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SNB Working Papers
17/2021

SCHWEIZERISCHE NATIONALBANK
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BANCA NAZIUNALA SVIZRA
SWISS NATIONAL BANK

Legal Issues

ISSN 1660-7716 (printed version)
ISSN 1660-7724 (online version)

Reserve Tiering and the Interbank Market*

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September 27, 2021

Abstract

Since the financial crisis, major central banks have introduced negative interest rates with the help of tiered reserve remuneration. We theoretically and empirically investigate monetary policy implementation via reserve tiering using a unique bank-level dataset from Switzerland. We find that reserve tiering can successfully be used to steer short-term interest rates. Furthermore, reserve tiering helps maintain sufficient activity in the interbank market, which is key for financial stability and reliable interest rate benchmarks. Due to frictions such as collateral constraints, trading costs, and window dressing around regulatory reporting dates, not only the aggregate level of reserves but also the reserve distribution matters for monetary policy implementation.

KEYWORDS: Interbank market, reserve tiering, negative rates, monetary policy

JEL CODES: E43, E58, G12, G21

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*We thank Katrin Assenmacher, Andreas Fuster, Petra Gerlach, Oliver Gloede, Mico Loretan, Antoine Martin, Benjamin Müller, Christian Myohl and participants of research seminars at the European Central Bank (2021), the SSES Annual Congress (2021) and the Swiss National Bank (2019) as well as an anonymous referee for very helpful and constructive comments. We would also like to thank Valentin Séchaud for help with the data. The views, opinions, findings, and conclusions or recommendations expressed in this paper are strictly those of the authors. They do not necessarily reflect the views of the Swiss National Bank. The Swiss National Bank takes no responsibility for any errors or omissions in, or for the correctness of, the information contained in this paper.

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1. Introduction

Interbank markets play a crucial role in the implementation of monetary policy. Central banks set conditions in the interbank market to steer short-term interest rates, which, in turn, affect the entire yield curve and the real economy. Most of the monetary policy literature discusses monetary policy transmission and simply assumes that a central bank can implement its policy stance perfectly. In reality, however, central banks face many challenges surrounding monetary policy implementation. After the financial crisis, monetary policy implementation has shifted from traditional systems with scarce reserves and positive interest rates to systems with abundant reserves and zero or even negative interest rates. Today, the question arises whether the post-crisis implementation frameworks have worked as intended and how to best implement monetary policy going forward.

A key component of the current implementation framework of many central banks including the European Central Bank, the Bank of Japan, and the Swiss National Bank (SNB), is tiered reserve remuneration. Reserve tiering means that banks' reserve holdings at the central bank below a certain threshold are remunerated at an upper interest rate (typically zero), while reserves above the threshold are remunerated at a lower interest rate (typically negative). Despite its central role in monetary policy implementation, reserve tiering is not yet well understood in the academic literature. In this paper, we fill this gap by providing the first systematic study of how reserve tiering affects interbank market activity and short-term interest rates. To that end, we study reserve tiering both theoretically and empirically.

First, we develop a simple model to derive theoretical predictions. The model is based on the traditional Poole (1968) model of reserve demand and is similar to the one of Boutros and Witmer (2020). It shows that central banks operating with reserve tiering not only have to account for the aggregate level of reserve requirements but also the aggregate level of tiering thresholds when steering short-term interest rates by adjusting the level of aggregate reserves. If aggregate reserves are below aggregate thresholds, the interbank interest rate lies in the corridor between the rates for borrowing reserves from and depositing reserves at the central bank. In contrast, if aggregate reserves exceed the aggregate tiering threshold, the tiered deposit rates form a new corridor. In this new corridor, the interest rate converges to the lower bound as reserves increase. When aggregate reserves are large relative to banks' deposit shocks, the model predicts that the sensitivity of interest rates to aggregate reserves is (virtually) zero and adjustments to central bank interest rates become the main tool available for the central bank to influence the interbank interest rate.

Activity in the interbank market depends on individual banks' trading incentives. Banks optimize their individual reserve holdings, considering the probabilities that reserves end up (i) below the minimum reserve requirement, (ii) above the minimum reserve requirement but below the tiering threshold, or (iii) above the tiering threshold. A bank has an incentive to trade when its reserves differ from the optimal level of reserves, which in turn depends on the bank's reserve requirement and tiering threshold. The larger the sum of banks' absolute trading incentives, the higher the total interbank market turnover. Thus, the distribution of initial reserves, reserve requirements, and tiering thresholds in the financial system matters for the aggregate turnover in the interbank market.

For the empirical analysis, we use a unique bank-level dataset in which we combine trading data from the Swiss Franc (CHF) overnight secured money market with banks' reserve holdings, tiering thresholds, and minimum reserve requirements at the SNB. We match these data with banks' regulatory ratios (capital and liquidity) and balance sheet information, including total assets and collateral availability.[1] We show that reserve tiering can be a useful tool to implement monetary policy. Tiering works as predicted by our model once we allow for frictions that keep some banks from participating in the interbank market.

In line with theory, we find little cross-sectional variation in interest rates and a nonlinear and negative relation between the market interest rate and the amount by which aggregate reserves exceed aggregated tiering thresholds. The interest rate becomes insensitive to changes in the aggregate level of reserves when aggregate reserves exceed the aggregate tiering threshold by 15% to 20%. In times of abundant reserves, the tiering threshold takes the role of the minimum reserve requirement as the main reference point for reserve management of individual banks. We find that banks with reserves below the tiering threshold borrow reserves in the interbank market. In contrast, there is little evidence that banks reallocate reserves if their reserves are above the threshold. This is consistent with the fact that banks have little to gain from lending when aggregate reserves are high, and rates are very close to the lower tiering rate. Any friction that is present can thus easily offset the gains, leading to less market activity. We show that collateral constraints, window dressing at regulatory reporting dates, and trading costs are the main frictions that prevent banks from trading reserves. Moreover, we find that banks appear to require a few months to fully adjust to changes in the tiering system. Due to the presence of frictions, not only the aggregate levels of thresholds and reserves but also the distribution of thresholds and reserves in the financial system affects interbank market activity and interest rates. Thus, accounting for frictions and the choice of thresholds are critical for successful monetary policy implementation and to foster interbank market activity, which is important for financial stability and for reliable interest rate benchmarks.

Our work is related to the following streams of literature. First, we add to the literature on how central banks affect the interbank market (e.g., Nautz, 1998; Bindseil, 2004; Whitesell, 2006; Lee, 2016; Vari, 2020; Bech and Keister, 2017; Fuhrer, 2018). So far, the literature on the impact of tiered reserve remuneration is scarce. From a theoretical perspective, our paper builds on Boutros and Witmer (2020), who extend the Poole (1968) model to include reserve tiering and show how cash holdings can limit the transmission of negative interest rates when tiering thresholds do not account for cash. From an empirical perspective, Bech and Malkhozov (2016) provide descriptive statistics of how various central banks have implemented negative interest rates and describe the transmission to money market rates. We analyze the impact of reserve tiering on interbank interest rates and market activity in depth and highlight how

[1] We focus on the secured market, as trading activity in unsecured markets has been very low since the financial crisis.

market frictions can lead to deviations from simple theoretical models. Such a comprehensive analysis is key to help central banks effectively implement monetary policy.

Second, our paper is related to studies on the transmission of negative interest rates and the pass-through to banks' customers and the real economy (see, e.g., Heider, Saidi, and Schepens (2019), Basten and Mariathasan (2020), Demiralp, Eisenschmidt, and Vlassopoulos (2019), Eggertsson, Juelsrud, and Wold (2017), Schelling and Towbin (2020) and Baeriswyl, Fuhrer, Gerlach, and Tenhofen (2021)). Berentsen, van Buggenum, and Ruprecht (2020) theoretically study the implications of negative interest rates and tiering thresholds on output and welfare, finding that tiering can reduce the negative effects of negative interest rates. Fuster, Schelling, and Towbin (2021) analyze how a parameter change in the Swiss reserve tiering system in 2019 was passed on to bank customers, finding only limited effects.

Third, we contribute to the literature on interbank markets more generally. Robust interbank markets are crucial for financial stability as demonstrated during several financial crises (Afonso, Kovner, and Schoar, 2011; Mancini, Ranaldo, and Wrampelmeyer, 2016). A common feature of money market theory is that the main purpose of the interbank market is liquidity insurance by enabling individual banks to efficiently offset temporary client flows or other liquidity shocks (e.g., Allen and Gale, 2000; Freixas, Parigi, and Rochet, 2000; Freixas, Martin, and Skeie, 2011; Afonso and Lagos, 2015a). Moreover, interbank market interest rates serve as benchmarks for a wide array of financial contracts, including derivatives, loans and securities worth trillions of dollars in the global economy (see, for example, Financial Stability Board (2014) or Financial Stability Board (2015)). Our results suggest that reserve tiering can foster an active interbank market that supports financial stability and reliable interest rate benchmarks.

The remainder of this paper is structured as follows. Section 2 introduces a simple model to derive predictions of how reserve tiering affects the interbank market. Section 3 provides the background on reserve tiering and the interbank market in Switzerland, while Section 4 provides the empirical analysis. Finally, Section 5 concludes and discusses policy implications.

2. A simple model for monetary policy implementation with reserve tiering

In this section, we derive theoretical predictions for banks' reserve holdings, trading activity in the interbank market and interbank interest rates. Large parts of the literature on monetary policy implementation use a variant of the Poole (1968) model to understand the relation between aggregate reserves and the interbank interest rate. The Poole model nicely describes the implementation framework that many central banks, including the Federal Reserve, the European Central Bank, and the SNB used before the 2007/08 financial crisis. We follow Boutros and Witmer (2020) and extend the Poole (1968) model to include reserve tiering. Whereas Boutros and Witmer (2020) focus on implementing negative interest rates when banks can transfer reserves to cash, we focus on reserve tiering more generally and discuss how central bank policy affects activity in the interbank market and the interbank interest rate. By providing comparative statics, we derive predictions for our empirical analysis. Moreover, we discuss how market frictions and new regulations may lead to deviations from the model outcome.

2.1 Model setup

To analyze the effects of reserve tiering on banks' reserve holdings, interbank interest rates and trading activity, we model banks' decision to participate in the interbank market with minimum reserve requirements and tiered reserve remuneration. A continuum of perfectly competitive banks indexed by i maximize expected profits.[2] Banks' balance sheets consist of bonds B^i and reserves R^i on the asset side and deposits D^i and equity E^i on the liability side. The model is static and includes four stages with the timeline shown in Figure 1.

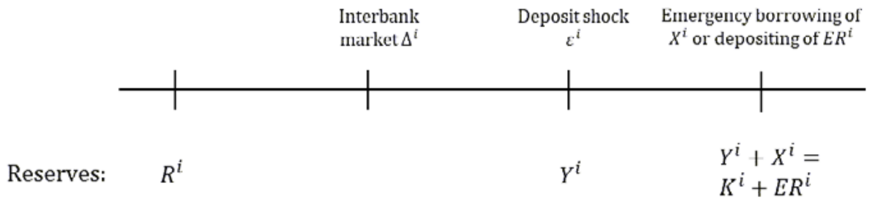


Fig. 1. *Model timeline:* shows the timing for banks' reserve management.

Stage 1 captures the time before interbank trading takes place. Before participating in the interbank market, banks hold reserves R^i. In reality, this starting position corresponds to reserves at the end of the previous day plus in- and outflows from clients. In stage 2, banks participate in the overnight interbank market to maximize expected profit. We let Δ^i denote the net turnover of bank i. When $\Delta^i > 0$ ($\Delta^i < 0$) the bank is a net borrower (net lender). In stage 3, the interbank market is closed, and banks are hit by a late deposit shock, ϵ^i, that is an independent and identically distributed random variable symmetric around zero. The shock is defined by its cumulative distribution function (CDF) $\mathcal{G}$. In stage 4, the late deposit shock has been realized and banks access central bank's standing facilities. If banks' reserves after the deposit shock, $Y^i = R^i + \Delta^i - \epsilon^i$, are below the minimum reserve requirement K^i, a bank borrows from the central bank's lending facility at rate r_X. We denote this borrowing by $X^i = \max\left(0, K^i - Y^i\right)$. If reserves are above the minimum reserve requirement, banks deposit excess reserves with the central bank: $ER^i = \max\left(0, Y^i - K^i\right)$. Reserves earn rate $r_M < r_X$ up to a tiering threshold of M^i and rate $r_R < r_M$ for reserves exceeding M^i.[3] To summarize, with a tiered system of reserve remuneration, the central bank sets rates such that $r_R < r_M < r_X$.

[2] Modeling a competitive market is consistent with the institutional characteristics of the secured CHF money market (Berentsen, Kraenzlin, and Müller, 2018).

[3] For simplicity, we assume that the rate on required reserves r_K is equal to the rate on excess reserves below the threshold r_M.

Banks' profits are then given by

$$
\begin{aligned}
\pi^i = & -r_\Delta \Delta^i + r_B B^i - r_D(D^i - \epsilon^i) + r_M K^i \\
& - r_X \max(0, K^i - Y^i) \\
& + r_M \max(0, Y^i - K^i) \\
& + (r_R - r_M) \max(0, Y^i - M^i),
\end{aligned}
\tag{1}
$$

where r_B denotes the bond return and r_D is the deposit rate for clients. Both r_B and r_D are given exogenously. The interbank interest rate r_Δ in equilibrium adjusts to clear supply and demand on the interbank market.

