Consumer bank runs in a world of central bank backed digital currency

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Abstract

This exploratory paper is intended to improve understanding of the potential effects of the implementation of E-krona or similar CBDC's, with emphasis on financial stability. Our proposed experiment measures the impact of instant or delayed withdrawals in a modified Diamond-Dybvig setup, where participants are exposed to changes in liquidity of their bank. We also propose running treatments of the experiment with deposit insurance, in order to explore how increased consumer liquidity may affect current deposit insurance policy. Our preliminary hypotheses indicate that an introduction of E-krona might decrease the stability of the financial system. They also indicate that current deposit insurance might not be sufficiently efficient in this new context of CBDC's.

Keywords: financial stability, bank run, experiments, CBDC, E-krona

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1 Introduction

Martin Dufwenberg's article "Banking on Experiments?" (2013) states three possible motives for running an economical experiment: "Speaking to theorists", "Searching for facts" and "Whispering in the ears of princes". While our intention of this thesis is not to whisper in the ears of princes, perhaps it is the other two. We hope to shed some light on the possible implications on the financial stability in the banking system, would a central bank introduce electronic cash such as proposed by Sveriges Riksbank due to the removal of physical cash. We also wish to address how the current Swedish deposit insurance policy is impacted by a new form of value storage and new media of transaction.

In this paper we propose an experiment which aims to do that, by answering the following questions:
Will a central bank central bank digital currency (CBDC) – such as that proposed by Sveriges Riksbank – increase consumers propensity to withdraw funds from their commercial bank in the face of financial distress?
Is the current implementation of deposit insurance similarly effective in a financial system with much greater liquidity of consumer funds?

Since the late 90's the use of physical cash has been down-trending[1]. Credit and debit cards were initially introduced to create convenience to the process of carrying money in a safe manner, while also it also offered unlimited (in most cases) access to your bank account. Introduction of credit cards has led to a dwindling amount of people feeling the need to carry coins and bills. In certain countries, such as Sweden, the development has been accelerated by retail banks (henceforth referred to as "banks", "retail bank" and "commercial banks") demoting the use of physical cash for their own commercial purposes. The reason for this is simple: management of physical cash is a large cost for banks that could be levied through the expulsion of physical cash as a payment method. Retailers, hotels and restaurants are following suit; more and more companies are refusing cash to take physical cash, even in the face of customer dissatisfaction.

While the eradication of physical money is another step in the evolution of a digitized society– which the Swedish government is actively promoting - the board members of Sveriges Riksbank

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[1] Sveriges Riksbank's Payment Statistics 2017. The decline is in relative acceleration and in 2015, only one in five payments were done with physical cash.

are worried[2]. One of the reasons is that the already oligopolic bank-sector in Sweden might introduce higher fees on bank accounts and transactions as the alternative methods of payment and storage of money disappear[3]. Such a situation, claims the Riksbank, would give Swedish banks the opportunity to impose excessive fees upon their customers. Another reason is the control over the M1 money supply. The Riksbank's control over physical cash supply has historically been a tool for controlling inflation, especially for consumer goods. Would physical cash disappear, that tool would be obsolete, and retail banks would become the Riksbank's sole intermediary for control over M1.

As a repercussion, the Riksbank has announced an investigation regarding the subject of a digital currency fully backed by the central bank, furthermore referred to as CBDC[4][5]. To guarantee the currency's value and safety, it is likely that a form of partially distributed ledger would be put in place. In order to counteract the banks' potential monopoly on deposit accounts, a suggestion has been to allow citizens to store their money with the Riksbank. Consumers would, in a similar fashion to banks, have direct access to the Riksbank's balance sheet.

There are two different propositions on how to implement said digital currency: a register-based E-krona and value-based E-krona. A register-based E-krona would be very similar to current banking systems, with the difference that individuals as well as corporations may open a bank account with the central bank. In principle, the central bank would then offer basic financial services such as transactions and payment services. A value-based model would correspond more closely to the limited use that physical cash represent today. E-kronas would be stored in a digital wallet, and used for daily transaction of smaller size. This system would be largely replicating the technology behind BitCoin and other cryptocurrencies.

In order to get E-kronor in your deposit account at Riksbanken or in your digital wallet, several methods have been suggested. Deposition through ATMs, digital transactions and digital "purchase" of E-kronor all seem like plausible solutions. Digital transactions from retail banks' account to the central bank account would also mean that consumers would have a more

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[2] Mats Dillén of Sveriges Riksbank, interview 2018-02-19

[3] Cecilia Skingsley, oral presentation, 11/4 Historiska Museet

[4] Central bank Backed Digital Currency

[5] Riksbankens E-kronaproject, 2017

convenient mode of access to their "cash" as compared to withdrawing physical cash from a retail bank office or an ATM.

There may be unintended side-effects from the introduction of CBDC's or E-kronor. Gabriele Camera (2017) comments in his paper on one of the possible risks – "[…] by design this instrument would be quickly and cheaply transferable from and to intermediaries. This might increase financial market volatility." and later adding "In periods of uncertainty, households might seek the safety of the central bank, thus giving rise to rapid outflows of funds from commercial banks, as in a digital version of a bank run. This kind of volatility in funding liquidity would naturally have implications for the way banks fund their projects and for the cost of deposit insurance.". It is likely that retail bank funding would become more unstable as a result of a CBDC implementation - a topic we are going to explore further in this paper.

The possible implications on the optimal design of a deposit insurance are also interesting. Sträter *et al.*'s (2008) paper show that many depositors choose to withdraw their funds from their bank in times of financial distress, despite being aware about the deposit insurance. Some possible reasons are that people are uncertain about the time it will take to get reimbursed, the consumers' distrust in government authorities and/or short-term needs for liquidity. Another possible reason is withdrawing funds being perceived as a less-risky option. For that reason, we believe it to be particularly important to specifically monitor how deposit insurance affects consumer decisions when new monetary technology is introduced.

The experiment we propose is intended to explore the implication of a banking system where withdrawals from bank accounts are administered much more quickly. In the current state of business, the withdrawal of significant amounts from a bank account, especially in times of crisis, is a protracted affaire. This was certainly the case during the bank run at Northern Rock in the UK (Shin, 2012). Due to sluggish withdrawals, Bank of England had time to partially or entirely suspend convertibility of depositor assets, and the banks could in the end be saved. By introducing a shared ledger technology where people can transfer electronic money Peer-to-Peer, or to and from their central bank account in the matter of seconds, the speed of bank runs could be elevated to a level never seen before – a case in which Bank of England would not have been able to save Northern Rock.

