

Shocking Interest Rate Floors*

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19 October 2019

Abstract: We analyze central bank debt as a tool to control money market rates. We show in a theoretical model that the money market rate increases with the volume of, and yield on, central bank debt. Moreover, issuing central bank debt implements an interest rate floor, similar to paying interest on reserves. We then exploit the unique institutional setting of a Swiss debt security program to identify the dynamic causal effects of two orthogonal shocks through heteroscedasticity. The money market rate shock has modest effects on other financial market variables. The expectation shock causes a strong and persistent appreciation of the Swiss franc, a decline in stock prices, a decline in long-term interest rates, and a rise in corporate bond risk premia. The two shocks explain up to 80% of the forecast-error variance in these variables.

JEL classification: E41, E43, E44, E52, E58, C32

Keywords: Exit strategies, interest rate floors, central bank debt securities, interest on reserves, monetary policy shocks, money demand, expectations, identification through heteroscedasticity, local projections

*We thank Fernando Alvarez, David Ardia, Adrian Avdyli, Luca Benati, Tamara Bischof, Fabrice Collard, Jordi Galí, Basil Guggenheim, Matthias Jüttner, Peter Karadi, Tim Kroencke, Carlos Lenz, Loïc Maréchal, Jonas Meier, Cyril Monnet, Thomas Nellen, Benjamin Müller, Christian Myohl, Dirk Niepelt, Alex Rathke, Samad Sarferaz, Silvio Schumacher, Andreas Schrimpf, Michael Siegenthaler, Jan-Egbert Sturm, Maude Tautou, Hugo van Buggenum, Raphael Wewita, Mark Watson, and Christian Wipf for valuable discussions and suggestions. Furthermore, we thank participants at the SNB Research Conference, the RCEA Macro-Money-Finance Conference, the Annual Congress of the EEA, the CEPR MMCN Conference, the SSES Annual Congress, as well as seminar participants at the Swiss National Bank, the KOF Swiss Economic Institute, the University of Bern, the Ruhr-University Bochum, the Université Paris Nanterre, and the University of Salzburg, for insightful comments and discussions.

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1 Introduction

In the wake of the financial crisis, numerous central banks massively increased reserves held by commercial banks through large-scale asset purchases or foreign exchange interventions. These interventions depressed money market rates until they reached the interest rate floor. To raise money market rates, without reducing the size of the balance sheet, central banks have started to use interest on reserves, reverse repurchase agreements, term deposits, and central bank debt securities (see e.g. Moser 2011; Hamilton 2019; Federal Reserve Board 2019). Policy makers suggested that they will continue to use these tools in the future (see e.g. Jordan 2009; Quarles 2019). Therefore, researchers increasingly develop theoretical models to analyze how these tools affect money market rates under various institutional settings. Empirical evidence on their impact on the economy is still scarce, however.

In this paper, we show theoretically that central bank debt securities allow to control the money market rate under both, scarce and excess reserves. We then exploit the unique institutional setting of a Swiss central bank debt security program, that the operations occurred on a pre-determined day of the week, to identify its dynamic causal effect in an event study. Our findings suggest that central bank debt can be used to steer money market rates with large excess reserve balances. However, we also show that this exit strategy affects financial market variables through an additional expectation dimension.

We develop a money market model in the spirit of Poole (1968), Bech and Keister (2017), and Boutros and Witmer (2019) to show how central bank debt securities raise the money market rate. The volume of central bank debt affects the money market rate for two reasons. First, debt securities absorb reserves; therefore, they increase the likelihood of a costly liquidity shortage (reserve-absorbing channel). Second, debt securities raise demand on the money market because they provide a profitable investment opportunity to commercial banks (cost channel). With large excess reserve balances, the probability of a liquidity shortage is close to zero; therefore, the reserve-absorbing channel is negligible. The cost channel implies, however, that central bank debt securities implement an interest rate floor, similar to interest on reserves.

To estimate the causal impact of a surprise change in a debt security program, we exploit that the

Swiss National Bank regularly auctioned so-called SNB Bills (see [SNB 2008](#); [Moser 2011](#)). Policy makers used these securities to soak up reserves created in liquidity provisions and foreign exchange interventions. The auctions were not accompanied by an official press release. We can therefore analyze the effect of a new monetary policy tool, independent of the central bank's communication. Because the auctions took place on a pre-determined day of the week we can identify the effect of an SNB Bill shock by comparing the variance-covariance of financial market variables on auction days to the variance-covariance on days without an auction (see [Rigobon 2003](#); [Rigobon and Sack 2004](#); [Nakamura and Steinsson 2018a](#)). We impose sign and zero restrictions to identify two orthogonal dimensions of an SNB Bill shock. First, we identify a money market rate shock assuming that it raises the one-week interest rate, in line with our theoretical model. Second, we identify an expectation shock, imposing that it causes a decline in stock market prices, but no change in the money market rate.