To maximize expected profits, banks need to choose the level of interbank market borrowing/lending before the deposit shock is realized. A bank borrows from the central bank when $Y^i < K^i$, i.e., when

$$\epsilon^i > R^i + \Delta^i - K^i \equiv \epsilon^i_K. \tag{2}$$

When $Y^i > M^i$, the bank receives a low rate for part of its reserves. This occurs when

$$\epsilon^i < R^i + \Delta^i - M^i \equiv \epsilon^i_M. \tag{3}$$

Using the CDF of ϵ^i, a bank's expected profit is given by

$$
\begin{aligned}
\mathbf{E}[\pi^i] = & - r_\Delta \Delta^i + r_B B^i - r_D D^i + r_M K^i \\
& - r_X \int_{\epsilon^i_K}^{\infty} (\epsilon^i - \epsilon^i_K) d\mathcal{G}(\epsilon^i) \\
& + r_M \int_{-\infty}^{\epsilon^i_K} (\epsilon^i_K - \epsilon^i) d\mathcal{G}(\epsilon^i) \\
& + (r_R - r_M) \int_{-\infty}^{\epsilon^i_M} (\epsilon^i_M - \epsilon^i) d\mathcal{G}(\epsilon^i)
\end{aligned}
\tag{4}
$$

Borrowing more in the interbank market affects expected profits directly through the cost of interbank borrowing, r_Δ. Moreover, there are two indirect effects: first, a higher Δ^i increases the probability that the bank deposits reserves in excess of the tiering threshold at rate r_R; and second, borrowing more decreases the probability that banks need to borrow from the central bank at rate r_X.

2.2 Equilibrium

An equilibrium is defined as a set of individual banks' choices for Δ^i and an interbank interest rate r_Δ such that banks maximize expected profits and the interbank market clears, i.e., $\Delta = \int_i \Delta^i di = 0$. The first order condition for bank i is given by:

$$0 = -r_\Delta + r_R \mathcal{G}(\epsilon^i_M) + r_M(\mathcal{G}(\epsilon^i_K) - \mathcal{G}(\epsilon^i_M)) + r_X(1 - \mathcal{G}(\epsilon^i_K)) \tag{5}$$

We can derive the equilibrium interbank interest rate by aggregating across banks and using

$\Delta = 0$:

$$r_\Delta = r_R \mathcal{G}(R - M) + r_M \left[\mathcal{G}(R - K) - \mathcal{G}(R - M)\right] + r_X \left[1 - \mathcal{G}(R - K)\right] \tag{6}$$

The interbank interest rate depends on the aggregate level of reserves R, minimum reserve requirements K, tiering thresholds M, central bank interest rates r_R, r_M, and r_X and the CDF of banks' deposit shocks. Figure 2 shows the equilibrium interbank interest rate when banks' deposit shock is normally distributed, i.e., $\epsilon \sim N(0, \sigma^2)$. For R close to K, the interbank interest rate moves in the traditional corridor between r_X and r_M. When R is close to M, r_M and r_R, form a new corridor. As R becomes large relative to M, r_Δ converges to r_R, the lower rate of the tiered system for reserve remuneration.

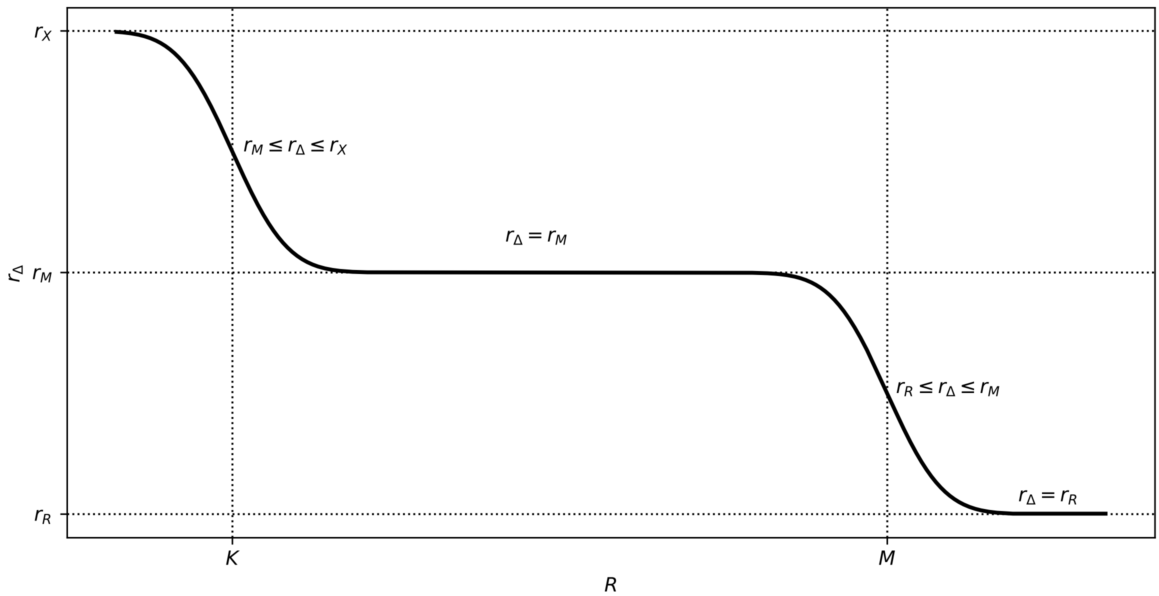


Fig. 2. *Interbank interest rate:* shows interbank interest rates in a tiered reserve remuneration system. It is derived from Equation (6) and assumes that banks' deposit shock is normally distributed. The vertical dashed lines mark the aggregate tiering threshold (minimum reserve requirement), $M = \sum M^i$ ($K = \sum K^i$). Reserves above (below) the threshold are remunerated at rate r_R (r_M). The top horizontal dashed line indicates the interest rate of the central bank's lending facility, r_X. The two lower horizontal dashed lines depict the interest rates for reserve deposits below and above the tiering threshold.

With reserve tiering, determining the sensitivity of interest rates with respect to the aggregate levels of reserves is more complicated than in the traditional framework. Using Equation (6), we can derive the sensitivity of the equilibrium interest rate to changes in the level of aggregate reserves,

$$\frac{\partial r_\Delta}{\partial R} = -\left(r_M - r_R\right) g(R - M) - \left(r_X - r_M\right) g(R - K) \tag{7}$$

where g denotes the PDF of banks' deposit shock. Reserve tiering thus introduces a second term that policy makers need to account for when assessing the impact of changes to the aggregate level of reserves on the equilibrium interest rate.

Knowing for what values of aggregate reserves interbank rates are flat is key for the implementation of monetary policy, especially in the context of monetary policy regimes with ample reserves.

$$\frac{\partial r_\Delta}{\partial^2 R} = -\left(r_M - r_R\right) g'(R - M) - \left(r_X - r_M\right) g'(R - K) \quad (8)$$

According to Equation (8), interest rates do not change with aggregate reserves when both $g'(R-M)$ and $g'(R-K)$ are zero. Policy makers thus have to consider not only the difference between aggregate reserves and the reserve requirements but also the difference between aggregate reserves and aggregate tiering thresholds. If g is the normal distribution, g' is equal to zero at exactly one point, so unless $K = M$, both terms cannot be equal to zero simultaneously. However, there can be combinations of R, M, and K, such that both terms can become virtually zero. For instance, when $R - M$ and $R - K$ are both large relative to the standard deviation of deposit shocks, adjustments in central bank interest rates r_R, r_M, and r_X become the main tool for influencing the interbank interest rate.

Aggregate turnover in the interbank market depends on individual banks' trading incentives. Our model also helps understand an individual bank's optimal level of reserves and its interbank market trading activity. An individual bank's optimal level of reserves, $R^{*,i} = R^i + \Delta^i$, depends on both the probability of falling short of the minimum reserve requirement, and the probability that reserves exceed the tiering threshold after the deposit shock. Given initial reserves R^i, all banks choose Δ^i such that the probabilities adhere to the following relation:

$$(1 - \mathcal{G}(R^i + \Delta^i - K^i)) = -\frac{r_M - r_\Delta}{r_X - r_M} + \frac{r_M - r_R}{r_X - r_M}\mathcal{G}(R^i + \Delta^i - M^i) \quad (9)$$

A bank's optimal level of reserves and interbank trading depend on K^i and M^i, as well as the distribution of deposit shocks. Moreover, central bank interest rates r_R, r_M, and r_X as well as the equilibrium interbank interest rate affect the optimal choice. To better understand how monetary policy in general and reserve tiering in particular affects the interbank market, we derive comparative statics on individual banks' optimal reserve holdings and interbank trading with respect to the interbank interest rate and the model primitives. The implicit differentiation of Equation (9) yields[4]

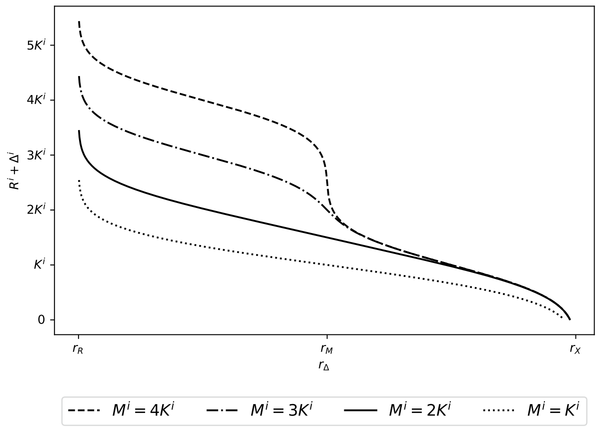
[4]In the derivations, we assume that the market aggregate level of R, M, and K are fixed, such that an increase in M^i (K^i) of bank i implies a reduction in the tiering threshold (reserve requirement) for one or more other banks. In this case, the partial derivatives of r_Δ with respect to model primitives are zero.

$$
\begin{aligned}
\frac{\partial(R^i+\Delta^i)}{\partial r_\Delta} &= \frac{\partial \Delta^i}{\partial r_\Delta} = \frac{\frac{1}{r_X-r_M}}{Q^i} \\
\frac{\partial(R^i+\Delta^i)}{\partial M^i} &= \frac{\partial \Delta^i}{\partial M^i} = \frac{r_M-r_R}{r_X-r_M}\frac{g(R^i+\Delta^i-M^i)}{Q^i} \\
\frac{\partial(R^i+\Delta^i)}{\partial K^i} &= \frac{\partial \Delta^i}{\partial K^i} = \frac{g(R^i+\Delta^i-K^i)}{Q^i} \\
\frac{\partial(R^i+\Delta^i)}{\partial r_X} &= \frac{\partial \Delta^i}{\partial r_X} = \frac{\frac{r_\Delta-r_M}{(r_X-r_M)^2}+\frac{r_M-r_R}{(r_X-r_M)^2}\mathcal{G}(R^i+\Delta^i-M^i)}{Q^i} \\
\frac{\partial(R^i+\Delta^i)}{\partial r_M} &= \frac{\partial \Delta^i}{\partial r_M} = \frac{\frac{r_X-r_\Delta}{(r_X-r_M)^2}+\frac{r_X-r_R}{(r_X-r_M)^2}\mathcal{G}(R^i+\Delta^i-M^i)}{Q^i} \\
\frac{\partial(R^i+\Delta^i)}{\partial r_R} &= \frac{\partial \Delta^i}{\partial r_R} = \frac{\frac{1}{r_X-r_M}\mathcal{G}(R^i+\Delta^i-M^i)}{Q^i},
\end{aligned}
$$

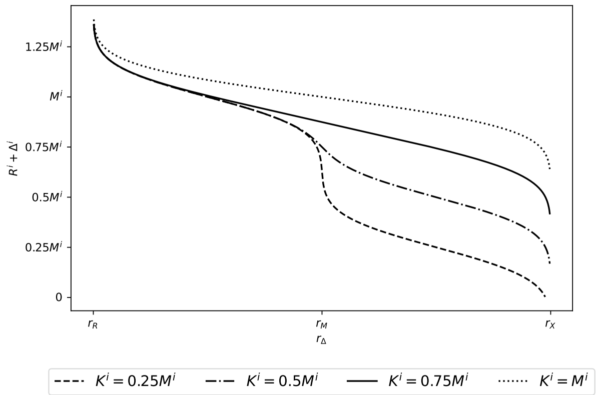
where $Q^i = g(R^i+\Delta^i-K^i)+\frac{r_M-r_R}{r_X-r_M}g(R^i+\Delta^i-M^i)$. Even in this simple model, understanding trading activity with reserve tiering is not straightforward.

Assuming that shocks are normally distributed, Figure 3 visualizes how optimal reserve holdings depend on the interbank interest rate. With interest rates close to r_R, the optimal level of reserves is higher than M^i, implying that the bank deposits reserves at the central bank at the low tiering rate. For the case that interest rates are close to r_X, the optimal level of reserve holdings is smaller than K^i, implying that the bank has to borrow from the central bank lending facility. While the relation is always downward sloping, the shape of the curve strongly depends on K^i, M^i, and the standard deviation of the deposit shock. Panel (a) shows the interbank rate and optimal reserve holdings of bank i for different levels of the tiering threshold. M^i positively affects optimal reserve holdings when r_Δ is smaller than r_M. For rates close to r_R, a one unit increase in M^i translates one-to-one to an increase in optimal reserve holdings. When $r_\Delta > r_M$, the effect of M^i vanishes unless M^i is close to K^i. The reason is that when the interbank interest rate is high, meaning that aggregate reserves are low, the risk of exceeding the threshold is small, such that increases in M^i only marginally affect a bank's decision to hold reserves. The results for K^i shown in Panel (b) are the opposite. Increases in reserve requirements only affect optimal reserve holdings when the interest rate is between r_M and r_X unless M^i is close to K^i. Panel (c) shows that the optimal level of reserves is close to $M^i = 4K^i$ when $r_\Delta < r_M$, especially if σ is small, i.e., a bank faces low uncertainty regarding its end-of-day reserve holdings. When $r_\Delta > r_M$, the optimal level of reserves is close to K^i. The effect of varying σ on optimal reserve holdings again depends on the level of interest rates. For $r_\Delta < (r_M+r_R)/2$, σ positively affects optimal reserve holdings. Similarly, σ is positively related to optimal reserve holdings when $r_M < r_\Delta < (r_X+r_M)/2$. For these interest rate ranges, a larger risk of a large shock means there is a larger risk of falling below M^i and K^i, respectively. In contrast, for $r_\Delta > (r_X+r_M)/2$ and $r_M > r_\Delta > (r_M+r_R)/2$, the relation is positive. If the interest rate is in these ranges, a larger σ implies a larger chance that reserves will be above M^i and K^i, respectively. A bank's interbank trading is given by the difference between its optimal reserve holdings and R^i. Figure 4 reverses the perspective and shows how a bank's interbank trading Δ^i depends on R^i, K^i, and M^i for different levels of interest rates. The higher R^i, the lower is Δ^i, independent of the interbank interest rate. Mirroring what we saw in Figure 3, interbank trading increases with M^i when $r_\Delta \leq r_M$. It increases with K^i when $r_\Delta \geq r_M$.

