]^+ / [(1-\ell)\xi] \leq 1$. The depositors that choose not to withdraw receive pro-rata the bank revenues, but only enjoy the convenience yields if their deposits are repaid in full (recall that all bank revenues accrue to depositors). With probability $1-\theta$, the remaining illiquid assets are worth zero at $t = 2$, and depositors do not enjoy a convenience yield. With probability θ, remaining depositors enjoy the convenience yields only if the pro-rata distributed payoff they receive is higher than one, i.e.,

$$\frac{R(1-\ell)(1-y) + [\ell - \lambda]^+}{1-\lambda} \geq 1, \tag{A.2}$$

or equivalently if $\lambda \leq \hat{\lambda}$ where

$$\hat{\lambda} = \frac{\xi R(1-\ell) - \xi + \ell R}{R - \xi}. \tag{A.3}$$

Then, given θ, the payoff differential for an individual depositor between not withdrawing and withdrawing at $t = 1$ to invest in CBDC is given by:

$$\nu(\theta, \lambda) = \begin{cases} \theta \dfrac{R(1-\ell)(1-y)}{1-\lambda} + \dfrac{[\ell-\lambda]^+}{1-\lambda} + \theta V - (\bar{R} + \bar{V}) & \text{if} \quad 0 \leq \lambda \leq \hat{\lambda} \\ \theta \dfrac{R(1-\ell)(1-y)}{1-\lambda} + \dfrac{[\ell-\lambda]^+}{1-\lambda} - (\bar{R} + \bar{V}) & \text{if} \quad \hat{\lambda} < \lambda \leq \overline{\lambda} \\ -\dfrac{\ell + (1-\ell)\xi}{\lambda}(\bar{R} + \bar{V}) & \text{if} \quad \overline{\lambda} < \lambda \leq 1 \end{cases}. \tag{A.4}$$

[60] As mentioned, if the payoff to the risky technology is R, which happens when $\theta > \overline{\theta}$, no depositor withdraws and $\lambda = 0$ in equilibrium.

Define by $\underline{\theta} = (\bar{R} + \bar{V} - \ell)/(R(1-\ell)+V)$ the solution to $\nu(\underline{\theta}, 0) = 0$ such that an individual depositor withdraws, i.e., $\nu(\theta, 0) < 0$, for $\theta < \underline{\theta}$ even if no other depositors withdrew.

Given the private signal, an individual depositor will update their posterior about θ, which will be uniform in $[x_i - \varepsilon, x_i + \varepsilon]$ and compute the expected payoff differential

$$\Delta(x_i) = \int_{x_i-\varepsilon}^{x_i+\varepsilon} \nu(\theta, \lambda) \frac{d\theta}{2\varepsilon}. \tag{A.5}$$

If $x_i \geq \overline{\theta} + \varepsilon$, the individual depositor can conclude that $\theta \geq \overline{\theta}$ and will not withdraw, independent of their belief about λ ($\Delta(x_i) > 0$). Similarly, if $x_i < \underline{\theta} - \varepsilon$, the individual depositor can conclude that $\theta < \underline{\theta}$ and will withdraw, independent of their belief about λ ($\Delta(x_i) < 0$). These are the *upper and lower dominance* regions for θ, where the individual action is independent of the beliefs about the actions of others.

For intermediate $x_i \in [\underline{\theta} - \varepsilon, \overline{\theta} + \varepsilon)$, the sign of $\Delta(x_i)$ depends on the beliefs about λ. To pin down these beliefs, we focus on a threshold strategy that all depositors follow. We show that there exists a unique signal threshold x^*, such that every investor withdraws if their private signal $x_i < x^*$ and does not withdraw if $x_i > x^*$. Given this threshold, an individual depositor can form well-defined beliefs about the total number of withdrawals, denoted by $\lambda^b(\theta, x^*)$, and given by the probability that other depositors receive a private signal below x^*. If $\theta > x^* + \varepsilon$, all depositors get signals $x_i > x^*$, none withdraw, and $\lambda^b(\theta, x^*) = 0$. If $\theta < x^* - \varepsilon$, all depositors get signals $x_i < x^*$, all withdraw, and $\lambda^b(\theta, x^*) = 1$. If $x^* - \varepsilon \leq \theta \leq x^* + \varepsilon$, some depositors get signals $x_i > x^*$, while others get signals $x_i < x^*$; thus, under the threshold strategy, $\lambda^b(\theta, x^*) = \Pr(x_i < x^*) = (x^* - \theta + \varepsilon)/(2\varepsilon)$. The following equation summarizes these beliefs:

$$\lambda^b(\theta, x^*) = \begin{cases} 1 & \text{if } \theta < x^* - \varepsilon \\ (x^* - \theta + \varepsilon)/(2\varepsilon) & \text{if } x^* - \varepsilon \leq \theta \leq x^* + \varepsilon \,. \\ 0 & \text{if } \theta > x^* + \varepsilon \end{cases} \tag{A.6}$$