Consistent with previous experiments on bank runs, our proposed experiment is based upon the framework created by Diamond and Dybvig (1983), henceforth referred to as DD. Almost all modern literature on general equilibrium bank runs draws its origins from this classic article The paper explains the origins of panics in the financial system and how it resembles a cooperation game in game theory. General conclusions are that banks are vulnerable to the unpredictability of deposits, but policy-making and optimal contracts can mitigate any risk of bank runs.

One of the points which Diamond and Dybvig raise is that under regular circumstances, the necessary level of liquidity required to serve withdrawers is random and unpredictable. This is due to the fact that the amount of people withdrawing their funds in a single time frame is random. It is, however, mathematically improbable that a critical amount of individuals will make withdrawals at the same point in time, since each individual withdrawal is expected to be mostly uncorrelated under normal circumstances. Hence, banks can sell long-term loans whilst only withholding a relatively low level of liquidity in correspondence to an expected, steady amount of withdrawals per day.

Problems arise when depositors attempt to withdraw their funds from their bank simultaneously. Simultaneous withdrawal may result in a liquidity crisis, as the bank's momentary level of liquidity falls short of the required amount to satisfy customers' demand. In order to accommodate to consumers' demand for liquidity, the bank starts selling long-term assets and loans. The drawback of selling long-term assets and loans is that it may normally only be sold at a considerable discount. It also leads to lower returns on capital in future states. Therefore, by accommodating to an excessive amount of withdrawers at the current point in time, the bank's long-term investors may take a considerable loss. As long-term savers notice that their holdings may not be safe, they attempt to withdraw their funds at current time in spite of preferring to save for the future. Further aggravation is caused by the fact that early runners may receive a larger amount of the available liquidity than late runners. The reaction to withdraw from long-term investors further deepens the crisis, which is the central finding of the DD model.

Hence, even banks with good financial stability and sufficient Tier 1 capital ratios, are susceptible to go into bankruptcy caused by a bank run. What the DD model finds is that if a bank run is anticipated by a depositor, the best response is to withdraw their money from the bank before the bank has run out of liquidity. In this case, to withdraw becomes the dominating strategy. In the extended model, including deposit insurance, DD arrives at the conclusion that optimal welfare may be achieved by a properly designed deposit insurance. The key features of the deposit insurance are that any lost funds will be reimbursed in full, but the cost of the insurance is carried by all depositors in the game.

DD concludes that with an efficiently implemented deposit insurance, no Nash Equilibria exists which are bank runs. However, they propose that the existence of sunspots[6] may allow for bank run equilibrias. This is consistent with the research of Peck *et al.* (2003). In our proposed experiment, we introduce the sunspot variable liquidity level, similarly used as in Chakravary's article. Liquidity level affects the risk which each player faces during a specific moment in the experiment. The pareto-efficient equilibrium of the game is still, in line with DD, not withdrawing funds from the bank.

In addition to the original model, we have introduced a temporal transaction cost for withdrawal of funds into cash from the consumers bank account. The logic is that the cost of time to withdraw any significant amount of money from the bank is a barrier to bank runs. It is most easily proven by visualizing a scenario from the opposite direction: In a case where consumers could freely transfer all their funds and assets from a financial institution momentarily, the variability in amount of funds available to a bank would differ greatly across time. We believe that in the face of financial distress, more depositors might decide to withdraw their funds from the retail banks, would the transaction costs be lower.

Our paper contributes to both theoretical and experimental bank run literature, as well as adding to experimental literature on co-ordination games and games with longer time horizons. In the first case, empirical evidence on bank runs is rare due to the infrequency of bank runs. In experiments, major topics have been correlation between fundamentals and bank runs (Calomiris and Mason, 1997; Schumacher, 2000; Martinez Peria and Schmukler, 2001) – and bank run contagions (Chakravarty *et al.,* 2013; Brown *et al.'s,* 2012). However, there is still a lack of empirical and experimental studies on bank runs, and we hope to add another dimension to this issue of escalating importance.

Their conclusions have later been questioned in two major articles by Green & Lin (2003) and Peck (2003)**,** where both sets of authors modifies the original model to include the unmitigatable risk of bank runs. The introduction of Peck's article clarifies the author's motives for his research: "Bank runs are historical facts. If bank runs were impossible, then much of banking

[6] Exogenous factors affecting consumers propensity to withdraw

policy would be directed toward a non-issue. Our goal is to put 'runs' back in the bank runs literature". By formally introducing "optimal contracts" and propensity to run triggered by sunspots, their updated DD framework can explain bank runs emerging in equilibrium of optimal deposit-contracts. Our model uses Peck's intuition of sunspot variables and expands on their effect on consumer behavior in times of financial distress.

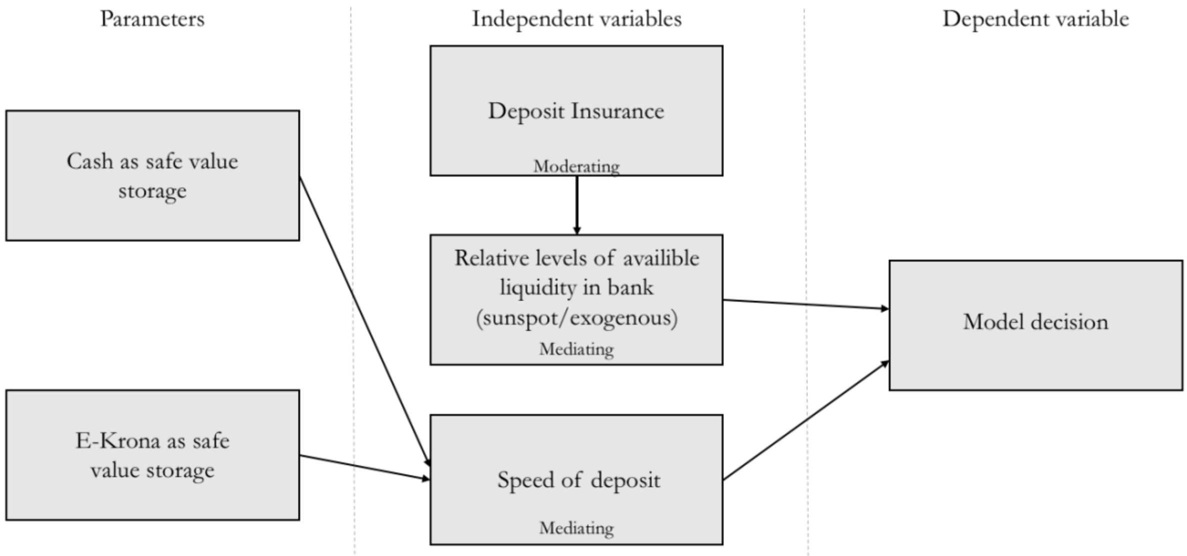
Empirical studies by Brown *et al* (2012) show that bank runs are strongly contagious. In their study they used followers and leaders to simulate the psychological effect on small bank customers when larger investors withdraw their funds from a bank. One conclusion is that failure of one bank often results in panic at other banks. This specific paper finds evidence for *fundamentals based contagion*, i.e. the linkage of risky assets between failing and non-failing banks leading to bank runs. In Chakravarty *et al's* paper "An Experiment on the Causes of Bank Run Contagions" (2013), the subject of bank-run contagion is further explored, in an experiment which remains very true to the DD-model. By comparing consumer's behavior when observing the behavior of depositors in another, related bank, they also arrive at the conclusion that bank runs may be fundamentally driven, but are also triggered by general "panic" observed in other banks. They also conclude that players propensity to withdraw increases if they can observe a low liquidity level (corresponding with high risk) in the bank of their deposits. By observing multiple different experiment treatments, we add an opinion to both the effects of deposit insurance as well as increased liquidity.