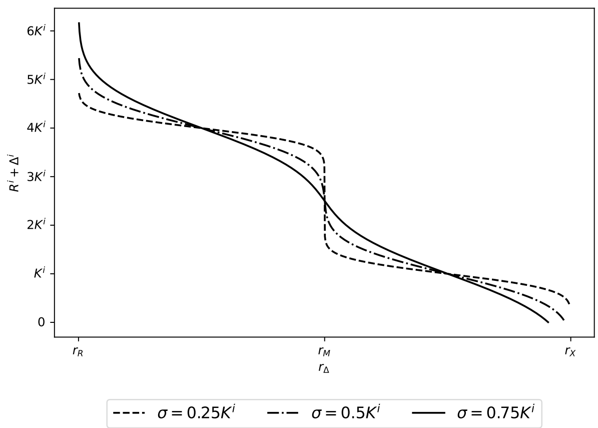
Based on these results, it becomes apparent that the distribution of R^i, K^i, and M^i across banks matters for the aggregate turnover in the interbank market. A bank has an incentive to trade when its initial reserves differ from the optimal level of reserves, which in turn depends on K^i and M^i. The sum of absolute trading incentives equals the aggregate interbank market turnover.



(a) Tiering threshold

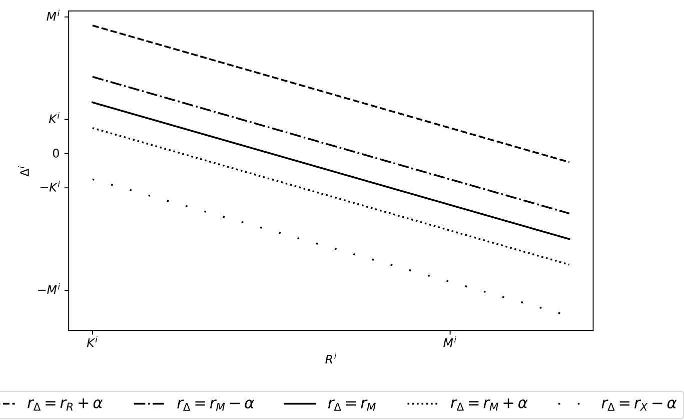


(b) Minimum reserve requirement

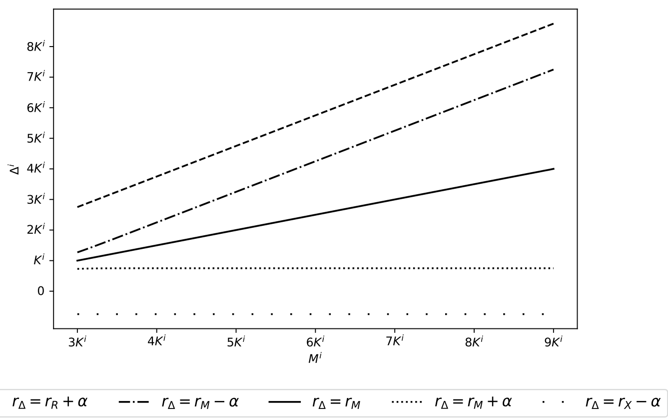


(c) Standard deviation of the deposit shock

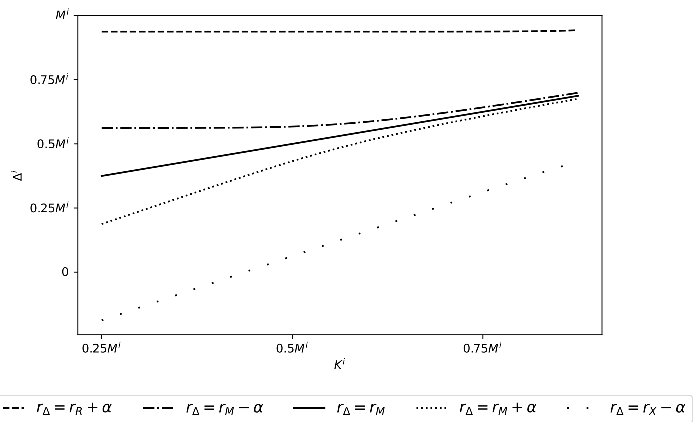
Fig. 3. *Optimal reserve holdings:* all three panels show the individually optimal reserve holdings, depending on the position of the interbank interest rate r_Δ relative to central bank interest rates r_R, r_M and r_X. We used the following numerical values to generate the plots: $r_R = -0.75$; $r_M = 0$; $r_X = 0.75$ In addition, Panel (a) varies the tiering threshold M^i from 20 to 80 with K^i fixed at 20 and $\sigma = 10$. Panel (b) varies the minimum reserve requirement K^i from 20 to 80 with M^i fixed at 80 and $\sigma = 10$, and Panel (c) varies the standard deviation of the payment shock σ from 5 to 15 with K^i fixed at 20 and M^i fixed at 80.



(a) Reserve holdings



(b) Tiering threshold



(c) Minimum reserve requirement

Fig. 4. *Optimal interbank trading:* Panels (a) to (c) show how the optimal interbank trading of an individual bank depends on the bank's initial reserve holdings R^i, the tiering threshold M^i, and the reserve requirement K^i for different levels of the interbank interest rate. For all plots, we used the following numerical values: $r_R = -0.75$; $r_M = 0$; $r_X = 0.75$, and $\alpha = 0.05$. In Panel (a), $M^i = 80$, $K^i = 20$ and R^i ranges from 20 to 100. In Panel (c), $R^i = K^i = 20$, and M^i ranges from 60 to 180. In Panel (c), $R^i = 20$, $M^i = 80$ and K^i ranges from 20 to 70.

2.3 Other factors that may impact reserve demand and the interbank market

While the simple model above describes an implementation framework with reserve tiering, it abstracts away from a number of complications that may affect reserve demand and the interbank market in practice. In this subsection, we discuss the key simplifying assumptions of the model that need to be taken into account when testing the model predictions empirically. Various factors that may impact reserve demand and the interbank market have been brought forward in the literature, ranging from additional reserve demand due to liquidity or capital regulation to frictions such as trading costs and collateral constraints. Which of these factors are relevant in an empirical analysis depends on the institutional setup, including characteristics of the interbank market and the central bank's implementation framework.

Regulatory requirements. Interbank market transactions may affect regulatory ratios for liquidity and capital and, in turn, influence banks' behavior. For instance, banks need to fulfill the Basel III Liquidity Coverage Ratio (LCR) which in turn affects their demand for reserves and hence their trading activity (see e.g., Logan (2019), Bech and Keister (2017)). Moreover, borrowing transactions increase the balance sheet size that imposes a regulatory cost under the Leverage Ratio (see, e.g., Allahrakha, Cetina, and Munyan (2018) or Kotidis and Van Horen (2018)). Munyan (2017) shows that regulatory requirements affect bank behavior in particular on reporting dates.

Liquidity hoarding. In periods of stress, some lenders may want to hoard reserves (Acharya and Skeie (2011), Heider, Hoerova, and Holthausen (2015)), meaning they aim to hold more reserves than in the model. This may lead to lower trading activity and higher interest rates. However, as the central bank determines reserves in the financial system, market wide liquidity hoarding considerations may only result in higher reserves if the central bank increases reserves in the financial system, otherwise reserve hoarding by one bank would automatically reduce reserve holdings of another bank.

Trading costs. In the model there are no direct or indirect costs when trading in the interbank market. In reality, there are various costs involved. First, banks that want to trade have fixed costs, e.g., to maintain a trading team and the necessary support systems. Second, there may be search and matching frictions (Afonso and Lagos (2015b), Bech and Monnet (2016)). Last, there can be transaction costs in the form of bid-ask spreads or trading fees. All these costs affect the profitability of interbank trading, which can lead to less trading than in the model. This, in turn, can affect the equilibrium interest rate. For instance, when the difference between the interbank rate r_Δ and r_R is smaller than a given bank's trading cost, this bank has no incentive to lend in the interbank market. Interest rates would need to go up to make it worthwhile for this bank to lend.

Default risk. Default risk translates into different forms of trading frictions in the interbank market (e.g., Pérignon, Thesmar, and Vuillemey (2018)).[5] In particular, lenders may demand

[5] Note that these considerations are particularly relevant when reserves are traded in the unsecured interbank market. However, they may also be relevant, though to a smaller extent, when transactions are secured by collateral market. The model does not distinguish between secured and unsecured transactions.

default risk premiums leading to higher interbank interest rates. Moreover, banks do not trade with all counterparties but select counterparties and impose credit limits. Credit limits may also not be counterparty specific but instead refer to the relative size of a bank's trading book. While counterparty selection and credit limits negatively affect trading activity, their impact on interest rates is not clear.

Collateral constraints. When reserves are traded in the secured market, the borrower needs to deliver collateral. If market participants are collateral constrained, they may not be able to satisfy their demand for reserves, which lowers trading activity and may decrease interest rates (Di Maggio and Tahbaz-Salehi, 2015).[6]

Market segmentation. In the model, all banks have access to the central bank and are equally eligible to use central bank facilities. If the interbank market is segmented (not all banks have access or not all are equally eligible), the market depends strongly on market participants trading with each other and using arbitrage opportunities such that the optimal reserve allocation is achieved. In case this allocation process is restricted by frictions, this may affect market activity and lead to differences in interest rates paid by certain categories of market participants (Williamson (2019), Lester and Armenter (2015), Kraenzlin and Nellen (2015), and Martin, McAndrews, Palida, and Skeie (2019)).

Bargaining power. If banks are not fully competitive, market participants' bargaining power may also play a role in determining bank-specific interest rates (see, e.g., Bech and Klee (2011), Kraenzlin and von Scarpatetti (2011), Fecht, Nyborg, and Rocholl (2011), and Afonso, Armenter, and Lester (2019)).

3. Background on reserve tiering and the interbank market in Switzerland

The SNB was one of the first central banks to introduce negative interest rates with a tiered reserve remuneration system in January 2015 (Swiss National Bank, 2014). We will use the Swiss setting to investigate reserve tiering empirically and test the predictions of the model. Given its large financial sector, internationally active banks, and a predominantly secured interbank market structure similar to other jurisdictions (e.g., euro area), the Swiss case is the ideal setting to analyze reserve tiering. In this section, we provide the most important background information about the Swiss institutional setting. We discuss the SNB's tiered reserve remuneration system, and describe the CHF interbank market in turn, highlighting how the model applies to the Swiss case and which of the frictions discussed in the previous section are relevant.

[6]Banks can mitigate collateral constraints if they re-use collateral. However, this implies that they have to borrow and lend cash at the same time to re-use collateral in a borrowing transaction which they received in a lending transaction (Fuhrer, Guggenheim, and Schumacher, 2016). If banks are only acting on one side of the market, they cannot mitigate collateral constraints.

3.1 Tiered reserve remuneration

The SNB introduced tiered reserve remuneration to implement negative interest rates, while limiting the pressure on banks' profitability (Swiss National Bank, 2014). In line with the model, banks are subject to both reserve requirements and reserve tiering. In the Swiss tiering system, reserves that exceed a bank-specific threshold are remunerated at $r_R = -0.75\%$, while reserves below this threshold are remunerated at $r_M = 0\%$. This is the reason why the tiering threshold is called exemption threshold in the Swiss context. The remuneration of reserves is based on banks' daily reserve holdings. In contrast, minimum reserve requirements have to be satisfied on average over a monthly reserve maintenance period.[7]

The model highlights that the specification of individual tiering thresholds relative to reserves are important for interbank market activity. In Switzerland, tiering thresholds vary across banks and across time. They are determined using two concepts: first, for domestic banks the tiering threshold is related to a bank's minimum reserve requirement (minimum reserve-based threshold); and second, for all other institutions with a reserve account at the SNB (e.g., domestic insurance companies, foreign banks, and financial market infrastructure providers), the tiering threshold is fixed for each institution and equals at least CHF 10mn (Swiss National Bank, 2015, 2019).

For the minimum reserve-based threshold, the SNB adjusted the calculation basis and changed the factor during the tiering period. From 2015 to October 2019, the threshold was calculated as 20 times the minimum reserve requirement as of the maintenance period October 20 until November 19, 2014, plus the change in cash holdings during the previous maintenance period. Thus, before November 2019, changes in a bank's reserve requirement did not affect its tiering threshold except monthly changes in cash holdings. Starting in November 2019, the tiering threshold corresponds to the moving average of the minimum reserve requirements over the preceding 36 maintenance periods, multiplied by a factor of 25, minus the cash holdings reported in the last period. With this adjustment, changes in the minimum reserve requirements lead to corresponding changes in the tiering threshold. However, the link is not immediate because thresholds are computed using a moving average. In the Swiss tiering system, cash holdings are deducted from a bank's threshold. Thus, banks do not have an incentive to convert reserves into cash to reduce the amount of reserves subject to negative interest rates, which would put upward pressure on interest rates (Boutros and Witmer, 2020).

[7] Maintenance periods last from the 20th of the current month until the 19th of the following month. The minimum reserve requirement is based on balance sheet items on a bank's liability side. Banks can use CHF coins, banknotes and reserves to fulfill minimum reserve requirements. If banks' reserve holdings fall short of the requirement, they have to pay a penalty rate equal to the secured overnight reference rate SARON plus 4%.

3.2 The interbank market

In this subsection, we briefly introduce the CHF interbank market.[8] Financial institutions can trade reserves in the secured or unsecured segment of the CHF money market. While the CHF unsecured market was predominant prior to the financial crisis, since 2007, the secured market is the prevailing market to trade reserves (Guggenheim, Kraenzlin, and Schumacher, 2011). This development mirrors developments in other jurisdictions (see, e.g., Di Filippo, Ranaldo, and Wrampelmeyer (2021) for evidence for a substitution from the unsecured to the secured euro interbank market).