Using (A.6), an individual depositor can compute the expected payoff differential using their posterior about θ, given her signal x_i and an assumed value for x^*:

$$\Delta(x_i, x^*) = \int_{x_i-\varepsilon}^{x_i+\varepsilon} \nu(\theta, \lambda^b(\theta, x^*)) \frac{d\theta}{2\varepsilon}. \tag{A.7}$$

Unlike in (A.5), beliefs in (A.7) are uniquely determined pinning down $\Delta(x_i, x^*)$.

A depositor does not withdraw ($\Delta(x_i, x^*) > 0$) if $x_i > x^*$ and withdraws ($\Delta(x_i, x^*) < 0$) if $x_i < x^*$. By continuity, the depositor that receives the threshold signal x^* is indifferent between not withdrawing and withdrawing, i.e.,

$$\Delta(x^*,x^*) = \int_{x^*-\varepsilon}^{x^*+\varepsilon} \nu(\theta,\lambda^b(\theta,x^*))\frac{d\theta}{2\varepsilon} = 0. \tag{A.8}$$

A threshold strategy implies thresholds for fundamentals $\theta_{\hat{\lambda}}$ and $\theta_{\bar{\lambda}}$ such that the depositors enjoy the convenience yield at $t = 2$ for $\theta \geq \theta_{\hat{\lambda}}$ and the bank has enough liquidity at $t = 1$ for $\theta \geq \theta_{\bar{\lambda}}$ given signal threshold x^* and withdrawals $\lambda^b(\theta,x^*)$. These thresholds are determined by $\hat{\lambda} = \lambda^b(\theta_{\hat{\lambda}},x^*)$ and $\bar{\lambda} = \lambda^b(\theta_{\bar{\lambda}},x^*)$. Using these, (A.8) can be expanded to

$$\begin{aligned}\Delta(x^*,x^*) = &-\int_{x^*-\varepsilon}^{\theta_{\bar{\lambda}}} \frac{\ell+(1-\ell)\xi}{\lambda^b(\theta,x^*)}(\bar{R}+\bar{V})\frac{d\theta}{2\varepsilon} \\ &+\int_{\theta_{\bar{\lambda}}}^{x^*+\varepsilon}\left[\theta\frac{R(1-\ell)(1-y)}{1-\lambda^b(\theta,x^*)}+\frac{[\ell-\lambda^b(\theta,x^*)]^+}{1-\lambda^b(\theta,x^*)}-(\bar{R}+\bar{V})\right]\frac{d\theta}{2\varepsilon}+\int_{\theta_{\hat{\lambda}}}^{x^*+\varepsilon}\theta V\frac{d\theta}{2\varepsilon}=0.\end{aligned} \tag{A.9}$$

As typical in the global games literature, we focus on the limiting case where noise $\varepsilon \to 0$, which allows us to derive a common threshold for fundamentals, θ^*, such that runs occurs for realizations $\theta < \theta^*$. Expressing (A.9) in terms of θ^* and changing variables from θ to λ, such that as θ decreases from $x^*+\varepsilon$ to $x^*-\varepsilon$, λ uniformly increases from 0 to 1, we get: [61]

$$\begin{aligned}\bar{\Delta}^* = &\int_0^{\hat{\lambda}}\theta^* V d\lambda + \int_0^{\bar{\lambda}}\left[\theta^*\frac{R(1-\ell)(1-y)}{1-\lambda}+\frac{[\ell-\lambda]^+}{1-\lambda}-(\bar{R}+\bar{V})\right]d\lambda \\ &-\int_{\bar{\lambda}}^1\frac{\ell+(1-\ell)\xi}{\lambda}(\bar{R}+\bar{V})d\lambda = 0.\end{aligned} \tag{A.10}$$