Gabriele Camera's paper "A perspective on electronic alternatives to traditional currencies" (2017) provides an essential introduction to the research and propositions about CDBC's from central banks across the world, as well as their possible implications on the financial system. Particularly interesting is his findings on volatile commercial bank funds as a result of CBDC implementation: "In periods of uncertainty, households might seek the safety of the central bank, thus giving rise to rapid outflows of funds from commercial banks, as in a digital version of a bank run. This kind of volatility in funding liquidity would naturally have implications for the way banks fund their projects and for the cost of deposit insurance." We hope that our proposed experiment may give some empiric evidence to Camera's statement.

The remainder of the paper is organized as follows. Section 2 outlines the theoretical framework of the proposed experiment. Section 3 describes the relationship between the experiment and previous theoretical models, as well as describing the experiment, the treatments and our hypotheses. Section 4 discusses our model and hypotheses.

2 Theoretical framework

The proposed experiment is intended to aid the prediction of fund withdrawal decisions by consumers based on the variables depicted in the model.



2.1 Cash

Historically, physical cash has been the primary place of refuge for scared consumers in times of financial distress. Even today, when many different options for value storage exist, cash seems to be a natural safe harbor asset for many depositors.

A few properties define the process of cash withdrawals in times of distress. To withdraw cash from the bank is a slow process, often limited to a fairly low amount per day. In Sweden, most banks require pre-registration for withdrawing amounts larger than 30,000 SEK at a time, and ATM's limit depositors to retrieving more than 10,000 SEK per day. The process of cash withdrawal is highly surveilled and regulated by the banks. Historically when banks have face liquidity crises, withdrawal has been suspended or "bank holidays" been introduced, limiting the amount withdrawn and extending the window under which the central banks may react to a threatening crisis. In the DD model this is referred to as suspension of convertibility and is a successful method for mitigating financial distress.

To represent the time it takes to deposit large sums of money (over 10,000 SEK in Sweden) from a bank account, cash are assumed to be "slower" to deposit than E-kronor. This is what we have and continue to refer to as the transaction cost of cash, and is largely mitigatable when establishing new monetary technology.

2.2 E-krona

As previously mentioned, the 2017 report ”Riksbankens e-kronaprojekt” from Sveriges Riksbank proposes different scenarios of the E-krona. The alleged most likely scenario is a register-based system, where consumers may store E-kronor within the Riksbank. Features would be a Riksbank account where consumers can deposit their money for E-kronor, payment and transaction services usable 365 days a year, 24 hours per day. Riksbank accounts would initially not carry interest, according to the report. These features are needed to achieve some level of interchangeability with the current system with physical cash.

Key properties derived from this register-based system would are lower transaction times, and safe storage of “digital cash”. It is obvious (and stated in the Riksbank report) that deposit and withdrawal speed between Riksbank accounts (the electronic version of cash) and commercial bank accounts would be much higher in comparison with withdrawal of physical cash from commercial bank accounts. If transactions are to be executed at all hours, the currency would also be more ‘liquid’ compared to the current digital payment system. Safer storage of cash equivalents would also promote use of E-krona in comparison with physical cash

It is fair-to assume that the speed of transaction and execution will be considerably higher and therefore more difficult to control than under current circumstances. According to Riksbankens report this is a concern that has been raised numerous times and confirms the validity of our assumptions.

2.3 Speed of transactions

This variable is the outcome of the different monetary technologies – cash or e-krona. A higher speed of transaction could change the pattern of deposits and withdrawals currently experienced by the financial system.

Transaction speed has been a non-issue until recent developments within financial services technology, as all players have been adhering to the same rules and use of the same technology. However, we believe that transaction speed and it’s effect on consumer behaviour is a vital issue to raise regarding the new technology. Earlier research has shown that for example, debit card payments increases the spending rate of consumers and other possible implications. (Runnemark et al., 2016)

The bank run on Northern Rock displayed in practice what a contemporary bank run could look like – but the fact is that withdrawal of funding from consumers took place over several months and many left a significant part of their money in their accounts (Hyun Song Shin, 2012). A reason for this is partial suspension of convertibility as discussed in the DD framework. Another reason, we believe, is consumers depositing their funds as cash.

2.4 Relative levels liquidity in the bank

The issue of fundamentals relating to propensity to run from a bank has been widely explored by Peck (2003) and others. A general conclusion is that both direct and indirect signs of lacking liquidity in a bank increases the propensity to run (Chakravarty et al. 2013). We assume that this relationship holds and a lower relative liquidity such as displayed by Chakravarty increases the probability of a run Nash Equilibrium.

2.5 Deposit insurance

According to the DD model a deposit insurance offering full coverage will lead to a stable and dominant Nash Equilibrium with consumer keeping deposits in their bank (Diamond and Dybvig, 1983). The extra tax imposed on consumer as a result of bank failure is incentivizing consumers to not trigger the insurance. Contemporary studies show that a majority of consumers are unaware of the deposit insurance – and many of those who are aware of it would still withdraw their funds and disregard the insurance (Bijlisma, 2015). However, it remains that deposit insurance in many cases have been a successful way of ensuring financial stability in practice, and is a predictor of elevated risk tolerance of an average investor.

Noteworthy is that the deposit insurance offered by central banks around the world was heavily criticized after the 2008 financial crisis. Arguments were made that it increased the risk taking by banks on a corporate level, and therefore destabilized the underlying financial system. The intention with the variable is not to measure the overall risk-taking of banks, but the behavior of the individual consumer.