The importance of the secured overnight market is underscored by the fact that transactions and quotes in this market are used to calculate the Swiss Average Rate Overnight (SARON). SARON is not only the CHF money market reference rate but also plays an important role for monetary policy implementation. Since June 2019, the SNB officially seeks to keep the SARON close to the SNB policy rate, replacing the target range for the three-month CHF LIBOR previously used in the SNB's monetary policy strategy.

In line with the assumptions of the model, the secured overnight market can be described as a competitive market (Berentsen, Kraenzlin, and Müller, 2018). Banks have little bargaining power, and variation in interest rates across banks is low.[9] Trading in the secured market takes place on an electronic trading platform, which is set up as a non-anonymous market with bilateral trade relationships. Quote-based trading is predominant and trading fees are low.

Most of the interbank trading is done overnight against the so-called SNB general collateral (GC) basket. General collateral transactions are cash-driven and borrowers can deliver any security that is part of the SNB GC basket as collateral. These securities are low risk as they need to fulfill stringent requirements with regard to credit rating and liquidity.[10] All SNB eligible securities are high-quality liquid assets (HQLA) under Basel III. Given that in our analysis transactions in the CHF interbank market are overnight and secured with high-quality collateral, counterparty risk is less of a concern for our empirical analysis. In contrast, it is important to account for potential collateral constraints.

To have access to the interbank secured market, market participants need to have a reserve account at the SNB. Thus, there is no market segmentation in the sense that some market participants have access to the central bank whereas others do not. Market participants can broadly be categorized into three groups: domestic banks, domestic nonbanks (e.g., insurance companies or financial market infrastructures) and foreign banks.[11]

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[8] For more details see, e.g., Kraenzlin (2007) and Fuhrer (2018).

[9] For more details, see Appendix A.1 and Fuhrer (2018).

[10] See, e.g., Swiss National Bank (2010) and Fuhrer, Müller, and Steiner (2017) for a more detailed description of the SNB's collateral framework.

[11] Although we use the term "interbank market" and "money market" interchangeably, strictly speaking, this is imprecise because the second group contains non-banks.

4. Empirical analysis

Our empirical analysis is structured as follows: First, we introduce the data set and provide descriptive statistics (Subsection 4.1). Then, we analyze banks' reserve holdings (Subsection 4.2), interbank trading activity (Subsection 4.3), and interest rates (Subsection 4.4).

4.1 Data

For our analysis, we collect bank-level data on (i) transactions in the secured overnight interbank market, (ii) reserve holdings, (iii) tiering thresholds, (iv) minimum reserve requirements and (v) regulatory ratios. For the secured overnight interbank market, we obtain transaction data from the electronic trading platform. We aggregate individual transactions to obtain the daily net interbank borrowing for each market participant.[12] We extend our data set by merging the interbank data with SNB data on daily reserve holdings, tiering thresholds, minimum reserve requirements, and regulatory ratios for each financial institution.

The tiering period used in our analysis ranges from January 22, 2015 to December 31, 2019, covering 1,247 working days. After cleaning the data, it contains 143,816 observations from 128 financial institutions.[13] The definition of our bank specific variables and abbreviations is provided in Table 1.

[12]Note that banks typically manage their reserve holdings in the overnight secured market. Banks are either cash takers or borrowers on a given day and market making activities (lending and borrowing at the same time) do not play a role.

[13]Cleaning the data removes approximately 1.6% of all observations. First, we excluded observations of institutions that are exempt from negative interest (0.9%). Second, we excluded observations around legal splits, mergers or termination of business (0.7%). Note that due to entrances and exits of institutions, we have an unbalanced panel. Moreover, for comparison, we also use data from the floor and corridor period starting on January 3, 2007. Including this period, the sample contains 374,861 observations from 3,274 trading days and 138 financial institutions.

				Availability if restricted	
Variable	**Description**	**Unit**	**Frequency**	**Time**	**Participants**
$\Delta_{i,t}$	Net turnover	bn CHF	daily		
$R_{i,t}$	Reserve level at the start of the day	bn CHF	daily		
$R^e_{i,t}$	Reserve level at the end of the day	bn CHF	daily		
$R\,(avg.\ MiRe)_{i,t}$	Reserve level averaged over minimum reserve maintenance period	bn CHF	monthly		domestic banks
$K_{i,t}$	Minimum reserve requirement	bn CHF	monthly		domestic banks
$M_{i,t}$	Tiering threshold	bn CHF	monthly	from January 2015 onwards	
$LCR_{i,t}$	Net Cash Outflows minus non-reserve High Quality Liquid Asset	bn CHF	monthly	from January 2015 onwards	domestic banks
$F_{i,t}$	Client flows	bn CHF	daily		
$Total\ Assets_{i,t}$	Total assets	bn CHF	annually		domestic banks
$I_{i,t}$	Incentive variable defined as reserves before interbank trading minus tiering threshold	bn CHF	daily	from January 2015 onwards	
$I^b_{i,t}$	Incentive variable ($I_{i,t}$ if negative, zero else)	bn CHF	daily	from January 2015 onwards	
$I^a_{i,t}$	Incentive variable ($I_{i,t}$ if positive, zero else)	bn CHF	daily	from January 2015 onwards	
$Intro^{3M}_t$	Dummy for introduction of tiering period at time t (one first three months after introduction, zero else)	binary	daily	January - March 2015	
$CC_{i,t}$	Dummy for collateral constraints of bank i at time t (one if incentive variable larger than available HQLA securities, zero else)	binary	monthly	from January 2015 onwards	domestic banks
$Large_{i,t}$	Dummy for large size of incentive of bank i at time t (one if incentive variable larger than 3% of total assets)	binary	daily	from January 2015 onwards	domestic banks
$LR^{low}_{i,t}$	Dummy for low leverage ratio of bank i at time t (one if ratio is below 50% percentile of distribution among banks)	binary	annually	from January 2015 onwards	domestic banks
$RWA^{low}_{i,t}$	Dummy for low risk weighted assets of bank i at time t (one if assets are below 50% percentile of distribution among banks)	binary	annually	from January 2015 onwards	domestic banks
$r_{\Delta,t}$	Interbank interest rate at time t	percentage	daily		
$r_{R,t}$	Central bank lower remuneration rate at time t	percentage	daily	from January 2015 onwards	
$r_{M,t}$	Central bank upper remuneration rate at time t	percentage	daily	from January 2015 onwards	
$r_{X,t}$	Central bank lending rate at time t	percentage	daily		

Tab. 1. *Description of variables:* This table provides an overview of the variables used in the empirical analysis.

Figure 5 shows the development of reserves, tiering thresholds and minimum reserve requirements. Since the introduction of reserve tiering, reserves exceed aggregated tiering thresholds. While there was a significant increase in reserves exceeding the threshold until November 2019, the increase in the factor reduced the amount subject to negative interest rates considerably.

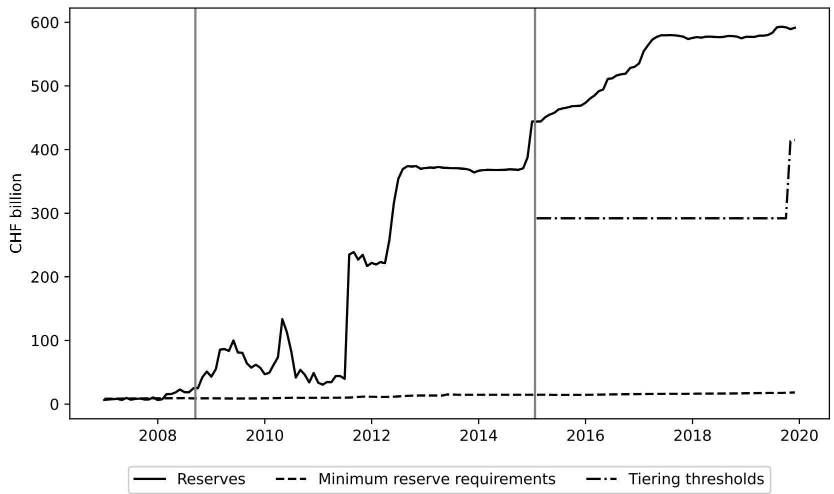

Fig. 5. *Reserves, minimum reserve requirements and tiering thresholds:* shows reserves, minimum reserve requirements and the approximated tiering thresholds (20, respectively 25 times the minimum reserve requirements). Reserves are defined as on the SNB data portal. The vertical lines indicate changes in the operational framework (corridor, floor, tiering). For more details about the variables see description in Table 1.

Figure 6 shows the development of the secured overnight interbank interest rate, SARON, and the tiered remuneration rates ($r_M = 0\%$ and $r_R = -0.75\%$), the lending rate as well as the deposit rate which was used prior to 2015. The figure illustrates that after the introduction of reserve tiering, SARON reached the lower rate r_R. After the SNB adjusted the basis for calculating the tiering threshold and increased the factor in November 2019, SARON increased and became more volatile.

Figure 7 shows the interbank trading activity. After the introduction of the tiered system for reserve remuneration, the turnover tripled from less than CHF 1 bn to approximately CHF 3 bn per day. With the adjustment of the tiering factor from 20 to 25, trading activity increased further to approximately CHF 6 bn per day, reaching the same level of activity as during the corridor period in 2008. Increased interbank activity indicates that banks reallocate more reserves in the presence of reserve tiering compared to the floor period.

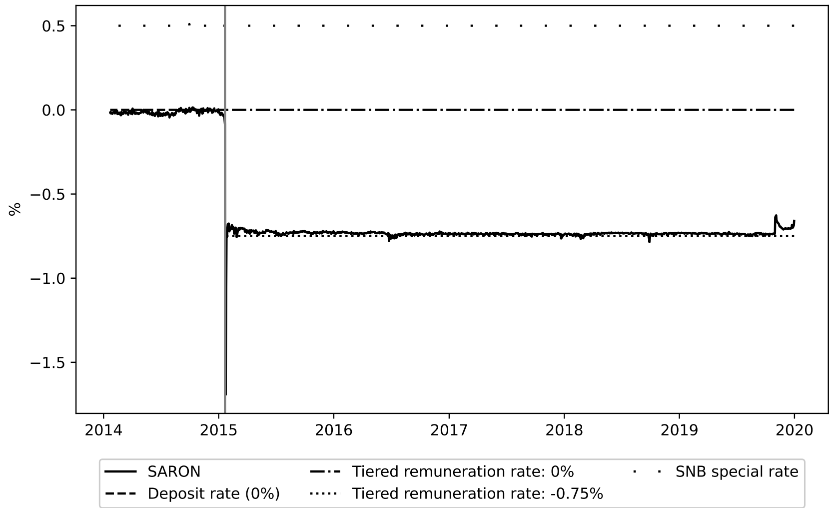

Fig. 6. *Interbank interest rates:* displays the average secured overnight interest rate SARON, the SNB's tiered reserve remuneration rates of 0% and -0.75%, the SNB's rate for the lending facility (SNB special rate) and the deposit rate (0%) used prior to January 22, 2015. The vertical line indicates introduction of reserve tiering on January 22, 2015. For more details about the variables see description in Table 1.

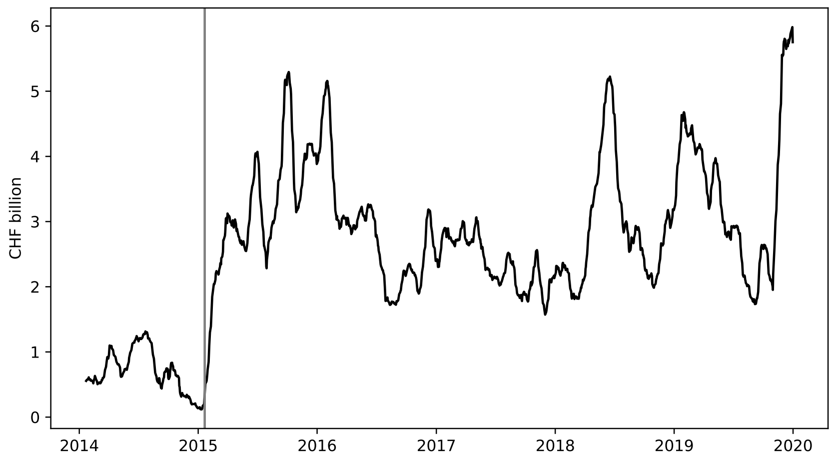

Fig. 7. *Interbank trading activity:* shows the turnover in the overnight secured market. The vertical line indicates introduction of reserve tiering on January 22, 2015. For more details about the variables see description in Table 1.

4.2 Reserve holdings

Before analyzing interbank trading and the interbank interest rate in the next subsection, we test whether banks' reserve holdings at the end of the trading day are consistent with the model.

In the model, banks' optimal reserve holdings depend on both the probability of falling short of the minimum reserve requirement and the probability that reserves exceed the tiering threshold. These probabilities depend on the levels of M and R and on the standard deviation of the banks' deposit shock. To test this relation, we conduct variants of the following fixed effect panel regression:

$$R^e_{i,t} = \alpha + \beta_1 M_{i,t} + \beta_2 K_{i,t} + \beta_3 SD(F)_{i,t-1} + \boldsymbol{\delta} Controls_{i,t-1} + \eta_i + \gamma_t + \epsilon_{i,t}, \qquad (10)$$

where $R^e_{i,t}$ are the end-of-day reserve holdings of bank i on day t, $M_{i,t}$ is the threshold, and $K_{i,t}$ are reserve requirements. To approximate the standard deviation of the deposit shock, we use the standard deviation of a bank's client flows during the previous maintenance period $SD(F)_{i,t-1}$.[14] We account for liquidity regulation as an additional reason to hold reserves as discussed in Section 2.3. More precisely, we include control variable $LCR_{i,t-1}$, defined as the difference between Net Cash Outflows (NCOF) and non-reserve HQLA held by the bank i in the previous months.[15] According to Bech and Keister (2017), banks with higher LCR requirements have an incentive to hold more reserves to satisfy the liquidity regulation.[16] Second, we also include banks' total assets as a control variable to check whether the size affects their reserve holdings in a way that is not captured by reserve requirements or tiering thresholds.[17] Additionally, we control for unobserved heterogeneity and market-wide developments by including bank group and time (day) fixed effects, denoted by η_i as well as γ_t, respectively and control for potential endogeneity issues by lagging the according variables. As thresholds for institutions without minimum reserve requirement are time invariant, we use bank group fixed effects in our baseline specification.