$\bar{\Delta}^*$ is continuous in θ^* because all integrands are continuous and the discontinuity in v occurs only at one discrete point, $\hat{\lambda}$. From the existence of the upper and lower dominance regions and the continuity of $\bar{\Delta}^*$, there exists a θ^* such that $\bar{\Delta}^* = 0$ using the intermediate value theorem. Moreover, $d\bar{\Delta}^*/d\theta^* > 0$, so θ^*, which implies that the probability that a run occurs is unique and given by

$$\theta^* = \frac{\int_0^{\bar{\lambda}}(\bar{R}+\bar{V})d\lambda + \int_{\bar{\lambda}}^1\frac{\ell+(1-\ell)\xi}{\lambda}(\bar{R}+\bar{V})d\lambda - \int_0^{\bar{\lambda}}\frac{[\ell-\lambda]^+}{1-\lambda}d\lambda}{\int_0^{\bar{\lambda}}\frac{R(1-\ell)(1-y)}{1-\lambda}d\lambda+\int_0^{\hat{\lambda}}V d\lambda}. \tag{A.11}$$

We now examine how a higher CBDC remuneration (or in the CBDC convenience

[61](See Goldstein and Pauzner, 2005, Infante and Vardoulakis, 2021, and Kashyap, Tsomocos, and Vardoulakis (2023) for detailed mathematical steps getting from (A.9) to (A.10)

yield), i.e., an increase in $\bar{R}$ (or $\bar{V}$), affects run risk for different levels of liquidity transformation and payment services. From (A.11) we get that

$$\frac{d\theta^*}{d\bar{R}} = \frac{\int_0^{\bar{\lambda}} d\lambda + \int_{\bar{\lambda}}^{1} \frac{\ell+(1-\ell)\xi}{\lambda} d\lambda}{\int_0^{\bar{\lambda}} \frac{R(1-\ell)(1-y)}{1-\lambda} d\lambda + \int_0^{\hat{\lambda}} V d\lambda} > 0, \tag{A.12}$$

which is also equal to $d\theta^*/d\bar{V}$. (A.12) implies that increasing CBDC remuneration (or CBDC convenience) increases run risk irrespective of the degree of liquidity transformation and payment services of deposit. Intuitively, if the central bank supplies a superior means to store funds (or transact), then the risk of depositors withdrawing is higher, independent of the amount of liquidity that the bank holds. However, rate at which the run probability would increase with CBDC remuneration depends on the amount of liquid funds the bank holds. To understand this more precisely, we compute the following cross derivative:

$$\frac{d^2\theta^*}{d\bar{R}d\ell} = \frac{\int_{\bar{\lambda}}^{1} \frac{1-\xi}{\lambda} d\lambda}{\int_0^{\bar{\lambda}} \frac{R(1-\ell)(1-y)}{1-\lambda} d\lambda + \int_0^{\hat{\lambda}} V d\lambda} - \frac{d\theta^*}{d\bar{R}} \frac{\int_{\ell}^{\bar{\lambda}} \frac{R(1-\xi)/\xi}{1-\lambda} d\lambda + \frac{d\hat{\lambda}}{d\ell} V - \int_0^{\ell} \frac{R}{1-\lambda} d\lambda}{\int_0^{\bar{\lambda}} \frac{R(1-\ell)(1-y)}{1-\lambda} d\lambda + \int_0^{\hat{\lambda}} V d\lambda}, \tag{A.13}$$

where $d\hat{\lambda}/d\ell = R(1-\xi)/(R-\xi) > 0$ from (A.3) and $d\theta^*/d\bar{R} > 0$ from (A.12) (similarly for $d^2\theta^*/(d\bar{V}d\ell)$). The cross derivative in (A.13) cannot be signed unambiguously due to opposing effects. On the one hand, higher ℓ reduces the need to inefficiently liquidate the risky asset as long as the number of withdrawals is less than what the bank can serve. On the other hand, a more liquid asset mix increases the probability of getting repaid conditional on the bank exhausting liquidity to serve all withdrawals, and, hence, increases the incentive to run. This trade-off is typical in bank run models with one-sided strategic complementarities akin to Goldstein and Pauzner (2005), and we perform numerical analysis to gauge the sign of the cross-derivative. Table A.1 reports the change in the probability of a run as $\bar{R}$ increases for different levels of ℓ. The left panel corresponds to lower ξ and the right panel to higher ξ. For both calibrations, $d^2\theta^*/(d\bar{R}d\ell)$ is negative moving across the columns, implying that lower liquidity transformation (higher ℓ) is associated with a *relative smaller* increase in run risk as $\bar{R}$ increases. This result is intuitive but, as said, we can not preclude the possibility that the opposite holds under some alternative parameterizations.