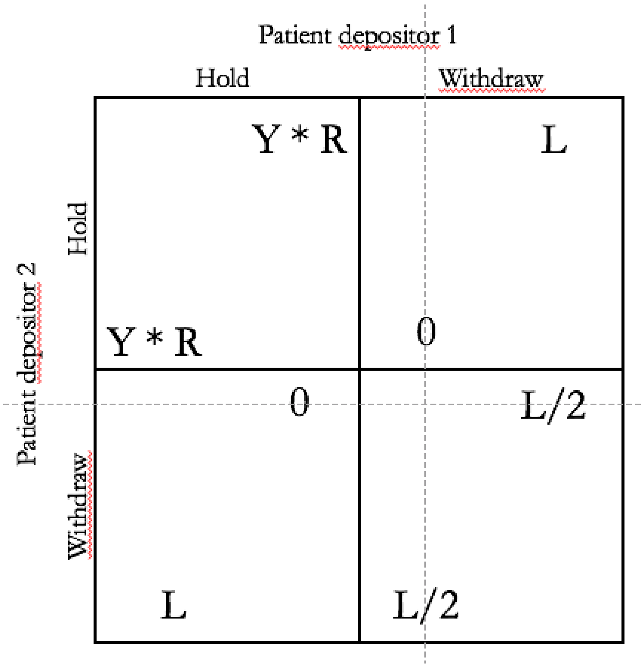
3 The Theoretical Model

3.1 Model Structure

The theoretical model proposed is based on the DD framework (1983) with a formalized sunspot variable sigma as in Peck (2003). Empirical studies by Sträter *et al.* (2008) has inspired a small adaptation of the deposit insurance to consider actual consumer knowledge

The Diamond-Dybvig bank run model provides the theoretical background for the proposed experiment, specifically on the scenario where deposit insurance is implemented. The DD model takes place over 3 periods, with an arbitrary number of consumers. In period 0 all consumers deposit their funds Y into a bank. In period 1 all consumers are randomly given one of two possible roles: patient or impatient, where the random variable t represents the relative share of impatient consumers. An impatient consumer derives utility only from consumption in period 1 and a patient consumer prefers consumption in period 2. From period 1 to 2 an interest $R * Y$ is endowed to patient consumers opting to keep their funds in the bank.

Due to limited liquidity in the bank, full deposits will be provided to consumers only if all patient consumer withdraw in period 2, otherwise only partial withdrawals will be provided to depositors in period. It also leads to significantly lower or no funds being paid out in period 2. Therefore, if a patient consumer believes that another patient consumer is to withdraw their funds in round 1, they would prefer to also withdraw in round 1.



Picture 1

Depicting a simplified example of the DD framework. Y is the initial endowment. R is the interest given for holding funds in the bank. L is the available liquidity in the bank. Impatient depositors are excluded from this game as they do not impact the Nash Equilibrium of the game. Pareto-efficient Nash is both players holding their funds in the bank. However, the risk-efficient equilibrium is both players withdrawing. Thus, one of two possible Nash Equilibria is depositors withdrawing their funds: a bank run.

When more players are added to the game the pay-offs become more complex, but the general rule of thumb remains: if another patient depositor withdraws in period 1, any given depositor prefers to withdraw in period 1.

As the DD model unfolds there are two Nash Equilibria of the game, none of them dominant. There is the pareto efficient Nash Equilibrium where all players choose to keep their funds deposited in the bank. There is also the alternative of all players withdrawing their funds, which is the risk efficient equilibrium.

3.1.1 Suspension of convertibility as a method of avoiding bank runs

During the 1930's financial crisis, the banks took "holidays" where all business was called off[7]. This was done to prevent further deposits and escalation of the already roaring crisis. In the DD framework, this is called suspension of convertibility. Suspending convertibility of funds after all impatient consumer have withdrawn their funds in period 1 would lock the game to the pareto-efficient Nash Equilibrium as depicted in the picture above – and welfare is maximized. If the number of impatient consumers was known this would have been the established way of avoiding bank runs. However, suspending convertibility is associated with a net welfare loss, as the random parameter t is unknown – the number of impatient consumers. By suspending

[7] Saunders & Wilders, Contagious Bank Runs: Evidence from 1929-1933 Period (1996)

convertibility without knowing t, there is a high probability that some players would be forced to withdraw their funds in a period against their choice.

Deposits are relatively slow in our current financial system and financial stability is improved due to this inefficiency. The lack of speed of deposits enables tools in the banks' that would not otherwise be useful. This fact is supported by empirical studies, which shows that banks holding illiquid assets are more stable in times of financial distress in comparison with those holding more liquid assets[8].

The Northern Rock case has shown that in reality, the central bank may enforce a *partial* suspension of convertibility after a crisis has been confirmed. This is done in order to gain some time for taking decisions on how to save the bank. It is, however, not yet possible to formalize suspension into a bank's safety system without considerable losses of consumer value.

3.1.2 Deposit insurance

The DD-framework incorporates deposit insurance to all withdrawers within aggregate resource constraints, meaning that any funds used to pay the deposit insurance must be drawn from within the model. It is implied that the tax levied upon those participating in the game will be of identical size as the total amount reimbursed by insurance. All players are assumed to know about the tax. The negative implications of the tax in case of activated deposit insurance (and the stabilizing implications by the fact that players' funds are entirely insured) leads to the pareto efficient Nash Equilibrium being the only outcome of the game, with the deposit insurance never getting used.

As previously stated, contemporary empirical studies show that consumers have relatively limited knowledge about deposit insurance (Sträter et al., 2008). Bijlisma (2015) also showed that among those who are well informed about their coverage of deposit insurance many still withdraw their funds in times of financial distress. One reason for that, according to the study, was the time value of money. Reimbursement from deposit insurance after a bank has failed takes time. Depositors who believed they could generate more value from withdrawing their funds and investing it elsewhere were more prone to withdraw than others who did not consider that option.

[8] Wolf Wagner, The liquidity of banks assets and banking stability (2007)

Due to the reimbursement delay of deposit insurance, all players are utility positive in trying to not activate the insurance.

3.1.3 Sunspots

Sunspots are mentioned in the DD framework as exogenous factors affecting players' propensity to run. Examples of sunspots are distress in the financial system, negative news about a specific bank or low liquidity levels forcing banks to publicly sell assets to fire-sale prices. The mathematical formulation of sunspots was formally introduced to the DD framework by Peck *et al.* (2003). In a game where sunspot variable σ is introduced in period 1, players take decision to deposit or not with regards to the variable s. When the random, exogenous sunspot variable σ is smaller than s the sub-game has a run-equilibrium and all players will choose to deposit in period 1. If σ is larger than or equal to s, the sub-game does not have a run-equilibrium and all patient players will choose to deposit in period 2.