Columns 1 and 2 of Table 2 show the regression results. Overall, the coefficient for the threshold is positive, ranging from 0.95 to 1.05, and statistically significant in both regression specifications. This is in line with the model prediction that optimal reserve holdings increase one-to-one with $M_{i,t}$ when the interbank interest rate is close to r_R (recall Figure 3 Panel a).

[14] Net client flows are calculated as the difference of daily reserve holdings excluding interbank transactions. Note that for simplicity, the lag is simply denoted by $t-1$ while it is lagged by one maintenance period. This also applies for the LCR and total assets.

[15] For more details about the LCR see, e.g., Fuhrer, Müller, and Steiner (2017).

[16] Note that we have only information on the LCR requirement of domestic banks. The LCR was phased-in stepwise from January 1, 2015. The requirement was 60% in 2015 and subsequently was increased by ten percentage points every year until reaching 100% in 2019. For simplicity, we assume that banks aimed to fulfill the requirement directly by 100%, i.e., we do not apply the lower weights for the years 2015-2018.

[17] Note that as we include time fixed effects, there is no need to include market wide indicators such as the volatility index VIX to control for the risk-sentiment.

Also in line with the model, the coefficient for the minimum reserve requirement is statistically indistinguishable from zero (recall Figure 3 Panel b). Thus, we find no evidence that the minimum reserve requirement affects banks' reserve holdings when reserves are so high that the interbank interest rate is close to r_R. The coefficient measuring the standard deviation of a bank's client flows during the previous maintenance period indicates that the larger a bank's deposit shock, the larger its reserve holdings. This is consistent with the fact that a larger standard deviation of the deposit shock decreases the probability of falling below the threshold (recall Figure 3 Panel c). Looking at the control variables, we document a positive link between banks' regulatory liquidity requirements and banks' reserve holdings.

Our results are robust to various specifications. In Columns 3 and 4 we repeat the regression with variables in logs, confirming our baseline results. Columns 5 to 6 show that our baseline finding of a close relation between tiering threshold and reserve holdings is robust when using bank fixed effects instead of bank group fixed effects. In Appendix A.2, we conduct a difference-in-difference regression around the exogenous change in thresholds in November 2019, showing that reserve holdings move with the threshold. Moreover, we provide a comparison with the floor and corridor system, showing that in line with theory, the minimum reserve requirement was the key determinant of banks' reserve holdings during the corridor period.

Overall, these results provide strong empirical evidence that the tiering threshold is a key determinant of banks' reserve holdings in the tiered reserve remuneration system.

	(1)	(2)	(3)	(4)	(5)	(6)
	$R^e_{i,t}$	$R^e_{i,t}$	$\ln(R^e_{i,t})$	$\ln(R^e_{i,t})$	$R^e_{i,t}$	$R^e_{i,t}$
$M_{i,t}$	1.05***	0.94***			0.61***	0.55***
	(0.14)	(0.08)			(0.12)	(0.08)
$K_{i,t}$		-0.30				0.16
		(1.14)				(2.65)
$SD(flows)_{i,t-1}$		4.98**				-0.10
		(1.93)				(1.72)
$LCR_{i,t-1}$		0.39***				0.12
		(0.12)				(0.11)
Total $Assets_{i,t-1}$		-0.01				0.02
		(0.01)				(0.04)
$\ln(M)_{i,t}$			1.01***	0.48***		
			(0.07)	(0.13)		
$\ln(K)_{i,t}$				-0.09		
				(0.12)		
$\ln(SD(flows)_{i,t-1})$				0.22***		
				(0.04)		
$\ln(LCR_{i,t-1})$				0.14***		
				(0.04)		
ln(Total $Assets_{i,t-1}$)				0.25*		
				(0.15)		
Constant	0.16	-1.13***	-0.48***	-0.35	0.97***	16.84***
	(0.40)	(0.30)	(0.15)	(0.57)	(0.13)	(4.92)
Observations	143816	84354	143744	71890	143816	84354
Adjusted R^2	0.909	0.958	0.628	0.942	0.980	0.984
Time FE	Yes	Yes	Yes	Yes	Yes	Yes
Institution Type FE	Yes	Yes	Yes	Yes	No	No
Institution FE	No	No	No	No	Yes	Yes
Institutions	all	MiRe	all	MiRe	all	MiRe
Sample period	Tiering	Tiering	Tiering	Tiering	Tiering	Tiering

Tab. 2. *Banks' reserve holdings:* shows different regression specifications illustrating the relationship between banks' end-of-day reserve holdings $R^e_{i,t}$ and the tiering threshold. $M_{i,t}$ corresponds to a bank's tiering threshold and $K_{i,t}$ to its minimum reserve requirement. Standard errors reported in parentheses are clustered by financial institution. ***, ** and * denote statistical significance (two-tailed) at the 1%, 5%, and 10% significance levels, respectively. The sample period lasts from January 22, 2015 to December 31, 2019. For more details about the variables see description in Table 1.

4.3 Interbank market turnover

In the model, banks trade in the interbank market to reach their optimal level of reserves. Figure 4 predicts that interbank borrowing increases one-to-one with $M_{i,t}$ and decreases one-to-one with $R_{i,t}$ when the interbank interest rate is close to r_R as is the case in Switzerland during reserve tiering. Thus, the model predicts that banks' interbank market borrowing is determined by the difference between reserve holdings before participating in the interbank market and tiering thresholds $R_{i,t} - M_{i,t}$. To test this relation, we estimate variants of the following fixed effect panel regression:

$$\Delta_{i,t} = \beta_1 I_{i,t} + \alpha_i + \epsilon_{i,t} \tag{11}$$

where $\Delta_{i,t}$ is the net turnover of bank i at time t in the overnight market, $I_{i,t} \equiv R_{i,t} - M_{i,t}$, and α_i are bank fixed effects.[18] Recall from Section 2 that net turnover is positive (negative) when bank i is a net borrower (lender) of reserves. $I_{i,t}$ is negative for banks below their threshold, while it is positive for banks above the threshold and approximates its trading incentive.[19]

Column 1 of Table 3 shows the regression results for the baseline specification. In contrast to the prediction of the model, turnover does not seem to be related to $I_{i,t}$. To understand the reasons why the model fails to explain banks' trading behavior, next we control for different frictions as discussed in Section 2.3. One the one hand, with interest rates close to r_R, the difference in interest rates between lending reserves in the interbank market and keeping reserves at the central bank is small. Thus, even small frictions could have the effect that trading is not profitable for banks with reserves exceeding their threshold. On the other hand, trading may be favorable for banks with reserves below their threshold as the difference between the rate on their reserves r_M and the borrowing rate in the interbank market (close to r_R) is large. To capture differences in opportunity costs across reserve lending and borrowing banks we use interaction terms, distinguishing banks that hold reserves above or below the tiering threshold.

$$\Delta_{i,t} = \beta_1 I^b_{i,t} + \beta_2 I^a_{i,t} + \alpha_i + \epsilon_{i,t}, \tag{12}$$

[18] Note that $R_{i,t}$ is the reserve holding of bank i at time t ahead of interbank trading. We do not include time fixed effects because the daily net turnover for the entire market is zero by definition. For the same reason, neither do we include additional control variables that are the same for all banks, such as the position of interest rates or quarter-end dummies.

[19] Note that bank's optimal reserve holding according to the model is somewhat larger than the threshold depending the level of interest rates. For simplicity, we use the threshold as approximation implying that we may underestimate (overestimate) the trading incentive for banks with reserve holding before participating in the interbank market below (above) the threshold.

where

$$I^b_{i,t} = \begin{cases} I_{i,t} & \text{if } I_{i,t} \leq 0 \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

and

$$I^a_{i,t} = \begin{cases} I_{i,t} & \text{if } I_{i,t} \geq 0 \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

Column 2 of Table 3 shows that there is no relation for banks with reserves above the threshold, whereas banks below the threshold exhibit a statistically significant link between I and turnover. This finding is consistent with differences in opportunity costs as described above. Even with low direct trading costs as in the CHF interbank market, there can be indirect costs such as maintaining a team or reporting requirements that make interbank trading unprofitable, such that banks deposit reserves with the central bank rather than lending in the interbank market. To further support the reasoning that market frictions have a different effect for banks below and above the threshold, we investigate the persistence of banks' trading incentive. The probability that a bank with an incentive to reduce reserves on day t also has an incentive to reduce reserves on the following day is 89%, which is consistent with the reasoning above that it might not be worthwhile for these banks to participate in the interbank market due to trading costs (see Appendix A.2 for more details). Banks with reserves below the threshold trade more in line with their trading incentive. For banks with an incentive to borrow reserves, i.e., a negative I, the coefficient is significantly negative, but with -0.10 smaller in absolute value compared with the model prediction of -1. Thus, even for banks that have reserves below the threshold and thus a large incentive to borrow in the interbank market, the model is not able to explain banks' trading activity entirely. Section 2.3 includes a number of potential explanations that we investigate in turn.

First, the introduction of negative rates with a tiered system for reserve remuneration in 2015 led to a significant and immediate change of opportunity costs for banks. In particular, some banks that were previously holding reserves exceeding minimum reserves – and instead had a cash providing incentive – may suddenly end up with reserves below the tiering threshold and an incentive to borrow reserves in the interbank market. Banks needed to become familiar with the new system and had to establish the necessary trading capacity to borrow reserves up to their tiering threshold. For instance, establishing new trading relationships, increasing counterparty or credit limits can be time consuming in practice. We interact I with a dummy variable that is one in the first three months after the introduction of reserve tiering in 2015 to capture delayed adjustment to the new implementation framework.

Second, given the secured nature of the CHF interbank market, collateral constraints are an important friction that may keep banks from borrowing reserves. To analyze whether banks change their trading activity when they are collateral constrained, we use banks' SNB eligible security holdings reported under the LCR.[20] As these securities can be used in the secured market and overnight transactions do not affect banks' LCR, we use this as a proxy for the available collateral. We create a dummy variable to indicate whether a bank's trading incentive exceeds the available collateral and interact it with the trading incentive below the threshold.

Third, the size of a bank's trading book may also play a role in banks' decision to borrow less than predicted. As discussed in Section 2.3, credit limits may not be counterparty specific but the relative size of the trading book compared to total assets might be pivotal. Accordingly, we analyze whether banks with large trading incentives relative to their balance sheet behave differently. To do so, we use a dummy variable, indicating whether the amount of reserves a bank would like to borrow to reach its tiering threshold is large. We define an incentive to be large if the incentive relative to total assets is larger than the median (i.e., it exceeds the 50% percentile across all banks).

Fourth, Basel III requires that banks disclose their LR publicly as of January 1, 2015. As the frequency of the disclosure needs to be concurrent with the publication of the financial statements (i.e., for most banks quarterly) and banks report the LR as of the end of the period, we analyze whether borrowers change their behavior on quarter-ends by interacting the incentive variable with month-end and quarter-end dummies.

Fifth, regulatory costs of reserve borrowing may be particularly large if a bank's leverage ratio is already low. Therefore, we investigate whether banks with a low leverage ratio (i.e., below the 50% percentile across all banks) borrow less if their reserve level is below the threshold.

Columns 3 and 4 of Table 3 analyze the different frictions in a multiple regression setting. When controlling for frictions, the coefficient of I for banks with reserves below the threshold ranges from -0.67 to -0.85, which is much closer to the model prediction of -1. Three main frictions appear to prevent banks from borrowing in the interbank market. First, we find evidence that there are adjustment costs after the introduction of a new monetary policy regime. The relation between I and turnover for banks below the threshold is significantly weaker in the first three months after the introduction of reserve tiering (see positive interaction term in Column 3). Second, collateral constraints appear to limit banks from borrowing in the interbank market. While unconstrained banks borrow as predicted by the model, the turnover of collateral constrained banks is not related to their trading incentive. Third, regulatory requirements appear to affect trading behavior of borrowers at quarter-ends. The interaction terms for quarter-ends are positive and statistically significant, suggesting that banks react less to their tiering incentive when they must disclose their balance sheet and leverage ratio. The size of the trading incentive and constraints due to regulatory requirements outside of quarter-ends do not appear to play a major role.

Overall, our empirical results show that the simple model is not able to fully explain individual bank's interbank market activity. Only when accounting for frictions, in particular, collateral constraints, adjustment costs, trading costs, and window dressing around regulatory reporting dates, are the results close to the model's prediction.

[20] In the LCR reporting, SNB eligible securities are reported separately as a subcategory of HQLA.