We find that a money market rate shock has modest effects on financial market variables. On impact, a one standard deviation shock leads to a 0.1% appreciation and a 0.3% decline in stock prices. A forecast-error variance decomposition shows that the money market rate shock explains less than 10% of the variation in the exchange rate and stock prices. By contrast, it explains 70% of the variation in the one-week interest rate. The expectation shock has more important effects. It causes an appreciation of the Swiss franc, a decline in stock prices, and a decline in long-term interest rates. In addition, it causes an increase in corporate bond risk premia. These findings suggest that expectations of future economic activity deteriorated after a contractionary SNB Bill shock. The effects are economically important. On impact, the expectation shock explains 70% of exchange rate fluctuations, 50% of stock prices fluctuations, 60% of long-term interest rate fluctuations, and up to 50% of risk premia fluctuations.

Our paper contributes to theoretical research showing how to control money market rates with large excess reserve balances under various institutional settings. [Poole \(1968\)](#) showed that central banks control money market rates through changes in the money supply with scarce reserves. We study whether central bank debt allows to control money market rates with large excess reserve balances. [Boutros and Witmer \(2019\)](#) analyze the effectiveness of monetary policy in a negative interest rate environment where commercial banks may exchange reserves for cash. Our model is closely related

because we introduce an option to exchange reserves for central bank debt. [Bech and Keister \(2017\)](#) study how macroprudential policies affect the overnight money market rate. In their model, a higher liquidity coverage ratio increases interest rates with a term of more than 30 days. Similar to our reserve-absorbing channel, the liquidity coverage ratio increases the probability of a liquidity shortage. [Berentsen et al. \(2018\)](#) investigate the welfare implications of central bank debt relative to other reserve-absorbing operations and interest on reserves.¹ In line with our model, they find that central bank debt securities determine an interest rate floor if commercial banks hold large excess reserve balances. In contrast to their work, we abstract from a welfare analysis. We focus on whether the SNB's debt security program had an effect, in theory as well as in practice.

Most other papers on exit strategies focus on interest on reserves and the institutional setting in the US. [Goodfriend \(2002\)](#) suggests that paying interest on reserves establishes an interest rate floor for the money market rate. An interest on reserves policy allows to control the money market rate independently of the money supply. We show that central bank debt securities determine an interest rate floor as well. In our model, interest on reserves and central bank debt securities differ only because the latter do not count towards reserves requirements. With large excess reserves balances, however, this difference becomes negligible. [Ireland \(2014\)](#) introduces interest on reserves in a New Keynesian DSGE model. He finds that an interest on reserves policy has quantitatively small effects on output and inflation. By contrast, [Hendrickson \(2017\)](#) finds empirical evidence that interest on reserves increased demand for reserves. Our results support the view that policies changing the demand for reserves have meaningful economic effects. [Armenter and Lester \(2017\)](#) discuss how a reverse repo facility supports the money market rate in an environment with interest on reserves and limited access to reserve accounts. Our model abstracts from segmented markets because the SNB's access policy is relatively broad (see [Kraenzlin and Nellen 2015](#)). [Williamson \(2018\)](#) shows that a reverse repo facility is always welfare improving when banks hold large excess reserves, and are subject to capital requirements. We do not explicitly model reverse repo operations. However, we show that, in practice, reverse repo operations affected the yield on SNB Bills, even though the latter were allotted in auctions.

¹Few papers analyze the impact of central bank debt on money markets and the economy. Most other papers on central bank debt securities focus on conceptual and operational issues (see e.g. [Dziobek and Dalton 2005](#); [Nyawata 2012](#); [Gray and Pongsaparn 2015](#)). These papers discuss eligibility of central bank debt as collateral in repurchase operations, treatment for capital requirements, liquidity of marketable central bank debt, coordination of debt management and monetary operations, possible threats to balance sheets of central banks (losses and recapitalization), and coordination of emissions with the treasury.

We then contribute to a literature estimating the causal effects of monetary policy (see [Gürkaynak and Wright 2013](#); [Nakamura and Steinsson 2018b](#), for surveys on event studies and other approaches). Most event studies with monetary policy applications focus on unexpected changes in interest rate futures around official decisions of central banks (see e.g. [Kuttner 2001](#); [Gürkaynak et al. 2005](#); [Gertler and Karadi 2015](#); [Cieslak and Schrimpf 2019](#)); they therefore measure the impact of a new interest rate target and the communication accompanying the decision, independent of the tools used to implement the target. Before the financial crisis, central banks operated with relatively scarce reserve balances. These monetary policy surprises therefore largely reflect liquidity or communication effects.² But also, recent studies showed that shocks identified from interest rate decisions include information effects because the communication reveals information about the state of the economy ([Nakamura and Steinsson 2018a](#); [Gürkaynak et al. 2018](#); [Jarociński and Karadi 2018](#); [Altavilla et al. 2019](#)). Our findings for the money market rate shock resonate well with existing evidence on monetary policy surprises before the crisis (see [Kuttner 2001](#); [Rigobon and Sack 2004](#); [Gürkaynak et al. 2005](#)). The shocks we identify, however, are neither information effects, nor liquidity effects. Rather, they reflect changes in money demand brought about by random variation in a debt security program. Through the lens of the theoretical model, the shocks thus reflect random variation in an interest rate floor. Therefore, we also shed light on the effects of interest on reserves.