In the game constructed by Peck, sunspots being introduced in period 1 affects the overall possibility of bank runs. As consumers are aware that a sunspot variable will be introduced after they deposit, the possibility of a game with a bank run equilibrium is positive – without affecting the period 0 deposit decision. Therefore, when sunspots are introduced, the bank run game has multiple more possible equilibria.

In reality, sunspots are often present in the occurrence of a bank run. As earlier referred to – the Northern Rock example showed that news about financial instability can trigger a bank run. The independent game variable s is impossible to determine in reality, but it is undoubtedly so that at certain external levels of uncertainty consumers will ponder whether to make a run.

3.2 Experiment design

Our experiment is based on the DD framework but expanded by the adding of exogenous liquidity levels of the bank and wealth accumulation across rounds for each consumer (player). A majority of the experiment design is an extension of the Bank Run Contagion experiment performed by Chakravarty *et al.* (2013) by adding the multiplayer and multi-round framework. We are using Brown *et al.'s* (2012) focus on consumers classified as *patient* in the DD framework, as they uniquely affect the liquidity of the bank.

The experiment consists of a group of consumers in a bank. The bank has 5 depositors, all of whom are patient. The game is played for a maximum of 10 rounds, in each of which the participant has to make a decision: to withdraw, hold or deposit funds from their bank account. The DD variable R is equal to 1.25, or 25% return on invested capital per round. Funds held externally is held without cost and interest, and deposits/withdrawals are without transaction cost. Participants are not informed on the length of the game. After each round a summary of the actions taken by the players is presented at the table: by amount withdrawn, deposited and held.

Depending on the level of liquidity in the bank (ranging from 0.8 – 0.2 throughout the game), a certain total amount of funding may be withdrawn during a single round. Each round, the liquidity may change one "step" in a random direction – higher or lower. The probability of change in either direction is 60% down and 40% up – to bias the game towards a situation where exogenous "sunspots" induces fear of losing the players funds. Players are not aware of this situation, and are to believe the probabilities are 50/50. If a higher amount of liquidity is requested during a round than what is available in the bank, liquidity will be served according to *sequential service agreement,* as described in the DD model[9]. Withdrawals can be actioned as long as the bank remains solvent.

In our game, bank solvency is defined as following: if all players choosing to withdraw their funds from the bank in any given round are endowed their full deposit, e.g. 100 in the table 1 below, the bank remains solvent. A *bank run* is defined as the situation where depositors choosing to withdraw their funds are not endowed the full amount. The solvency level of the bank is dependent on number of net withdrawers per round. *Net withdrawers* is defined as numbers of withdrawers subtracted by number of depositors.

Observe the following example: Four players are fully deposited in round t. In round $t + 1$, the player with her funds fully withdrawn decides to *deposit* her funds into the retail bank. In addition, one of the players with funds fully deposited decides to *withdraw* her funds. The *net withdrawal* is 0, thus pay-offs are unaffected.

The design of the game is such that players can end the game with different amounts of funds depending on their decisions. Therefore, the levels of liquidity in the retail bank differs between

[9] Pay-offs according to the sequential sevice agreement are specified in table 1.

rounds throughout the game. However, we have decided to treat pay-offs during each round indifferently depending on the amount deposited into the bank. Pay-offs are therefore only determined by the fixed number of players withdrawing or depositing each round. Some level of complexity might be lost due to this simplification, but clarity is won – as is experiment measurement accuracy.

In the case of a bank run, the bank will be liquidized as according to the DD framework. Any remaining funds will be distributed as according to the table below, and the game will end.

Table 1

Table
Payoffs

	Total # of players withdrawing today				
	0	1	2	3	4
L=0,8					
Withdraw today	100	100	100	100	90
Withdraw tomorrow	125	117	104	78	0
L=0,6					
Withdraw today	100	100	100	88	79
Withdraw tomorrow	125	106	82	0	0
L=0,4					
Withdraw today	100	100	87	77	69
Withdraw tomorrow	125	92	71	0	0
L=0,2					
Withdraw today	100	86	75	67	60
Withdraw tomorrow	125	0	0	0	0

The table depicts pay-offs in percentage (%) of funds held in the bank.

The game is divided into four different treatments across two dimensions: monetary technology and deposit insurance. Monetary technology is a variable intended to map the difference between physical cash deposits or equal and the described CBDC, distributed ledger with central bank deposit accounts. Players in the CBDC treatment can withdraw or deposit their entire account during each round of the game. Players treated with the cash scenario are limited to withdrawing or depositing their funds in two rounds – one "half" during each round[10].

[10] In the second round of withdrawal, more than half of the original funds will be deposited or withdrawn due to interest effects.

Deposit insurance is intended to map the difference between actions of the proven majority of bank customers who are not familiar with the concept of deposit insurance, and those who are familiar with it on a higher level. In the first treatment, no information is given regarding deposit insurance. In the second treatment players are given the information that deposit insurance will cover up to 100 units of currency if the bank was to fail, but the reimbursement of lost funds will take place after a period of 3 turns.

From a strategic point of view, the pareto-efficient Nash Equilibrium is not changed between different treatments of the experiment: the game always favours keeping your funds in the bank. However, Chakravarty et al. has shown that many players in their treatment of the game behave increasingly irrationally as signs of low liquidity emerge.

3.2.1 Treatment 1

Treatment 1 is defined as CBDC technology and no deposit insurance. It is similar to Left Bank players standard treatment in Chakravarty's article. Players may deposit and withdraw their entire account during each turn. This treatment is intended to serve as a benchmark when analyzing the other treatments.

When players do not have deposit insurance, optimal decisions for each round should follow the following function, assuming a neutral risk preference:

(1) $$Decision_t = (Current\ Funds * R) - (Current\ Funds * Estimated\ Loss\ (\%) * p(L))$$

where $p(L)$ is the players estimated risk of losing some of their funds caused by other players withdrawing, dependent on the level of liquidity in the bank. As liquidity level falls in the bank, the amount lost increases for each player withdrawing their funds from the bank and players will have a higher propensity to withdraw. Thus, $p(L)$ accommodates for both larger losses, as well as larger risk of losing funds. When $Decision\ \geq 0$, the rational decision is to keep funds deposited in the bank.

3.2.2 Treatment 2

Treatment 2 is similar to treatment 1, with deposit insurance added as a feature. It is intended to illustrate the effect of deposit insurance on consumer behavior in the case of CBDC. Deposit insurance lowers the amount of value at risk, thus increasing the risk tolerance for all players.