To analyze whether V amplifies or mitigates the increase in run risk induced by higher CBDC remuneration, we compute the following cross derivative:

$$\frac{d^2\theta^*}{d\bar{R}dV} = -\frac{\int_0^{\hat{\lambda}} d\lambda}{\int_0^{\bar{\lambda}} \frac{R(1-\ell)(1-y)}{1-\lambda} d\lambda + \int_0^{\hat{\lambda}} V d\lambda} \frac{d\theta^*}{d\bar{R}} < 0. \tag{A.14}$$

$\bar{R}$	$\xi = 0.7$				$\xi = 0.9$			
	$\ell = 0.05$	$\ell = 0.10$	$\ell = 0.15$	$\ell = 0.20$	$\ell = 0.05$	$\ell = 0.10$	$\ell = 0.15$	$\ell = 0.20$
1.00	-	-	-	-	-	-	-	-
1.01	0.62%	0.60%	0.58%	0.57%	0.44%	0.43%	0.43%	0.43%
1.02	1.25%	1.20%	1.17%	1.14%	0.88%	0.87%	0.86%	0.86%
1.03	1.87%	1.80%	1.75%	1.71%	1.31%	1.30%	1.29%	1.28%

Table A.1: Change in run risk for ℓ as $\bar{R}$ increases, relative to $\bar{R} = 1$ for different levels of $\ell = 0.05$ and ξ. $R = 3$, $V = 80bps$, $\bar{V} = 0$.

This result is intuitive. Depositors forfeit the convenience yield when they withdraw their deposits for CBDC, which essentially reduces run risk all else being equal. [62]

Finally, we consider how CBDC remuneration affect run risk if institutions are also allowed to invest ℓ in CBDC earning $\bar{R}$ (but not $\bar{V}$). Adjusting (A.11) we get that

$$\frac{d\tilde{\theta}^*}{d\bar{R}} = \frac{\int_0^{\bar{\lambda}} d\lambda + \int_{\bar{\lambda}}^1 \frac{\ell\bar{R}+(1-\ell)\xi}{\lambda} d\lambda + \int_{\bar{\lambda}}^1 \frac{\ell}{\lambda}\bar{R} d\lambda - \int_0^{\ell\bar{R}} \frac{\ell}{1-\lambda} d\lambda}{\int_0^{\bar{\lambda}} \frac{R(1-\ell)(1-y)}{1-\lambda} d\lambda + \int_0^{\hat{\lambda}} V d\lambda} - \tilde{\theta}^* \frac{\int_{\ell\bar{R}}^{\bar{\lambda}} \frac{R\ell}{\xi(1-\lambda)} d\lambda + \frac{d\hat{\lambda}}{d\bar{R}} V}{\int_0^{\bar{\lambda}} \frac{R(1-\ell)(1-y)}{1-\lambda} d\lambda + \int_0^{\hat{\lambda}} V d\lambda} \tag{A.15}$$

where $\tilde{\theta}^*$ is the run probability when institutions can also earn the CBDC remuneration. Adjusting (A.3) we also get $d\hat{\lambda}/d\bar{R} = \ell R/(R-\xi) > 0$. Compared to (A.12), (A.15) has two extra negative terms, mitigating the effect of higher $\bar{R}$ on run risk, and one extra positive term, accruing from the one-sided complementarity property discussed earlier. Table A.2 shows the run risk for various ℓ and remuneration rates on CBDC. Comparing Table A.2 and Table A.1 shows that for sufficiently high ℓ, run risk is lower when institutions are allowed to hold CBDC and earn its remuneration rate (see, for example, $\ell = 0.2$, $\bar{R} = 1.03$, and $\xi = 0.9$). Hence, higher remuneration rates on CBDC mitigate run risk. For lower ℓ, the adverse effect of more liquidity in run incentives, described earlier, dominates and run risk may be higher (see, for example, $\ell = 0.05$, $\bar{R} = 1.03$, and $\xi = 0.7$).

$\bar{R}$	$\xi = 0.7$				$\xi = 0.9$			
	$\ell = 0.05$	$\ell = 0.10$	$\ell = 0.15$	$\ell = 0.20$	$\ell = 0.05$	$\ell = 0.10$	$\ell = 0.15$	$\ell = 0.20$
1.00	-	-	-	-	-	-	-	-
1.01	0.63%	0.62%	0.60%	0.58%	0.44%	0.43%	0.43%	0.42%
1.02	1.27%	1.23%	1.20%	1.16%	0.88%	0.87%	0.86%	0.84%
1.03	1.90%	1.85%	1.80%	1.74%	1.32%	1.30%	1.29%	1.27%

Table A.2: Change in run risk for ℓ as $\bar{R}$ increases when institutions can hold CBDC and earn its remuneration rate, relative to $\bar{R} = 1$ for different levels of $\ell = 0.05$ and ξ. $R = 3$, $V = 80bps$, $\bar{V} = 0$.

[62] Our assumption that payment services are enjoyed by depositors only if they are repaid at $t = 2$ in their entirety is important for this result.