The results also relate to [Altavilla et al. \(2019\)](#) and [Swanson \(2017\)](#), who show for the euro area and the US, respectively, that monetary policy surprises comprise multiple dimensions. In particular, monetary policy surprises stemming from forward guidance and large-scale asset purchases affect a different segment of the yield curve than surprises in the interest rate target. In addition, recent research emphasized that large-scale asset purchases may be expansionary due to a signalling effect, which changes expectations about future policy actions (see e.g. [Woodford 2012](#); [Bauer and Rudebusch 2014](#)). Our expectation shock shows some similarities to a (contractionary) large-scale asset purchase or signalling shock. However, a contractionary large-scale asset purchase shock leads to an increase in long-term interest rates through higher risk premia. Meanwhile, we find a decline in long-term interest rates. This suggests that lower long-term interest rates may well be associated

²[Bernanke and Mihov \(1998\)](#) discuss that the empirical evidence for a liquidity effect was mixed in the past. But, in their application, they find little evidence for rejecting the liquidity effect in a quarterly US structural VAR. However, the new tools used in an environment with large excess reserve balances may render liquidity effects less important than in the past. [Ireland \(2014\)](#) shows in a New Keynesian model that liquidity effects vanish when paying interest on reserves.

with a contractionary monetary policy (see [Friedman 1968](#)).

From a methodological perspective, this paper is related to [Wright \(2012\)](#), who identifies monetary policy surprises through heteroscedasticity in a vector-autoregression (VAR). [Swanson \(2017\)](#) uses local projections to estimate dynamic effects identified with high-frequency monetary policy surprises.³ In addition, [Swanson \(2017\)](#) and [Altavilla et al. \(2019\)](#) recover multiple dimensions of monetary policy surprises using a factor rotation approach. Because we lack information on the exact intra-day timing of the auctions, we cannot use a high-frequency identification scheme. Instead, we show how to recover multiple dimensions of SNB Bill auctions through heteroscedasticity, and estimate dynamic effects with local projections.

The remainder of this paper is structured as follows. Section 2 describes the SNB Bills program to motivate our modelling choices and identification strategy. Section 3 incorporates central bank debt in a money market model to study its impact on interest rates. Section 4 presents the identification and estimation strategy, before we discuss the empirical findings in Section 5. Section 6 concludes.

2 The SNB Bills program

From October 2008 to July 2011, the SNB issued 232 debt securities, so-called SNB Bills, on 167 auction days. Most securities had a short time to maturity from 7 to 85 days; some of them had a maturity of up to one year.⁴ The securities were denominated in Swiss franc.⁵ The main purpose of the program was to soak up reserves created during the financial and sovereign debt crisis.⁶ This allowed to keep the operational interest rate target, the 3M Libor, from falling to zero. This interpretation is supported by a press release in which the SNB announced that SNB Bills “[...] will serve to absorb liquidity, thereby neutralizing the monetary policy impact of measures to inject liquidity.” (SNB

³A VAR yields more precise estimates ([Stock and Watson 2018](#)), while local projections are more robust with respect to model misspecification ([Jordà 2005](#)).

⁴Sometimes, the SNB auctioned two securities with different term to maturity on the same day. The term was determined in such a way that the security matured on a day with a new auction.

⁵The SNB also issued USD denominated SNB Bills to finance a fund buying assets from a commercial bank during the financial crisis ([SNB 2009b](#)).

⁶The literature stresses two main purposes to issue central bank debt in advanced economies. First, central banks finance particular operations with debt securities (see e.g. [Rule 2011](#); [SNB 2009b](#)). For example, the Bank of England emits debt securities in foreign currency to finance its foreign exchange reserves. The central banks of Malaysia and Switzerland issued foreign currency debt to finance subsidiaries supporting troubled commercial banks during the Asian crisis and the 2008 financial crisis, respectively (see [Rule 2011](#); [SNB 2009b](#)). Second, industrialized countries have started to consider and employ central bank debt securities to drain reserves ([Nyawata 2012](#)). Developing economies frequently use central bank debt securities to sterilize foreign exchange interventions.

2008).⁷ In principle, the SNB could also increase reserves by open-market purchases. According to Moser (2012), however, no purchases occurred before the SNB stopped the program in August 2011.

The volume of the program was large. At the peak in 2011, outstanding SNB Bills accounted for more than 45% of total SNB liabilities, more than 17% of Swiss nominal GDP, and 20% of the Swiss bond market capitalization.⁸ Although the SNB also drained reserves with reverse repo operations, the volume outstanding was much smaller (less than 10% of total liabilities).

SNB Bills were bought by a broad range of counterparties. Buyers either had reserve accounts at the SNB, access to the CH Repo Market, or access to the OTC Spot Market of the SIX Exchange (see SNB 2016).⁹ The SNB has a relatively broad access policy to its facilities (see Kraenzlin and Nellen 2015). Reserve accounts can be held by domestic securities brokers/dealers, insurance companies, asset managers of collective investment schemes, as well as foreign banks.¹⁰ Participants in the CH Repo Market largely coincide with banks having access to the SNB's reserve accounts.¹¹ Issuing SNB Bills therefore reduced reserves (see Figure 1, panel a). In early 2010, for example, reserves rose quickly because of foreign exchange interventions.¹² Thereafter, the SNB issued more SNB Bills, leading to an increase in the outstanding volume of debt securities and a strong decline in domestic reserves.