(2) $$Decision_t = (Current\ Funds * R) - [(Current\ Funds - \frac{Deposit\ Insurance}{(1+R)^3}) * Estimated\ Loss\ (\%) * p(L)]$$

3.2.3 Treatment 3

Treatment 3 is defined as cash technology and no deposit insurance. While the CBDC treatments are similar to earlier experiments executed by other researchers, this treatment is intended to illustrate the actual difference in transaction speed between the old (cash) and the new (CBDC) technology.

While the decision equation for CBDC partially holds for cash, the difference is the slower rate of withdrawal. As it takes two turns to withdraw a players entire amount from the bank, part of their equation is the anticipation of the events of next turn. The players are not aware of the bias towards lower bank liquidity, and if rational, will calculate the estimated benefit of their decision next turn. Both calculated outcomes of this turn and the next will affect the decision during any round t.

(3) $$Decision_t = \Big[\big[(Current\ Funds * R) - \big(Current\ Funds * Estimated\ Loss\ (\%) * p(L)\big)\big] * \ Decision_{t+1}^{Liquidity\ Up}\Big] + \Big[\big[(Current\ Funds * R) - \big(Current\ Funds * Estimated\ Loss(\%) * p(L)\big)\big] * \ Decision_{t+1}^{Liquidity\ Down}\Big]$$

3.2.4 Treatment 4

Treatment 4 is similar to treatment 3, with deposit insurance added as a feature. It is intended to be used as comparison with the CBDC case, and the implications of transaction costs on financial stability.

The equation for player decisions shows that cash is exposed towards deposit insurance to a higher degree than CBDC. Since the player may experience a loss due to a bank run in both present time and future states, deposit insurance will affect decisions in all states. Due to the monetary technology slowing down transactions, the players must be forwards looking and thus accommodates for the effects of bank runs in any of the future states. Deposit insurance acts as a risk mitigator in all states and lowers the players propensity to withdraw in all states, as compared to CBDC.

(4) $Decision_t =$

$$\left[\left[(Current\ Funds * R) - \left(\left(Current\ Funds - \frac{Deposit\ Insurance}{(1+R)^3}\right) * Estimated\ Loss\ (\%) * p(L)\right)\right] * \ Decision_{t+1}^{Liquidity\ Up}\right] +$$

$$\left[\left[(Current\ Funds * R) - \left(\left(Current\ Funds - \frac{Deposit\ Insurance}{(1+R)^3}\right) * Estimated\ Loss(\%) * p(L)\right)\right] * \ Decision_{t+1}^{Liquidity\ Down}\right]$$

3.3 Hypotheses

The game depicted in the CBDC treatment without deposit insurance is very similar to the DD model. There are multiple equilibria available. In some equilibria, depositors choose to hold their funds in the bank of for each consecutive round and a bank run does not occur. In other equilibria, patient depositors will choose to withdraw their funds in any sequence of events, and a bank run does occur. Nash Equilibria does not exclude any relationship between liquidity level L and the probability of a bank run. Temzelides (1997) states that lower liquidity of banks increases the probability of a run. As previously proven a low L should predict a higher fraction of bank runs.

3.3.1 Hypothesis 1

The frequency of withdrawals in all treatments will be higher when the bank's liquidity levels are low.

This hypothesis is already established in *An experiment on the Causes of bank run Contagion* by Chakravarty. It is of weight, however, to re-establish this hypothesis in this new context, as it is not explained by standard theoretical frameworks.

As previously stated, $p(L)$ is the function measuring the probability of some loss during a specific round of the game. When L falls, the amount lost increases in case of bank run, and players should estimate a higher risk of losing some part of their funds. Therefore, we believe that a lower liquidity level in the bank will lead to a higher rate of withdrawals.

Hypothesis 1 will be tested as percentage of players withdrawing at each level of liquidity level.

3.3.2 Hypothesis 2

Players in all treatments will be more prone to withdraw their funds if other players withdrew their funds in the previous round.

This hypothesis corresponds to the 'bank run contagion' referred to in Chakravarty's and Brown's articles. According to their research, consumers respond to their peers when taking decisions on whether to deposit or withdraw their funds from the bank. It could also be referred to as a momentum effect – when fear of bank failure sets in, players might believe their peers will be more prone to deposit than otherwise. If this turns out to be the case, results in subsequent hypothesis will need to be cleared from this momentum effect.

Hypothesis 2 will be tested by running the following regression

$$withdrawals_{it} = \beta_0 + \beta_1 TW_{t-1} + \beta_2 L_{t-1} + \beta_3 L_t + \beta_4 DI + \varepsilon_{it}$$

The regressors are TW_{t-1}, total number of withdrawals executed in the previous round; L_t, liquidity level in the current round; L_{t-1}, liquidity level in the previous round; and DI, a dummy variable considering whether deposit insurance is active or not.

3.3.3 Hypothesis 3

Withdrawals will be more frequent at higher liquidity levels when the monetary technology is cash as opposed to when the monetary technology is CBDC, in games with no deposit insurance.

We present physical cash as a less liquid form of assets in the proposed experiment. The point is to hopefully demonstrate the mechanism of making plans for withdrawals. As players in treatments where the monetary technology is cash are aware that they need two rounds to withdraw their full deposit in event of uncertainty, we believe they will choose to withdraw at a higher liquidity level than their CBDC counter-parts.

This is demonstrated by (3) and (4), players using cash technology will, if rational, account for the possible events of the following turns when deciding if to withdraw, deposit or hold. The negative effects of lower liquidity for the players are by game design larger than the positive effects of increased liquidity.

Hypothesis 3 will be tested as a comparison between percentage of players withdrawing at different liquidity level depending on different monetary technologies.

3.3.4 Hypothesis 4

In treatments where the players have deposit insurance; bank runs and the following liquidation of the retail bank will happen earlier in the game when players are using CBDC monetary technology.

Physical cash is presented to players as a monetary technology with significant transaction costs, as compared to CBDC. Therefore, when some funds are insured, we believe that players using physical cash technology will refrain from depositing to a higher degree than players using CBDC technology, as to avoid the cost of transaction.

Comparing (2) and (4), we see that the exposure towards deposit insurance is different. Players using CBDC monetary technology accounts for deposit insurance once, while those who use cash monetary technology accounts for it twice. Thus, the deposit insurance has a higher impact while using cash monetary technology. Instantaneous deposits also acts as a self-regulated deposit insurance, meaning some players might choose to control their risk exposure instead of relying on deposit insurance.