	(1)	(2)	(3)	(4)
	$\Delta_{i,t}$	$\Delta_{i,t}$	$\Delta_{i,t}$	$\Delta_{i,t}$
$I_{i,t}$	-0.01			
	(0.01)			
$I^b_{i,t}$		-0.10**	-0.67***	-0.85***
		(0.05)	(0.21)	(0.08)
$I^a_{i,t}$		-0.00	0.00**	0.01***
		(0.00)	(0.00)	(0.00)
$I^a_{i,t} * Intro^{3M}_t$			0.01	
			(0.02)	
$I^b_{i,t} * Intro^{3M}_t$			0.35***	
			(0.05)	
$I^b_{i,t} * CC_{i,t}$			0.53***	0.89***
			(0.10)	(0.05)
$I^b_{i,t} * Large_{i,t}$			0.08	0.02
			(0.22)	(0.03)
$I^b_{i,t} * QuarterEnd_t$			0.08**	0.01***
			(0.03)	(0.00)
$I^b_{i,t} * MonthEnd_t$			0.06	0.01
			(0.04)	(0.00)
$I^b_{i,t} * LR^{low}_{i,t}$				0.19
				(0.31)
$I^b_{i,t} * LR^{low}_{i,t} * Large_{i,t}$				-0.27
				(0.26)
Constant	0.02*	0.00	-0.03***	-0.05***
	(0.01)	(0.01)	(0.00)	(0.01)
Observations	83817	83817	83817	33887
Adjusted R^2	0.010	0.061	0.338	0.516
Institution FE	Yes	Yes	Yes	Yes
Institutions	all	all	all	all
Sample period	Tiering	Tiering	Tiering	Tiering

Tab. 3. *Turnover and trading incentive:* $\Delta_{i,t}$ is the net turnover of bank i at time t and $I_{i,t} \equiv R_{i,t} - M_{i,t}$, is the trading incentive. To capture differences in opportunity costs across reserve lending and borrowing banks, we use interaction terms, distinguishing banks that hold reserves above the tiering threshold, $I^a_{i,t}$, and banks that hold reserves below the tiering threshold, $I^b_{i,t}$. Standard errors reported in parentheses are clustered by financial institution. ***, ** and * denote statistical significance (two-tailed) at the 1%, 5%, and 10% significance levels, respectively. The sample period lasts from January 22, 2015 to December 31, 2019. For more details about the variables see description in Table 1.

4.4 Interest rates

Last, we analyze the relation between the interbank interest rate and aggregate reserves and tiering thresholds. Consistent with the model, we use the daily volume-weighted average overnight rate as a measure for the interbank interest rate as there is little bank-specific interest rate variation (see Section 3 and Appendix A.1).

Figure 8 shows the relation between the interbank rate and the amount of reserves exceeding tiering thresholds. Consistent with the model, it shows a nonlinear and negative relation. The lower the amount of reserves subject to negative interest rates, the higher the level of interest rates relative to the lower remuneration rate r_R. Thus, with reserve tiering, it is crucial to account for the level of aggregate tiering thresholds when steering interest rates by adjusting the level of aggregate reserves. In line with the model's predictions, the sensitivity of interest rates to aggregate reserves is (virtually) zero when aggregate reserves are large relative to the aggregate threshold.

For central banks, it is important to understand the level of aggregate reserves at which interest rates become sensitive to changes in aggregate reserves. To shed light on this, we specify a functional form for the demand curve for reserves. Following Veyrune, della Valle, and Guo (2018) and in the spirit of Bech and Monnet (2016) and Bindseil (2014), we use a bivariate logistic function which has the following form:

$$r_{\Delta,t} - r_{R,t} = \gamma + \frac{\kappa - \gamma}{1 + \beta e^{-\alpha(R^e_{t-1} - M_{t-1}) + c}}, \tag{15}$$

This functional assumption has the properties that interbank rates converge to the ceiling of the corridor κ with very low levels of reserves exceeding tiering thresholds and to the bottom of the corridor γ with very large levels of reserves exceeding tiering thresholds. Analogous to Veyrune, della Valle, and Guo (2018), we estimate the following three parameters: (i) the lower asymptote γ, (ii) the coefficient α linking reserves exceeding thresholds ($R^e_{t-1} - M_{t-1}$) with interest rates ($r_{\Delta,t} - r_{R,t}$) and (iii) the constant c which indicates the positioning of rates without reserves exceeding thresholds.[21]

The estimated demand curve is depicted in Figure 8, together with the estimated parameters. The lower asymptote is estimated at approximately 1.5 bps above the lower remuneration rate $r_{R,t}$. Thus, with sufficient reserves, the interbank rate is converging very close to the SNB's lower deposit rate. This also reflects the fact that trading costs are low and approximately 1.5 bps are sufficient for the cash provider to place reserves more profitable in the interbank market (covering trading costs) than to deposit them at the central bank. The interest rate sensitive part, here defined as the part when rates are more than 5 bps above r_R, begins at CHF 25 and 50 bn, which corresponds to approximately 15–20% of aggregated tiering thresholds. For comparison, in the floor period, the interest rate sensitive part seems to be somewhat lower with approximately CHF 25 bn required for the interbank interest rate to reach approximately

[21] The ceiling κ is set at 75 bps ($r_M - r_R$) and for β we use a value of one.

5 bps above r_R.[22]

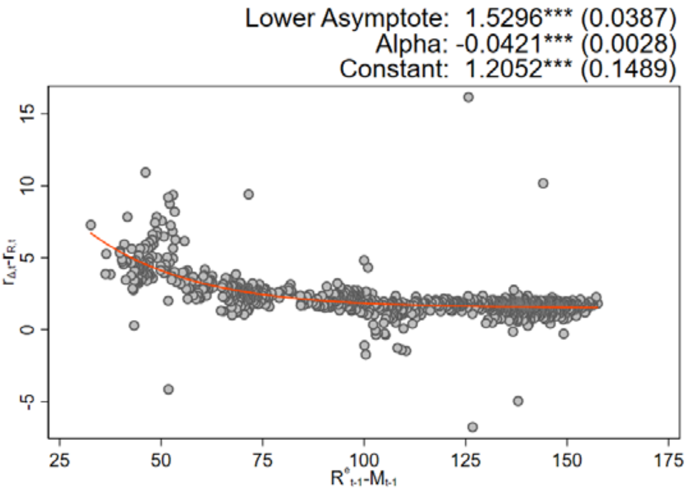

Fig. 8. *Interbank interest rates and reserves:* shows the spread between volume weighted average interbank interest rates and the lower remuneration rate, $r_{\Delta,t}$–$r_{R,t}$, and the aggregate amount of reserves exceeding tiering thresholds, $R^e_{t-1} - M_{t-1}$, in CHF bn. The fitted line is based on the estimated logistic function (see Equation (15)). Parameters estimated are the lower asymptote γ, the coefficient α linking reserves exceeding thresholds $R^e_{t-1} - M_{t-1}$ with interest rates and the constant c, which indicates the positioning of rates without reserves exceeding thresholds. The ceiling κ is set at 75bps ($r_M - r_R$) and for β we use a value of one. The sample period lasts from January 22, 2015 to December 31, 2019. Five days with SNB fine-tuning operations (in November and December 2019) as well as two days with interest rates below -1% directly after the discontinuation of the minimum exchange rate have been excluded. For more details about the variables see description in Table 1.

Overnight interbank interest rates may, however, also be affected by bank regulation and market frictions, which may significantly affect the amount of reserves required for a certain interbank rate (Afonso, Kim, Martin, Nosal, Potter, and Schulhofer-Wohl, 2020). Therefore, we study whether the frictions that affect interbank market turnover also affect the interbank interest rate.

$$r_{\Delta,t}–r_{R,t} = \alpha + \beta_1(R^e_{t-1} - M_{t-1}) + \beta_2(R^e_{t-1} - M_{t-1})^2 + Controls_t + \epsilon_t, \tag{16}$$

where the dependent variable $r_{\Delta,t}$–$r_{R,t}$ is the spread between the volume weighted average overnight interbank interest rate and the lower remuneration rate. For this analysis, we do not assume a specific functional form for the relationship between the position of interest rates and reserves exceeding thresholds but only account for a potential negative and nonlinear relationship. Thus, we include aggregate reserves above the tiering threshold, $R^e_{t-1} - M_{t-1}$, as the explanatory variable. To account for the nonlinear relation between reserves above the tiering threshold and the interest rate spread, we include the squared term of this variable as well. We control for market frictions by including dummy variables for the first three months to account

[22] Note, this comparison is not straightforward as the lending facility was changing over time and, hence, the corridor width was normalized. Results are available from the authors upon request.

for the fact that banks required some time to get used to the new system. Additionally, we capture aggregate collateral constraints of banks, denoted as CC_t. To measure collateral constraints, we create a dummy variable to indicate whether a bank's reserve borrowing incentive exceeds the available collateral, interact it with the according trading incentive and sum over all banks. Finally, we include month-end and quarter-end dummy variables to account for potential window dressing effects (e.g. Munyan, 2015). To ensure the exogeneity of our independent variables, all variables are lagged by one business day except the dummy variables.

	(1)	(2)
	$r_{\Delta,t}-r_{R,t}$	$r_{\Delta,t}-r_{R,t}$
$R_{t-1} - M_{t-1}$	-0.1226***	-0.0527***
	(0.0142)	(0.0163)
$(R_{t-1} - M_{t-1})^2$	0.0005***	0.0002***
	(0.0001)	(0.0001)
CC_{t-1}		-0.1241***
		(0.0359)
Jan. 2015_t		-0.3087
		(1.4722)
Feb. 2015_t		1.8324***
		(0.5108)
Mar. 2015_t		0.9780**
		(0.4258)
Apr. 2015_t		0.1446
		(0.2233)
$QuarterEnd_t$		-0.6838*
		(0.3920)
$MonthEnd_t$		0.0521
		(0.2064)
Constant	9.0245***	5.1359***
	(0.7446)	(0.8637)
Observations	1239	1239
Adjusted R^2	0.454	0.536
Fine-tuning days	excl.	excl.
Period	Tiering	Tiering
Errors	NW (6 lags)	NW (6 lags)

Tab. 4. *Interbank interest rates:* provides the regression results for the position of interest rates. The dependent variable is the spread between volume weighted average interbank interest rate and the lower remuneration rate, $r_{\Delta,t} - r_{R,t}$, at time t in basis points. R^e_t denotes aggregate reserves, M_t aggregate tiering thresholds, K_t aggregate minimum reserve requirements, and CC_t aggregate collateral constraints at time t. Independent variables (except dummy variables) are lagged by one business day. Heteroskedasticity and autocorrelation robust t-statistics are presented in parentheses, using the Newey and West (1987) correction. The number of lags used for the Newey and West (1987) correction are indicated in bottom row. ***, ** and * denote statistical significance (two-tailed) at the 1%, 5%, and 10% significance levels, respectively. The sample ranges from January 22, 2015 to December 31, 2019. Five days with SNB fine-tuning operations (in November and December 2019) as well as two days with interest rates below -1% directly after the discontinuation of the minimum exchange rate have been excluded. For more details about the variables see description in Table 1.

Table 4 shows our regression results. The coefficient for reserves subject to negative interest rates is statistically significant and negative while the squared term is statistically significant and positive, supporting again the hypothesis that an increase in reserves exceeding the tiering threshold lowers interest rates in a negative and nonlinear way.[23]

When focusing on the specification with the additional control variables (Column 2), we find that accounting for banks' collateral constraints seems to be important. The negative and statistically significant coefficient indicates that when potential borrowers in the interbank market are collateral constrained, interbank interest rates are lower. This result makes sense as demand for reserves is reduced which lowers, for a given supply of reserve, the interbank rate. Two of the four dummy variables for the introduction period of reserve tiering are statistically significant, too. Consistent with the results for trading volume, which indicate a reduced activity for banks with reserves below the threshold, the interest rate is higher in February and March 2015 while the coefficient for April 2015 is no longer statistically significant. Thus, our results are consistent with banks' adjustment cost also affecting the equilibrium interest rate. Looking at the dummy variable for period-end effects there is some evidence for lower rates at the end of a quarter. The direction of the effect is consistent with reserve borrowing banks requiring a higher compensation to extend their balance sheet over the reporting dates. However, the effect is only significant at the 10% level and economically small, which is likely because the interest rates are relatively close to r_R and, hence, have little room to decline.

5. Conclusion and policy implications

This paper theoretically and empirically analyzes monetary policy implementation via reserve tiering and its transmission in the interbank market. We show how reserve tiering affects interbank market activity and the short-term interest rate based on an in-depth analysis of banks' reserve holdings, interbank market activity and interest rates in Switzerland. In times of abundant reserves, the level of aggregate reserves that exceed the tiering threshold determines the level of the interbank interest rate. For individual banks, the tiering threshold takes the role of the minimum reserve requirement as main reference point for reserve management and it explains the redistribution of reserves in the interbank market. Moreover, we show that market frictions can affect monetary policy implementation. Due to frictions such as collateral constraints, window dressing at regulatory reporting dates and trading costs, the distribution of reserves in the financial system can affect interbank market activity and interest rates.

Our results have various policy implications. First, we show that reserve tiering can be an effective tool to implement monetary policy. Interbank interest rates exhibit little variation and there is a clear relation between aggregate reserves and the interbank interest rate. Moreover, reserve tiering can help ensure robust interbank market activity, which is key for financial stability and for robust interest rate benchmarks (see, e.g., Financial Stability Board (2014) and Duffie, Dworczak, and Zhu (2017)).

Second, our results show that market frictions are important and can cause deviations in interest rates and trading activity compared to simple theoretical considerations. Thus, central

[23]In Appendix A.3, we provide additional evidence using a regression model using changes in the variables of interest, supporting our baseline findings.

banks should not only be aware of basic theoretical relationships but also account for and monitor market frictions when choosing the framework to implement their policy stance.

Third, it is important to account for new regulations that may affect the aggregate demand for reserves. We find evidence that individual banks borrow less at quarter-ends, which is consistent with window dressing on regulatory reporting days. Moreover, we find that the interest rate sensitive part with reserve tiering starts at approximately 15-20% of current thresholds. This seems to be somewhat higher than in past episodes, consistent with an increased demand for reserves due to fundamental changes in bank regulation as suggested by Afonso, Kim, Martin, Nosal, Potter, and Schulhofer-Wohl (2020).

Fourth, with reserve tiering, central banks not only have to determine banks' reserve requirements but also set the tiering thresholds. The choice of individual banks' thresholds is important as it not only has a direct effect on banks' profits but also has implications for interbank market activity and, hence, the robustness of benchmark rates. For central banks it is important to carefully account for these effects when determining thresholds. Our results suggest that interbank markets stay active as long as there are sufficient banks with reserves below the threshold.

Fifth, many central banks implemented reserve tiering to implement negative interest rates. However, the framework is universal and could also be applied in a positive interest rate environment. The central bank would need to adjust the two tiering rates. In a tightening cycle, such a tiering framework would enable central banks to increase interest rates by paying interest on reserves, but at the same time it can facilitate an active interbank market.