SNB Bills were allotted in auctions happening on a specific day of the week from 2pm to 2:30pm. The results were published in the afternoon. Several days before an auction, the SNB announced the auction day, a price range for valid bids, the term to maturity, and the payment date.¹³ In addition, most of the auctions occurred on a predictable weekly schedule.¹⁴ In the first half of the sample, most auctions occurred on Tuesdays (see Figure 1, panel b). In the second part of the sample, the auction

⁷Policy makers viewed the program as irrelevant for the stance of monetary policy as long as commercial banks held substantial reserves. Moser (2011): "From a monetary policy perspective, liquidity draining operations are negligible, as long as commercial banks hold excess liquidity and interest rates are close to zero." (our translation).

⁸Bond market capitalization data stem from www.six-group.com/exchanges/statistics/annual_statistics/2018_en.html (accessed on 6 October 2019).

⁹SNB Bills were transferable and traded on the SIX Exchange. Parties without access to SNB's facilities could therefore purchase SNB Bills too, but only through a counterparty eligible to participate in an SNB Bill auction. In addition, given the large denomination of CHF 1 million, buyers were likely large firms or institutional investors.

¹⁰Kraenzlin and Nellen (2015) report that in December 2010, 62 of 170 participants in the CH Repo Market were located abroad, most of them in Austria (24), Germany (16), and in the UK (6).

¹¹According to Kraenzlin and Nellen (2015): "As a rule of thumb, banks that have access to the Swiss repo system are also eligible to participate in the SNB's open market operations and have access to the SNB's standing facilities."

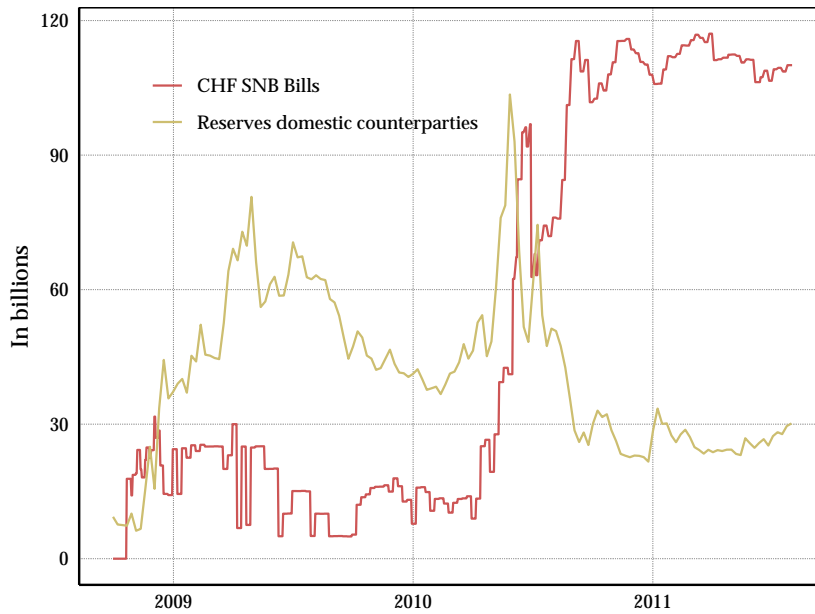
¹²Foreign currency investments rose from CHF 95 billion in December 2009 to CHF 225 billion in June 2010. See data.snb.ch/en/topics/snb#!cube/snbbipo (accessed on 6 October 2019).

¹³The transactions were usually settled two working days after the auction. This information stems from a small number of announcement forms stored on a web archive. We cannot establish, however, whether the content and release date of these announcement forms changed over time.

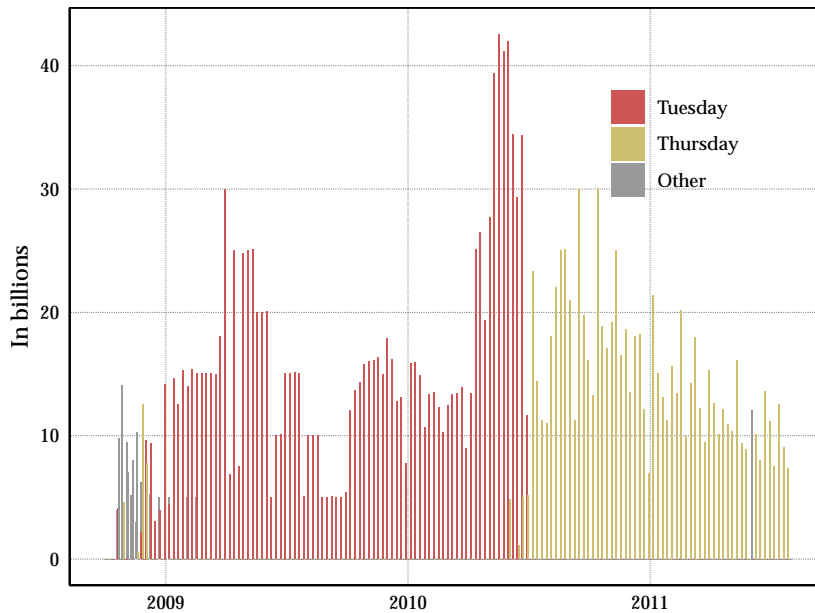
¹⁴Only in the last week of the years 2009 and 2010 no auction took place. In the beginning of the program, the SNB sometimes held two auctions per week.