As according to Sträter *et al* (2008), withdrawals are likely to be executed when a consumer has uninsured funds in the bank. However, when transaction fees are significant, we believe that participating players will be more optimistic about fellow players propensity to withdraw.

Hypothesis 4 will be tested by running the following regression:

$$round\_of\_liquidation_{it} = \beta_0 + \beta_1 MT + \beta_2 DI + \varepsilon_{it}$$

The regressors are MT, a dummy-variable expressing what the monetary technology is; and DI, a dummy variable considering whether deposit insurance is active or not.

3.5 Experimental Procedures

Instructions are provided in Appendix A, which will inform all participants of all the features of the game. For statistical validity, each of the four treatments of the game shall be generated 20 times. Each session shall have five participants, who has limited interaction before the game. The participants may not talk during the game.

Optimally, the game is played via a computer terminal, which calculates the pay-offs for each person after each round of the game. At the end of each round, participants shall be reminded of their decision, and shall also be informed about the decisions of others (how many withdrawals occurred during the round). They shall also be reminded what the liquidity levels were during the round, and what liquidity level will be provided for the bank in the next round.

3.5.1 Participants

The participants shall be paid their payoff from the game in full, after they have filled a socio-demographic questionnaire. Each session is estimated to last about 60 minutes. In total, 400 participants is required for the experiment, and a wide mixture of social backgrounds are preferred. No one shall participate in more than one session or be previously exposed to similar experiments.

The experiment executed by Brown suffers in our opinion from sub-optimal significance levels and fairly large standard errors on statistical results. This is likely due to the low number of observations. In total, Brown used 264 participants across three treatments, among which 60 participated in the baseline experiment. 144 participants were corresponding with the paper's research question. All participants played two games, totaling 528 observations, or 288 observations relevant for the research question.

Chakravarty's results are more robust which can be explained by the higher number of observations. For each of the two treatments, six independent games were played. In each independent game, 20 players part-took across 30 rounds. In total, 7200 decisions were observed in the experiment. Of those, 25% - or 1600 - of the observations were relevant for the research question. Chakravarty managed to achieve results on the 5% or 1% for most relevant questions.

We suggest our experiment be played with 100 participants per treatment. Each participant plays one game, for a total of 2-10 rounds. We anticipate that the average game will last some 4-6 rounds. Our expected amount of observations is 2000, of which 500 are baseline and 1500 are relevant for research questions. While the total number of observations is considerably lower than in Chakravarty's example, we believe that it is sufficient to achieve significance levels of 5% for our main research questions.

4 Discussion

Previous literature has had it's focal point on the behavioral aspects on bank run contagion. It's main questions have been concerned with the validity of the Diamond-Dybvig framework, and the anatomy of sunspots. We owe a debt of gratitude to their research, and have tried to deepen the understanding of the foundation of rational and irrational behavior in the context of consumer bank runs – and what the implications would be were some of the environmental parameters changed.

Hypothesis 3 seeks to answer if a more liquidid form of money would affect the general group of consumers' behaviors in times of financial distress. As mentioned previously, a majority of consumers are largely unaware about deposit insurance, and will therefore make their decision to withdraw without information about it Sträter *et al.* (2008), and the case for excluding deposit insurance in experiments have been argued for previously by Brown *et al.* (2012). If Hypothesis 3 is verified, it would indicate a shifting behavior caused by the introduction of new monetary technology, and should be considered when further researching the topic of CBDC's. The finding would hold importance even if CBDC's were not introduced, as the effect would also be true in the comparison between cash and debit cards as primary form of payment. It is undoubtedly so that payments and value storage is becoming increasingly digitized, and the result of this fundamental change should be carefully considered.

Hypothesis 4 seeks to answer our question about the effectiveness of the deposit insurance in a new technological environment with CBDC's. In discussion with our supervisor, we theorized that central bank accounts used by the public could be interpreted as a super-liquid form of deposit insurance, as a consumer would be able to withdraw their funds from their commercial bank instantly and at practically any time. We believe that consumers prefer to be in control of their funds, instead of relying on the deposit insurance, would their commercial bank fail as previously argued by Sträter. If this hypothesis turns out to be true, deposit insurance in its current form might require thorough reconsideration.

The experiment we've proposed in this paper is intended to as accurately as possible test these two main hypotheses, regarding transaction cost and deposit insurance. After duly discussing and exploring different options, our conclusion is that transaction costs are best expressed as time – not as money. Although money and time are closely related in the world of finance, perhaps they're not equally regarded in the mind of the consumer. This is especially true when consumers are reliant on the funds in their bank account to finance expenses in the near-term.

The side effects of experimenting with time constraints on transactions is increased complexity of the game. Previous researchers' experiments, specifically Brown et al. (2012) and Chakravarty *et al.* (2013), are fairly successful in honoring the original DD model by limiting the rounds of the game. It produces clear results and facilitates interpretation by referral to the original model – as should a good experiment. In our take of a consumer experiment, the complexity is slightly raised.

We are particularly concerned about two aspects of our experiment design: multiple-round games diverging from the DD-framework and *net withdrawals* creating uncertainty pay-off interpretation by the players. However, within the context of the study, we believe we are in the right to do so. First; in order to produce results that imitates nature, one must create a nature-like environment. Our multiple-round and interest-accumulating game imposes aspects upon the consumer that the DD-model had previously removed.

Regarding the issue of wealth accumulation previous studies have been done. In a study conducted by the Bank of Italy Giuseppe Calietta (2012), the conclusion was that risk-aversion decreases as individual wealth increases, but research by Brunnermeier and Nagel (2008) and Chiappori and Paiella (2008) concluded that no significant effect was found. In our theoretical experiment, we have assumed players being risk-neutral, which may or may not be disputed by the results. Thus, the issue of risk-aversion and wealth continues to be an area of discussion. Second; *net withdrawals* arose as a rule of necessity rather than by inherent experiment design. It was a necessary design decision, because otherwise, you might have found in some games that players which remained deposited would be endowed risk-free returns as all other players had withdrawn over several rounds of the game.

The larger question is if these two factors will in a significant way impact the results of the game. For the first part, we believe that accumulating funds over several rounds is a viable way of experimenting and adds a vital aspect to the game – long-term decisions. What may be discussed is the level of interest that should be endowed depositors. In essence, our experiment likens the bank to an investment decision with much similarity to a stock.

Our equations, calculating players optimal response show that a higher interest rate improves risk-tolerance of players, as the pay-off for keeping funds deposited offsets the fear of losing some or all of their funds. This is very much similar to a risk-premium of a stock. Thus, the question arises: should the banks of the future offer risk-premium based interest rates, and are the consumers of the future informed enough to demand it? Or should rather policy be so strict that consumers never need to worry about the safety of their funds, whatever their size? One might argue that, although bank runs have occurred, they are infrequent enough to be treated as anomalies in an otherwise secure system - and thus should be rewarded similarly as a risk-free investment. Another argument would be that banks globally are continually increasing their risk exposure, which should imply a risk-premium endowed to their investor.