References

Acharya, V. V., and D. Skeie, 2011, "A model of liquidity hoarding and term premia in interbank markets", *Journal of Monetary Economics*, 58(5), 436–447.

Afonso, G., R. Armenter, and B. Lester, 2019, "A model of the federal funds market: yesterday, today, and tomorrow", *Review of Economic Dynamics*, 33, 177–204.

Afonso, G., K. Kim, A. Martin, E. Nosal, S. Potter, and S. Schulhofer-Wohl, 2020, "Monetary policy implementation with an ample supply of reserves", *FRBNY Staff Reports*, No. 910.

Afonso, G., A. Kovner, and A. Schoar, 2011, "Stressed, not frozen: the federal funds market in the financial crisis", *Journal of Finance*, 65(4), 1109–1139.

Afonso, G., and R. Lagos, 2015a, "Trade dynamics in the market for federal funds", *Econometrica*, 83(1), 263–313.

——— , 2015b, "Trade dynamics in the market for federal funds", *Econometrica*, 83(1), 263–313.

Allahrakha, M., J. Cetina, and B. Munyan, 2018, "Do higher capital standards always reduce bank risk? The impact of the Basel leverage ratio on the US triparty repo market", *Journal of Financial Intermediation*, 34, 3–16.

Allen, F., and D. Gale, 2000, "Financial contagion", *Journal of Political Economy*, 108(1), 1–33.

Baeriswyl, R., L. M. Fuhrer, P. Gerlach, and J. Tenhofen, 2021, "The dynamics of bank rates in a negative-rate environment – the Swiss case", *SNB Working Paper*, 2021-5.

Basten, C., and M. Mariathasan, 2020, "Interest rate pass-through and bank risk-taking under negative-rate policies with tiered remuneration of central bank reserves", *Swiss Finance Institute Research Paper*, No. 20-98.

Bech, M., and T. Keister, 2017, "Liquidity regulation and the implementation of monetary policy", *Journal of Monetary Economics*, 92, 64–77.

Bech, M., and C. Monnet, 2016, "A search-based model of the interbank money market and monetary policy implementation", *Journal of Economic Theory*, 164, 32–67.

Bech, M. L., and E. Klee, 2011, "The mechanics of a graceful exit: Interest on reserves and segmentation in the federal funds market", *Journal of Monetary Economics*, 58(5), 415–431.

Bech, M. L., and A. Malkhozov, 2016, "How have central banks implemented negative policy rates?", *BIS Quarterly Review March*, March 2016.

Berentsen, A., S. Kraenzlin, and B. Müller, 2018, "Exit strategies for monetary policy", *Journal of Monetary Economics*, 99, 20–40.

Berentsen, A., H. van Buggenum, and R. Ruprecht, 2020, "On the negatives of negative interest rates and the positives of exemption thresholds", *University of Zurich, Department of Economics, Working Paper*, No. 372.

Bertrand, M., E. Duflo, and S. Mullainathan, 2004, "How much should we trust differences-in-differences Estimates?", *The Quarterly Journal of Economics*, 119(1), 249–275.

Bindseil, U., 2004, "The operational target of monetary policy and the rise and fall of reserve position doctrine", *ECB Working Paper*, No. 372.

——— , 2014, *Monetary policy operations and the financial system*. OUP Oxford.

Boutros, M., and J. Witmer, 2020, "Monetary policy implementation in a negative rate environment", *Journal of Money, Credit and Banking*, 52(2-3), 441–470.

Demiralp, S., J. Eisenschmidt, and T. Vlassopoulos, 2019, "Negative interest rates, excess liquidity and retail deposits: banks' reaction to unconventional monetary policy in the euro area", *ECB Working Paper*, No. 2283.

Di Filippo, M., A. Ranaldo, and J. Wrampelmeyer, 2021, "Unsecured and secured funding", *Journal of money credit and banking*.

Di Maggio, M., and A. Tahbaz-Salehi, 2015, "Collateral shortages and intermediation networks", *Columbia Business School Research Paper*, No. 14-40.

Duffie, D., P. Dworczak, and H. Zhu, 2017, "Benchmarks in Search Markets", *The Journal of Finance*, 72(5), 1983–2044.

Eggertsson, G. B., R. E. Juelsrud, and E. G. Wold, 2017, "Are negative nominal interest rates expansionary?", *NBER Working Paper*, No. 24039.

Fecht, F., K. G. Nyborg, and J. Rocholl, 2011, "The price of liquidity: The effects of market conditions and bank characteristics", *Journal of Financial Economics*, 102(2), 344–362.

Financial Stability Board, 2014, *Reforming major interest rate benchmarks*.

——— , 2015, *Implementation and effects of the G20 financial regulatory reforms*.

Freixas, X., A. Martin, and D. Skeie, 2011, "Bank liquidity, interbank markets, and monetary policy", *Review of Financial Studies*, 24(8), 2656–2692.

Freixas, X., B. M. Parigi, and J.-C. Rochet, 2000, "Systemic risk, interbank relations, and liquidity provision by the central bank", *Journal of Money, Credit and Banking*, 32(3), 611–638.

Fuhrer, L. M., 2018, "Liquidity in the repo market", *Journal of International Money and Finance*, 84, 1–22.

Fuhrer, L. M., B. Guggenheim, and S. Schumacher, 2016, "Re-use of collateral in the repo market", *Journal of Money, Credit and Banking*, 48(6), 1169–1193.

Fuhrer, L. M., B. Müller, and L. Steiner, 2017, "The liquidity coverage ratio and security prices", *Journal of Banking & Finance*, 75, 292–311.

Fuster, A., T. Schelling, and P. Towbin, 2021, "Tiers of joy? Reserve tiering and bank behavior in a negative-rate environment", *SNB Working Paper*, No. 2021-10.

Guggenheim, B., S. Kraenzlin, and S. Schumacher, 2011, "Exploring an uncharted market: evidence on the unsecured swiss franc money market", *Aussenwirtschaft*, 66(1).

Heider, F., M. Hoerova, and C. Holthausen, 2015, "Liquidity hoarding and interbank market rates: The role of counterparty risk", *Journal of Financial Economics*, 118(2), 336–354.

Heider, F., F. Saidi, and G. Schepens, 2019, "Life below zero: Bank lending under negative policy rates", *The Review of Financial Studies*, 32(10), 3728–3761.

Kotidis, A., and N. Van Horen, 2018, "Repo market functioning: The role of capital regulation", *BoE Working Paper*, No. 746.

Kraenzlin, S., 2007, "The characteristics and development of the Swiss franc repurchase agreement market", *Financial Markets and Portfolio Management*, 21(2), 241–261.

Kraenzlin, S., and T. Nellen, 2015, "Access policy and money market segmentation", *Journal of Monetary Economics*, 71, 1–12.

Kraenzlin, S., and B. von Scarpatetti, 2011, "Bargaining Power in the Repo Market", *SNB Working Paper*, No. 2011-14.

Lee, J., 2016, "Corridor system and interest rates: Volatility and asymmetry", *Journal of Money, Credit and Banking*, 48(8), 1815–1838.

Lester, B., and R. Armenter, 2015, "Excess reserves and monetary policy normalization", *FRB of Philadelphia Working Paper*, No. 15-35.

Logan, L. K., 2019, *Observations on implementing monetary policy in an ample-reserves regime. Speech by Lorie K. Logan remarks senior vice president, Federal Reserve Bank of New York. Money marketeers of New York University, New York City.*

Mancini, L., A. Ranaldo, and J. Wrampelmeyer, 2016, "The Euro Interbank Repo Market", *Review of Financial Studies*, 29(7), 1747–1779.

Martin, A., J. McAndrews, A. Palida, and D. R. Skeie, 2019, "Federal reserve tools for managing rates and reserves", *FRBNY Staff Report*, No. 642.

Munyan, B., 2015, "Regulatory arbitrage in repo markets", *Office of Financial Research Working Paper*, No. 15-22.

——— , 2017, "Regulatory arbitrage in repo markets", *Office of Financial Research Working Paper*, (15-22).

Nautz, D., 1998, "Banks' demand for reserves when future monetary policy is uncertain", *Journal of Monetary Economics*, 42(1), 161–183.

Newey, W. K., and K. West, 1987, "A simple, positive semi-definite, heteroskedasticity and autocorrelation consistent covariance matrix", *Econometrica*, 55(3), 703–708.

Pérignon, C., D. Thesmar, and G. Vuillemey, 2018, "Wholesale funding dry-ups", *The Journal of Finance*, 73(2), 575–617.

Poole, W., 1968, "Commercial bank reserve management in a stochastic model: Implications for monetary policy", *Journal of Finance*, 23(5), 769–791.

Schelling, T., and P. Towbin, 2020, "Negative interest rates, deposit funding and bank lending", *SNB Working Paper*, No. 5 2020.

Swiss National Bank, 2010, *Instruction sheet on collateral eligible for SNB repos.*

——— , 2014, *Press release: Swiss National Bank introduces negative interest rates.*

——— , 2015, *Instruction sheet governing negative interest on sight deposit account balances (valid until 31 October 2019).*

——— , 2019, *Instruction sheet governing negative interest on sight deposit account balances (valid from 1 November 2019).*

Vari, M., 2020, "Monetary policy transmission with interbank market fragmentation", *Journal of Money, Credit and Banking*, 52(2-3), 409–440.

Veyrune, R., G. della Valle, and S. Guo, 2018, "Relationship between short-term interest rates and excess reserves: A logistic approach", *IMF Working Papers*, No. 18/80.

Whitesell, W., 2006, "Interest rate corridors and reserves", *Journal of Monetary Economics*, 53(6), 1177–1195.

Williamson, S. D., 2019, "Interest on reserves, interbank lending, and monetary policy", *Journal of Monetary Economics*, 101, 14–30.

A. Appendix

A.1 Distribution of interest rates

Figure 9 depicts daily overnight interest rates calculated using various measures based on all transactions (for descriptive statistics, see Table 5). The figure reveals that in the tiered reserve remuneration period, daily secured overnight interest rates follow each other closely and interest rate developments are well captured by SARON. Further evidence of concentrated trading is provided by the histogram of all secured overnight interest rates, illustrated in Figure 10. On average, secured interest rates are -0.727% and very concentrated with a standard deviation of only approximately 3.8 bps across all trades. Overall, we conclude that the cross-sectional dispersion in interest rates is very small.

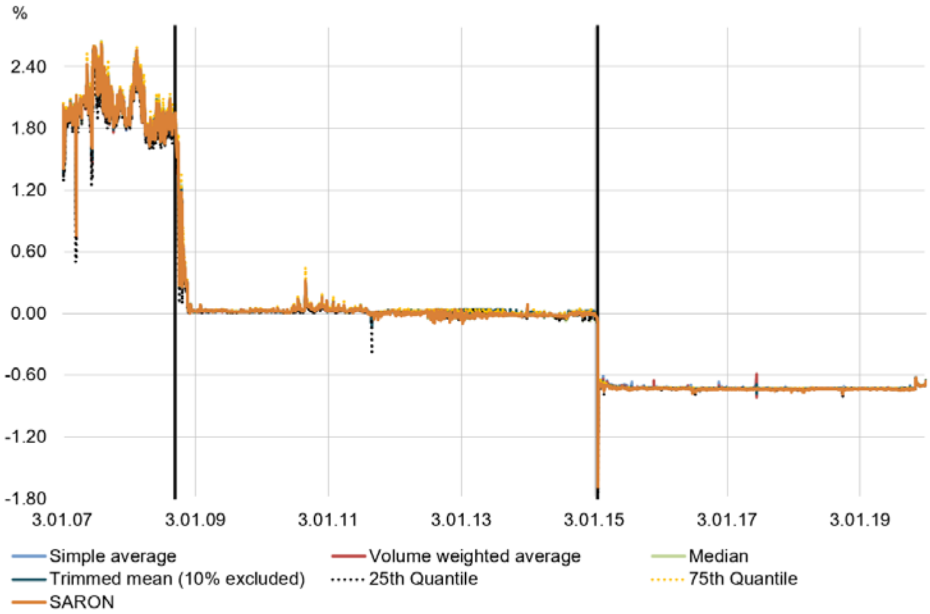

Fig. 9. *Daily secured overnight interest rates:* depicts besides SARON aggregated daily secured overnight interest rates. The following aggregations are conducted on all overnight secured interest rates per day: 1) simple average 2) volume weighted average 3) median 4) trimmed mean (10% of all observations excluded), and 5) 25^{th} and 75^{th} quantiles.