Figure 1 — Timing and volume of the SNB Bills program

(a) Outstanding volume and domestic reserves



(b) Allotted volume by weekday



Notes: Panel (a): Daily volume of outstanding CHF SNB Bills and average weekly reserves of domestic counterparties from October 2008–August 2011. Panel (b): Allotted volume by day of the week.

day changed to Thursday.¹⁵

SNB Bills were issued in American auctions in a variable rate tender. Each participant submitted the amount of securities he or she was willing to buy, jointly with a price. After the submission of the bids, the SNB chose the marginal price above which participants' offers were satisfied. Thereafter, participants paid the price they offered in their bids. Although SNB Bills were issued in auctions, their yield was influenced by the SNB for two reasons. First, the SNB published a price range for valid bids. Second, because reverse repos are close substitutes for SNB Bills, the reverse repo yield influenced SNB Bill yields.

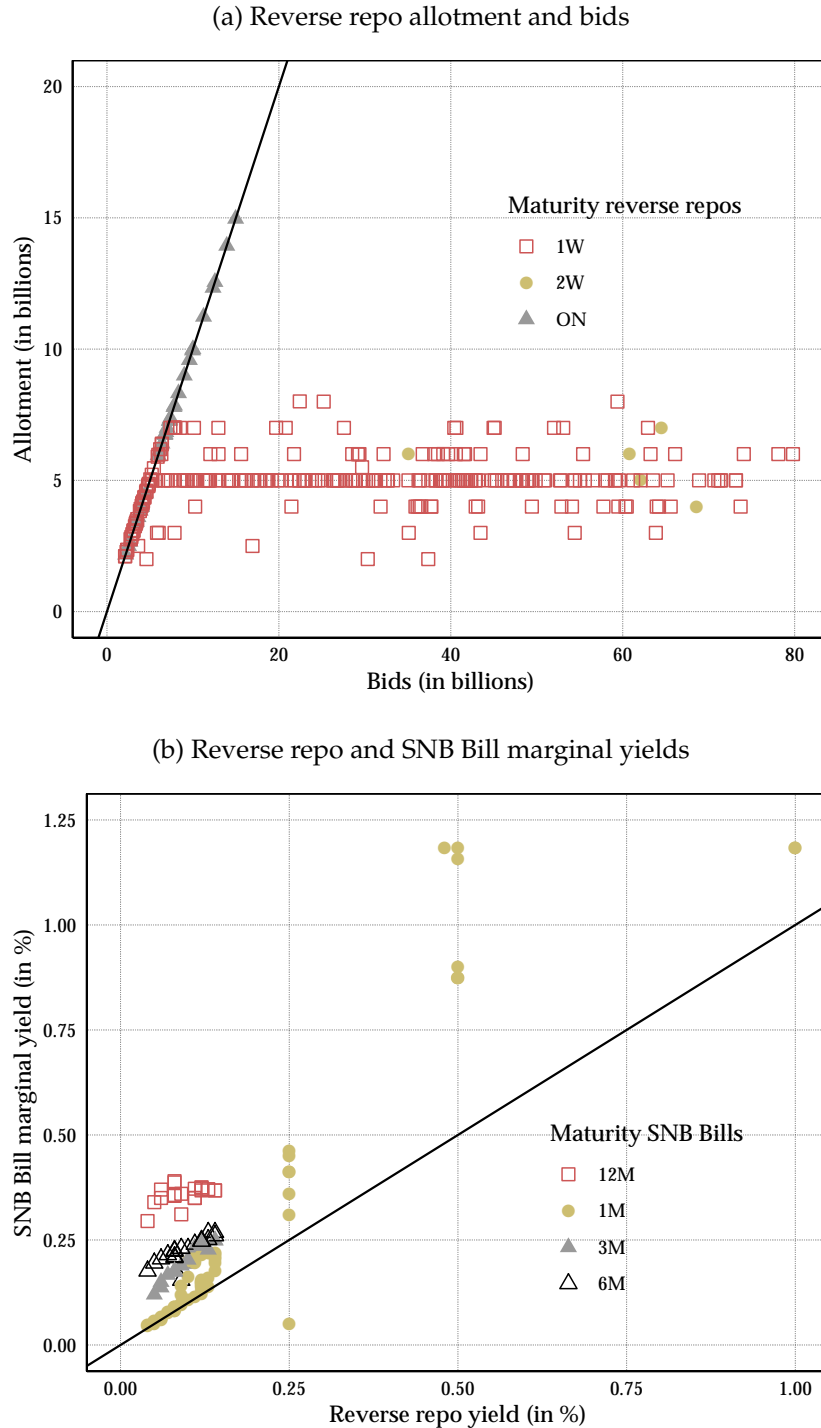
Reverse repo operations were conducted until November 2008, as well as, between July 2010 and the end of the SNB Bills program.¹⁶ On 69 of 167 SNB Bill auction days, there was also a reverse repo operation. Reverse repo operations were held at 9:00 in the morning as a fixed rate tender (volume tender). That is, the SNB determined the reverse repo yield before the operation. Panel (a) in Figure 2 shows that the SNB usually allotted a volume of around 5 billion, although counterparties were willing to bid up to 80 billion at the given reverse repo yield. This is in line with Moser (2011), suggesting that reverse repo operations were mainly used to control the money market rate, rather than the volume of reserves. Meanwhile, panel (b) shows that there is a strong relationship between the SNB Bill marginal yield and the reverse repo yield of the same day. This suggests that the reverse repo yield affected the bidding behavior of counterparties in the SNB Bill auctions as well.