The topic of interest and risk leads us to the validity of an experiment which in many ways treats bank deposits and equity investments equally. If we would reframe the setting of our experiment and instead present it as a study about consumers attitude to risk-reward rates in equity markets, it would probably be accepted as such without any major arguments. The following question becomes: is it likely that the framework our experiment uses (and to some extent Chakravarty's and Brown's, too), is equally valid in equity markets as well as consumer bank deposits? Or should perhaps consumers' temporary storage of funds be treated as a completely separate matter from equity investments, with independent mechanisms such as reliability, accessibility and other benefits? If the answer of such a question is a new, intelligently designed way of researching average consumer behavior – either through big data or experiments – the field of behavioral finance would certainly be benefited. Whatever the conclusion, the subject of interest rates and financial stability is an area in where further research could prove fruitful.

The robustness of the experiment is another key area. Experimenting with human behavior is an area where results by definition are highly open for interpretation and always subject to external noise, be it non-verbal communication, setting, emotion or any number of other disturbances. To draw any broad conclusion we believe that the results must be clear and robust. Due to the complexity of our experiment (in comparison to our referral papers)[11], it is especially important to have a sufficient amount of observations. We also recognize the constraints attached to research experiments, and have limited the number of participants to 400 – which is still a considerably large amount. Potentially insufficient significance due to resource constraints is therefore one of the major hurdles for this experiment.

There are multiple other areas that demands investigation to approximate the full effects of CBDC implementation. The level of interest rates required to incentivize consumers to keep their funds with the commercial banks is a question in need of answering, as a free and independent alternative for value storage emerges. Capital requirements for commercial banks in relation to potentially increased financial instability is another important question. Finally, macroeconomic

[11] Chakravarty *et al.* (2013) and Brown *et al.* (2012)

effects from CBDC implementation offers many interesting topics, such as economic gain from reduced transaction costs and improved opportunity for micro-entrepreneurs.

This field of research is young and filled with pressing matters. Our view is that academic research may make a substantial contribution to the development of policy and technology in this area within the next few years.

5 Appendix

Note: The different treatments, monetary technology and deposit insurance, will be presented separately for the different groups. The participants will have a common section and a treatment-specific section.

Common Section

Verbal introduction

Welcome to this experiment. Make sure you read the given instructions thoroughly. In this game, you will take a decision every round. The decisions you make will determine your net wealth at the end of the game. All of your accumulated wealth in the game will be rewarded to you and paid out in SEK at the end of the game.

Initially all five players will be endowed with 100 units of currency (UoCs). The funds will be granted in a bank, on a deposit account. In the game, you will be able to choose one of three actions:

1. Withdraw your funds from your bank account.
2. Hold your funds where they are (inside or outside the bank)
3. Deposit funds into the bank.

All of your deposits in your deposit accounts generates interest every round. The interest is 25%, so if you choose to hold your funds in the bank during the first round of the game, in round two you will have 125 UoCs – 25% interest on 100 UoCs. The game will last for at most 10 rounds.

Your deposits in the bank in the bank are exposed to risk. Depending on the actions of the other players at the table, your pay-off may be altered from the 25% interest accumulated per round. The pay-off is also determined by the liquidity level in the bank. The pay-offs are structured in the following way:

[Hand-out 1 to participants]

In the handout, pay-offs are expressed as percent of your current holdings. # of players withdrawing today is expressed as number of net withdrawal. That means, if one players decides to deposit their funds into the bank, and two players decides to withdraw, then net withdrawals are one.

As you can see – depending on how the number of net withdrawals during a round, the pay-offs will be changed. Specifically, if you choose to hold your UoCs in your bank account when others choose to withdraw, you are at risk of earning a lower pay-off.

These pay-offs are also determined by the liquidity level of the bank. The liquidity level starts at 0,8 and is changed every round, one step of 0,2 up or down. The maximum liquidity level is 0,8 and the minimum is 0,2. In the beginning of each round I will tell you what the liquidity level is for the current round. Lower liquidity means lower pay-offs if players decide to withdraw.

After every round, a summary of number of withdrawals and deposits will be communicated. You will also receive a statement of your current net worth of UoCs. You may not discuss strategies with each other during the game. You may only signal when you have made your decision for a particular round.

If any player receives 0 in pay-off after a round, the bank is liquidized and the game is over. At the end of the game all players will net worth will be calculated and paid out.

Hand-out 1

Table
Payoffs

	Total # of players withdrawing today				
	0	**1**	**2**	**3**	**4**
L=0,8					
Withdraw today	100	100	100	100	90
Withdraw tomorrow	125	117	104	78	0
L=0,6					
Withdraw today	100	100	100	88	79
Withdraw tomorrow	125	106	82	0	0
L=0,4					
Withdraw today	100	100	87	77	69
Withdraw tomorrow	125	92	71	0	0
L=0,2					
Withdraw today	100	86	75	67	60
Withdraw tomorrow	125	0	0	0	0

The following treatment information is verbally communicated to each of the four treatment groups, depending on their treatment.

Treatment-specific Section 1: Monetary Technology CBDC

In this economy, there exists a central backed digital currency, which means that you have a deposit account at the central bank. This means that you can deposit or withdraw all of your UoCs during one round.

Treatment-specific Section 2: Monetary Technology Cash

In this economy, you hold your withdrawed UoCs as cash. Since it takes time to withdraw and deposit cash, it will take you two rounds to withdraw or deposit your entire net worth. The UoCs still kept in the bank after a first round decision to withdraw will still accumulate interest. The full "remaining" amount will however always be available to withdraw or deposit.

In the event you hold half of your UoCs in cash and half of your UoCs in the bank, you may choose whether you want to withdraw or deposit your funds into the bank. You may, however, not hold half of your funds in each for of value storage, and must therefore choose one of the decision withdraw or deposit.

Treatment-specific Section 3: Deposit Insurance

[Verbally added to either Cash or CBDC treatment information]

Furthermore, you have a deposit insurance. A deposit insurance means that 100 of your UoCs are insured by the state. If you, after a round, fall below a net worth of 100 UoCs, the difference will be reimbursed by the insurance company. The insured UoCs will be paid out after 3 rounds of the game, after your claim has been processed.

Treatment-specific Section 4: No Deposit Insurance

The participants are not to be informed of a deposit insurance.

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