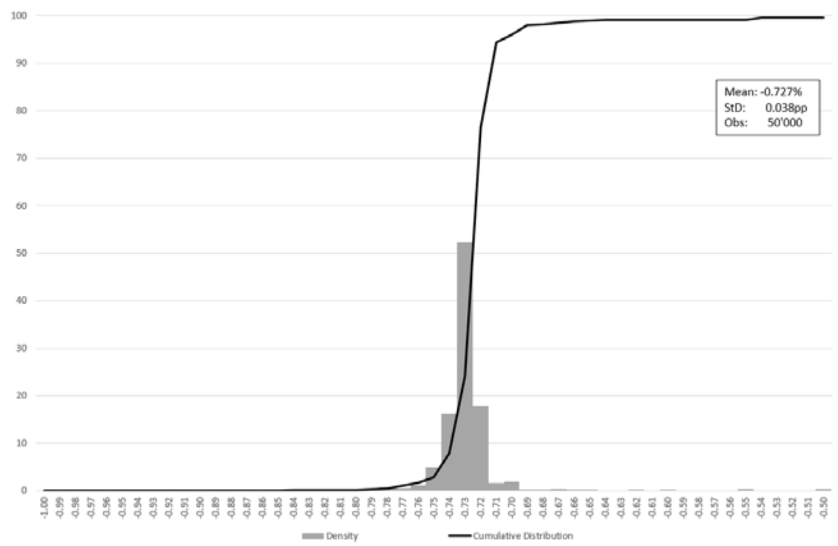

Fig. 10. *Histogram:* provides a histogram for secured overnight interest rates of all transactions in the reserve tiering period. The sample period ranges from January 22, 2015 to December 31, 2019.

	mean	p50	sd	min	max	count
Deposit rate (low)	-0.750	-0.750	0.000	-0.750	-0.750	1247
Deposit rate (high)	0.000	0.000	0.000	0.000	0.000	1247
SARON	-0.734	-0.735	0.038	-1.693	-0.627	1247
Simple avg.	-0.728	-0.730	0.026	-1.340	-0.612	1247
Vol. weighted	-0.730	-0.732	0.027	-1.351	-0.588	1247
Median	-0.727	-0.730	0.026	-1.500	-0.630	1247
Tr. mean	-0.729	-0.731	0.025	-1.349	-0.624	1247
25th quantile	-0.733	-0.730	0.040	-1.750	-0.630	1247
75th quantile	-0.724	-0.730	0.013	-0.770	-0.620	1247
SARON - r(low)	1.551	1.512	3.763	-94.348	12.336	1247
Simple avg. - r(low)	2.245	1.957	2.600	-58.952	13.769	1247
Vol. weighted - r(low)	2.020	1.824	2.723	-60.124	16.155	1247
Median - r(low)	2.284	2.000	2.563	-75.000	12.000	1247
Tr. mean - r(low)	2.096	1.883	2.516	-59.895	12.602	1247
Standard deviation	2.185	1.209	3.384	0.168	49.173	1247
Quantile range (25-75)	0.872	0.500	3.846	0.000	100.000	1247
Skewness	0.872	-0.469	3.521	-8.766	8.817	1247
Kurtosis	15.338	9.008	16.169	-1.997	78.964	1247

Tab. 5. *Descriptive statistics:* provides descriptive statistics of secured overnight interest rates for the reserve tiering period. Interest rates are in %, interest rate differentials and standard deviation are reported in basis points. The sample period ranges from January 22, 2015 to December 31, 2019.

A.2 Tiering thresholds and bank reserve holdings

A.2.1 Difference-in-difference analysis

As thresholds show only little bank specific variations over time, a difference-in-difference regression around the exogenous change in thresholds in November 2019 could be useful to strengthen our finding that banks' optimal reserve holdings depend on their thresholds.[24] As the changes in the threshold were unknown for banks, the treatment variable can be considered exogenous, and it is continuous to the extent that changes in thresholds differ for each bank. To assess the impact of the change on banks' reserve holdings, we estimate the following regression:

$$\Delta R_i^e = \alpha + \beta_1 \Delta M_i + \epsilon_i, \tag{17}$$

where our dependent variable is a bank's change in reserve holdings before and after the change in the threshold $\Delta R_i^e = \bar{R}_{i,post}^e - \bar{R}_{i,pre}^e$. As an explanatory variable, we used the according change in the threshold $\Delta M_i = \bar{R}_{i,post} - \bar{R}_{i,pre}$. In this regression specification, we eliminate the time series dimension by calculating averages for each bank before and after the change in thresholds. Doing so has the advantage that the regression standard errors do not suffer from a potential serial autocorrelation problem (Bertrand, Duflo, and Mullainathan, 2004). For calculating pre- and post-sample averages, we use banks' daily reserve holdings and thresholds over a six months window.[25]

Table 6 illustrates the difference-in-difference regression results. While Column 1 shows the result based on changes in thresholds, Column 2 also includes changes in various control variables as in our baseline analysis. In both regression specifications, the change in the threshold has a statistically significant and positive effect on banks' reserve holdings in line with our baseline findings. Moreover, Column 2 reveals that, similar to our baseline analysis, the LCR requirement of a bank turns out to play an important role. The positive and statistically significant point estimate indicates that banks with a higher LCR requirement also increased their reserve holdings, accordingly. Overall, these results confirm our finding in the baseline specification and indicate that irrespective of the methodological approach, we find strong evidence that banks' reserve holdings are determined according to their thresholds.

[24] See also Fuster, Schelling, and Towbin (2021) which study the implications of the change in the thresholds on banks' lending and borrowing behavior.

[25] Note that our results are robust with regard to the length of the pre- and post-period sample length.

	(1)	(2)
	Δ R$_i$	Δ R$_i$
Δ M$_i$	0.47***	0.45***
	(0.05)	(0.05)
Δ K$_i$		-13.81***
		(4.85)
Δ SD(flows)$_i$		-4.23
		(2.69)
Δ LCR$_i$		1.02***
		(0.33)
Constant	-0.32**	0.03
	(0.13)	(0.09)
Observations	118	69
Adjusted R^2	0.521	0.882
Sample period	Nov. 19 (+/-6M)	Nov. 19 (+/-6M)

Tab. 6. *Banks' reserve holdings – difference-in-difference estimation:* illustrates the relationship between banks' reserves and the tiering threshold using a difference-in-difference approach. The dependent variable is the change in bank's reserve holdings before and after the change in the threshold $\Delta R_i^e = \bar{R}_{i,post}^e - \bar{R}_{i,pre}^e$. The independent variable is the according change in the bank's threshold $\Delta M_i = \bar{R}_{i,post}^e - \bar{R}_{i,pre}^e$. The change in the threshold occurred on November 1, 2019. The pre- and post-sample periods last six months. M^i corresponds to a bank's tiering threshold and K^i to its minimum reserve requirement. Heteroskedasticity robust standard errors are reported. ***, ** and * denote statistical significance at the 1%, 5%, and 10% significance levels, respectively. For more details about the variables see description in Table 1.

A.2.2 Persistence in trading incentive

To support our reasoning that market frictions have a different effect for banks below and above the threshold, we investigate the persistence of bank's trading incentive. If persistence was not high and banks often switched between being a cash taker and a cash provider, banks above the threshold would also have an incentive to introduce a sophisticated trading desk, such that costs would be so low that they would also trade. To measure persistence, we calculate the transition probability for banks' trading incentive and trading activity. This is, the probability that bank i having a cash taking trading incentive yesterday is having a cash taking or cash providing incentive today. Table 7 shows the results. Consistent with persistent incentives, the average probability that an institution has a negative trading incentive given that it also had a negative incentive yesterday is approximately 89%.

	Incentive cash taker in t	Incentive cash provider in t
Incentive cash taker in $t-1$	48.4	51.6
Incentive cash provider in $t-1$	10.9	89.1

Tab. 7. *Transition probability matrix – trading incentive:* describes the transition probability matrix averaged over the individual institutions and scaled over the sum of the average such that the properties of a probability function are fulfilled. The sample period lasts from January 4, 2015 to December 31, 2019. For more details about the variables see description in Table 1.

A.3 Interest rates, aggregate reserves, and tiering thresholds.

To support our main result of a nonlinear relation between interbank interest rate and $R - M$, we present the regression results based on a first difference regression to account for a potential non-stationarity in our variables. In this specification, we explain changes in the spread between volume weighted average interbank interest rates and the lower remuneration rate $\Delta(r_{\Delta,t} - r_t^R)$ with changes in reserves exceeding tiering thresholds $\Delta(R_{t-1}^e - M_{t-1})$. To account for the nonlinear relationship, changes in the independent variable are interacted with five dummy variables indicating according quantiles of the variable. Note that as collateral data is only available on a monthly frequency, the daily changes in this variable are mostly zero and, hence, this variable is not included in the regression analysis. Results are shown in Table 8. Consistent with our baseline findings, the coefficient for the first quantile of reserves exceeding tiering thresholds is negative and statistically significant while other coefficients are mostly negative as well but not statistically significant.

	(1)	(2)	(3)	(4)
	Δ ($r_t^\Delta - r_t^R$)	Δ ($r_t^\Delta - r_t^R$)	Δ ($r_t^\Delta - r_t^R$)	Δ ($r_t^\Delta - r_t^R$)
Δ $(R_{t-1} - M_{t-1})$: 1st q.	-0.0791***	-0.0800***	-0.0803***	-0.0815***
	(0.0132)	(0.0124)	(0.0141)	(0.0132)
Δ $(R_{t-1} - M_{t-1})$: 2st q.	-0.0165	-0.0196	-0.0149	-0.0183
	(0.0159)	(0.0153)	(0.0157)	(0.0150)
Δ $(R_{t-1} - M_{t-1})$: 3st q.	-0.0651	-0.0671	-0.0688	-0.0704
	(0.0465)	(0.0470)	(0.0548)	(0.0552)
Δ $(R_{t-1} - M_{t-1})$: 4st q.	-0.0114	-0.0139	-0.0101	-0.0123
	(0.0090)	(0.0092)	(0.0153)	(0.0153)
Δ $(R_{t-1} - M_{t-1})$: 5st q.	-0.0185*	-0.0174**	-0.0173*	-0.0162*
	(0.0100)	(0.0086)	(0.0101)	(0.0087)
Year-end (dummy)		0.1222		0.1167
		(0.3770)		(0.3920)
Quarter-end (dummy)		-0.9195**		-0.9351**
		(0.3835)		(0.3930)
Month-end (dummy)		-0.0899		-0.0866
		(0.1584)		(0.1561)
Constant	-0.0096	0.0029	0.3881	0.3924
	(0.0337)	(0.0337)	(0.6900)	(0.6919)
Observations	1239	1239	1239	1239
Adjusted R^2	0.047	0.053	0.004	0.010
MiRe period FE	no	no	yes	yes
Fine-tuning days	excl.	excl.	excl.	excl.
Period	Tiering	Tiering	Tiering	Tiering

Tab. 8. *Interbank interest rates – first difference approach:* provides the regression results for the position of interest rates based on a first differences regression. The dependent variable is the change in the spread between volume weighted average interbank interest rates and the lower remuneration rate $\Delta(r_{\Delta,t} - r_{R,t})$. R^i denotes bank's reserves before participating in the interbank market. M^i corresponds to a bank's tiering threshold. Changes in the independent variable are interacted with five dummy variables indicating according quantiles of the variable to account for the nonlinear relationship. Heteroskedasticity robust standard errors are reported. ***, ** and * denote statistical significance (two-tailed) at the 1%, 5%, and 10% significance levels, respectively. The sample ranges from January 22, 2015 to December 31, 2019. Five days with SNB fine-tuning operations (in November and December 2019) as well as two days with secured interest rates below -1% directly after the discontinuation of the minimum exchange rate have been excluded. For more details about the variables see description in Table 1.

A.4 Monetary policy implementation before 2015

A.4.1 Institutional setup

The SNB implemented a corridor system until the financial crisis. After September 15, 2008, the SNB operated a floor system until the introduction of negative interest rates. In the corridor system, the SNB provided reserves such that aggregate demand was met. During this time, the SNB communicated the level of money market rates it wanted to maintain with a target range for the three-month CHF LIBOR (i.e., not an overnight interbank rate). Reserves were supplied predominantly via daily open market operations. As a result of the measures taken to dampen the effects of the global financial crisis and the foreign exchange rate interventions, reserves increased significantly from CHF 5 bn in 2007 to roughly CHF 300 bn in 2014. At the same time, aggregated minimum reserve requirements only increased from approximately CHF 9 bn to CHF 15 bn, see Figure 5. As interest rates were close to 0% during this period, the SNB operated a floor system until the introduction of negative interest rates.

A.4.2 Banks' reserve holdings in the corridor and floor system

To compare our findings with the corridor and floor systems, we conduct a similar regression for two periods prior to the introduction of reserve tiering. In addition to an analysis of daily data, we also repeat the regressions using average values over the minimum reserve maintenance period to account for the fact that banks need to satisfy reserve requirements on average. The regression results for the corridor period are reported in Columns 1–3 of Table 9. The coefficients for bank's minimum reserve requirements are statistically significant and the point estimates vary between 0.7 and 1.7, indicating that banks' reserve holdings depend on their minimum reserve requirement. In the floor period, point estimates increase considerably ranging from 20 to 40, indicating that banks hold a multiple of their reserve requirement. Thus, before 2015, banks' reserve holdings were driven by the minimum reserve requirement.

	(1)	(2)	(3)	(4)	(5)	(6)
	$R^e_{i,t}$	$R^e_{i,t}$	$R^e_{i,t}(avg.MiRe)$	$R^e_{i,t}$	$R^e_{i,t}$	$R^e_{i,t}$ (avg. MiRe)
$K_{i,t}$	1.30^{***}	1.68^{***}	0.68^{***}	19.71^{***}	41.62^{***}	41.99^{***}
	(0.47)	(0.34)	(0.08)	(3.91)	(7.72)	(7.43)
$SD(flows)_{i,t-1}$		0.03	-0.05^{**}		1.97^{***}	2.04^{**}
		(0.02)	(0.02)		(0.69)	(0.98)
Total $Assets_{i,t-1}$		-0.00^{***}	-0.00		0.01	0.00
		(0.00)	(0.00)		(0.01)	(0.01)
Constant	-0.06^{**}	-0.03^{***}	0.05^{***}	-1.36^{***}	-4.64^{***}	-4.60^{***}
	(0.03)	(0.01)	(0.01)	(0.31)	(0.95)	(0.87)
Observations	45005	30887	1041	186040	120977	4160
Adjusted R^2	0.037	0.044	0.276	0.421	0.542	0.588
Institution FE	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes (MiRe)	Yes	Yes	Yes (MiRe)
Institutions	all	MiRe	MiRe	all	MiRe	MiRe
Sample period	Corridor	Corridor	Corridor	Floor	Floor	Floor

Tab. 9. *Banks' reserve holdings – corridor and floor system:* shows different regression specifications illustrating the relationship between banks' reserves and the minimum reserve requirement for the corridor and floor system. Columns 1, 2, 4 and 6 are based on daily data, while Columns 3 and 6 are estimated using maintenance period averages for all variables. Time fixed effects are dummy variables for each working day, respectively, during the maintenance period. Standard errors reported in parentheses are clustered by financial institution. ***, ** and * denote statistical significance (two-tailed) at the 1%, 5%, and 10% significance levels, respectively. The corridor period lasts from January 3, 2007 to September 14, 2008 and floor period from September 15, 2008 until January 21, 2015. For more details about the variables see description in Table 1.

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