Table 1 confirms that the reverse repo yield had an influence on the SNB Bill marginal yield, that is, the maximum yield paid by the SNB after the auction. The first column shows a significantly positive constant, as well as a slope coefficient above one. Apparently, counterparties bid in such a way that the SNB Bill marginal yield ended up on average above the reverse repo yield. In addition, variation in the reverse repo yield explains 76% of the variation in SNB Bill yields. When we take into account that SNB Bills had a longer term to maturity than reverse repo auctions, the share explained rises to 86%. As we would expect, SNB Bills with a higher maturity tend to have higher yields. When adding

¹⁵One motivation to change the auction day may have been to highlight the difference between treasury bill auctions and SNB Bill auctions, which were both held on Tuesday in the first half of the sample. Rule (2011) discusses general guidelines for issuing central bank debt securities suggesting that "[...] clear and precise announcements mean that market participants have a clear knowledge as to the size and regularity of central bank operations which they can separate from the governments issuance." Indeed, the auction day changed in July 2010, when the SNB started to regularly issue SNB Bills with a similar maturity as treasury bills. Treasury bills have a maturity of three months and more. All SNB Bill auctions with a maturity of three months and more indeed occurred on Thursday or Friday.

¹⁶See also Figure D.1 in Appendix D.

Figure 2 — SNB Bills and reverse repo operations



Notes: Panel (a): bids and allotment in reverse repo operations for various maturities from October 2008–August 2011. Panel (b): SNB Bill marginal yield for various maturities and the reverse repo yield on the same day. 45 degree lines in black.

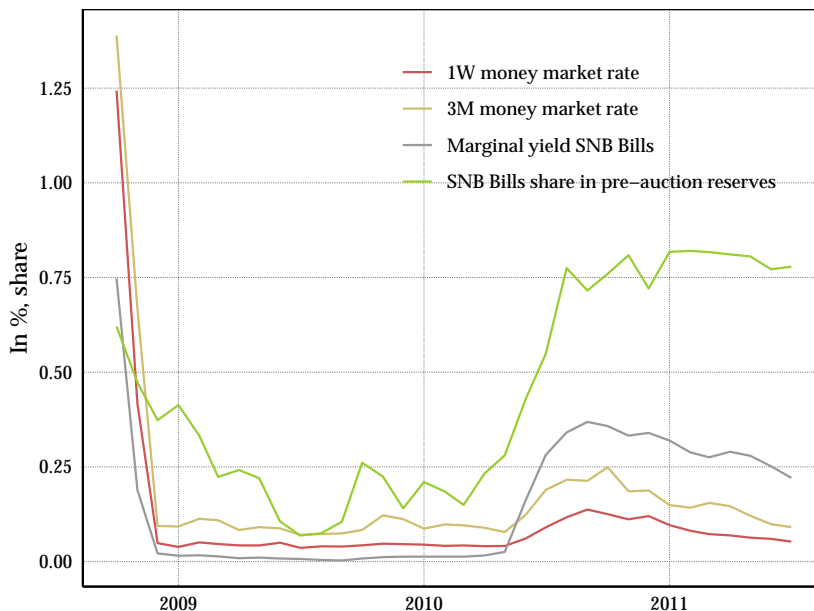
Table 1 — Determinants of SNB Bill marginal yields

	SNB Bill yields (in %)			
Reverse repo yield (in %)	1.43*** (0.17)	1.54*** (0.16)	1.47*** (0.20)	1.50*** (0.13)
3M SNB Bill (dummy)		0.06*** (0.01)	0.06*** (0.01)	0.07*** (0.01)
6M SNB Bill (dummy)		0.09*** (0.01)	0.09*** (0.01)	0.11*** (0.02)
12M SNB Bill (dummy)		0.22*** (0.01)	0.23*** (0.01)	0.25*** (0.02)
Reverse repo allotment (in bio.)			0.02*** (0.01)	0.02*** (0.00)
Reverse repo bids (in bio.)			−0.00 (0.00)	−0.00 (0.00)
SNB Bill allotment (in bio.)				0.00 (0.00)
SNB Bill bids (in bio.)				0.00 (0.00)
Constant	0.06*** (0.01)	−0.01 (0.01)	−0.10*** (0.03)	−0.13*** (0.04)
Observations	127	127	127	127
R ²	0.76	0.86	0.87	0.88

Notes: OLS regressions of SNB Bill marginal yields on characteristics of reverse repo operations and SNB Bill auctions of the same day. HAC-robust standard errors in parentheses. ***, **, and * denote statistical significance at the 1%, 5%, and 10% level.

the volume allotted and bid in reverse repo operations and SNB Bill operations, respectively, we only explain marginally more of the variation in marginal yields. Therefore, the SNB Bill marginal yield was largely determined by the reverse repo yield on the same morning, not by the SNB Bill auction mechanism.

Figure 3 — SNB Bills and money market rates



Notes: The marginal yield on SNB Bills is an average over all securities auctioned on a particular day (monthly average). The 1W and 3M money market rates are Swiss Average Rates (SAR), that is, interest rates based on actual repo transactions and binding quotes (monthly average). The share of outstanding SNB Bills in pre-auction reserves is based on our calculations (end of month values) from October 2008–August 2011, and does not take into account potential repurchases of SNB Bills. Pre-auction reserves comprise outstanding CHF SNB Bills, and reserves of domestic and foreign counterparties.

Did the SNB Bills program affect money market rates? Figure 3 shows a strong correlation between the average marginal yield on SNB Bills and the 3M SAR, a secured money market rate based on actual repo transactions and binding quotes. Until June 2010, the average marginal yield of SNB Bills remained below the money market rate. In the wake of the substantial expansion of the balance sheet in 2010, both, the money market rate and the marginal yield increased. The movements of the 1W SAR are similar. The figure also shows the share of SNB Bills in terms of pre-auction reserves. We compute pre-auction reserves as the sum of SNB Bills outstanding and reserves of domestic and foreign counterparties. Pre-auction reserves therefore indicate the volume of reserves if the SNB would not roll over the SNB Bills when they mature. The share of SNB Bills in pre-auction reserves declined somewhat until the end of 2009. Thereafter, this share increased strongly because the SNB

drained the reserves it created in the wake of its foreign exchange interventions.¹⁷

In sum, SNB Bills auctions occurred on pre-determined days of the week. In addition, the marginal yield of SNB Bills was largely determined by the reverse repo yield. Finally, there is a reduced-form relationship between money market rates and the volume of, and yield on, SNB Bills.

3 Central bank debt in a money market model

We develop a money market model closely related to [Poole \(1968\)](#) and [Boutros and Witmer \(2019\)](#) to show that central bank debt securities allow to control the money market rate with large excess reserve balances.¹⁸ In addition, we compare a debt security policy to interest on reserves.

3.1 Agents

We assume a continuum of commercial banks on the interval $i \in [0, 1]$. Each commercial bank holds an exogenous amount of pre-determined reserves $R_i > 0$, manages an exogenous amount of deposits $D \geq R_i$, and experiences a zero-mean liquidity shock $Z \leq D$, where $Z > 0$ is a liquidity outflow.¹⁹ Assets A_i are residually determined by R_i and D , assuming commercial banks' capital to be zero (see Figure 4). A commercial bank borrows additional reserves B_i from the money market at the net money market rate i_m .²⁰ Reserves bear no interest, deposits cost i_d , and assets earn i_a .

Commercial bank i invests a fraction π_i of its pre-auction reserves ($F_i \equiv B_i + R_i$) in central bank debt securities. Pre-auction reserves denote commercial bank i 's reserve holdings prior to investing in central bank debt.²¹ After the debt security settlement, commercial bank i holds $(1 - \pi_i)F_i$ in post-auction reserves. Because the commercial bank has to hold an exogenous amount K as minimum reserve requirement, it has a buffer of $E_i \equiv (1 - \pi_i)F_i - K$ to absorb potential liquidity outflows. If a commercial bank faces a liquidity shortage, it has to borrow at the central bank's discount window. The amount of reserves that a commercial bank borrows at the discount window

¹⁷We find a high correlation between monthly changes in money market rates and the marginal SNB yields (0.9). By contrast, the correlation between the change in the share of SNB Bills and the interest rates is not significantly different from zero (0.04).

¹⁸We follow [Afonso and Lagos \(2015\)](#), [Bech and Monnet \(2016\)](#), and [Bech and Keister \(2017\)](#) who use similar models to analyze the implementation of monetary policy and the properties of money markets.

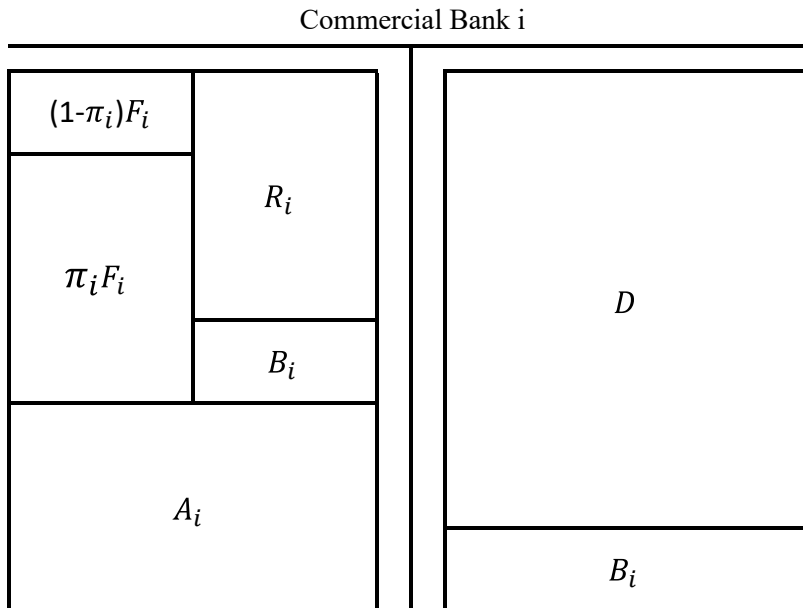
¹⁹For tractability, we assume that commercial banks do not differ in terms of D and K .

²⁰Negative money market borrowing, that is money market lending, is constrained by the amount of available reserves ($-B_i \leq R_i$).

²¹Pre-auction reserves resemble what [Gagnon and Sack \(2014\)](#) call "Fed liquidity", that is, the sum of reserves and overnight reverse repurchase agreements. In our paper, pre-auction reserves are the sum of reserves and central bank debt securities (see Figure 4). We use the term pre-auction reserves because, in reality, the SNB used auctions to issue Bills.

is $X_i \equiv \max(0, Z_i - E_i)$.

Figure 4 — Stylized commercial bank balance sheet



Notes: F_i : pre-auction reserves; $(1 - \pi_i)F_i$: post-auction reserves; $\pi_i F_i$: commercial bank i 's holdings of central bank debt securities; R_i : pre-determined reserves; A_i : other assets; D : deposits. The commercial bank borrows additional reserves on the money market in this example ($B_i > 0$). In equilibrium, aggregated money market borrowing must be zero.

The central bank provides reserves ($R = \int_0^1 R_i di$) and runs a discount window facility at which commercial banks can borrow an unlimited amount of additional reserves at the exogenous discount window rate i_x .²² Beyond that, the central bank has two levers to affect the money market rate. First, the central bank decides over the maximum fraction of pre-auction reserves that each commercial bank can invest in debt securities ($\pi^{cb} \in [0, 1]$). Second, the central bank determines the yield on debt securities ($0 \leq i_b \leq i_x$).

Even though in reality, SNB Bills were issued in auctions, we analyze the role the volume of, and yield on, debt securities independently. First, as shown in the previous section, the marginal yield on SNB Bills was largely determined by the reverse repo yield. Second, the SNB defined a price range for valid bids. The price ceiling therefore established an implicit minimum yield.

3.2 Timing

We assume a standard timing convention (see e.g. [Boutros and Witmer 2019](#)). First, the central bank determines the volume of, and yield on, debt securities (π^{cb} and i_b). Second, commercial banks

²²In reality, the SNB determines a bank specific limit to potential discount window borrowing. In our model, discount window borrowing is implicitly constrained by the maximum size of the liquidity shock ($Z \leq D$).

decide on the optimal amount of money market borrowing (B_i) and the optimal amount of debt securities ($\pi_i \in [0, \pi^{cb}]$). These two decisions pin down the commercial banks' money demand functions. Third, commercial banks engage in the money market. At this stage, we impose the market clearing condition ($\int_i B_i di = 0$). Fourth, central bank debt securities are settled and each commercial bank holds post-auction reserves $((1 - \pi_i)F_i)$ and debt securities $(\pi_i F_i)$. Fifth, the liquidity shock materializes.²³ Sixth, a commercial bank borrows at the central bank's discount window if it faces a liquidity shortage (i.e. if $X_i > 0$).

3.3 Commercial bank problem

The commercial bank maximizes expected profits $\mathbb{E}(\Pi_i)$ over the optimal amount of money market borrowing B_i and the fraction of pre-auction reserves invested in debt securities π_i .²⁴ The expected profit of commercial bank i is:

$$\mathbb{E}(\Pi_i) = i_a A_i + i_b \pi_i (R_i + B_i) - i_m B_i - i_d \mathbb{E}(D - Z) - i_x \int_{\hat{z}_i}^{\infty} X_i f(Z) dZ, \quad (1)$$

where \hat{z}_i is the realization of the liquidity shock that is associated to zero borrowing at the discount window. Reserve requirements K do not enter the commercial bank's problem as a constraint, but only through the probability of a liquidity shortage. K is not a constraint to the expected profit maximization problem because commercial banks can borrow at the discount window before having to comply with reserve requirements.

Commercial banks have an incentive to hold reserves for two reasons. First, a higher stock of reserves lowers the probability of a liquidity shortage. A lower probability of a liquidity shortage is beneficial because, in equilibrium, the discount rate is higher than the money market rate. Second, borrowing reserves on the money market allows the commercial bank to invest a larger amount in debt securities and receive larger interest payments.

Commercial banks trade-off the marginal benefits of borrowing on the money market (a lower probability of a liquidity shortage and a higher interest rate income from investing in debt securities)

²³The fact that the liquidity shock materializes after the money market closes captures imperfections on the money market that prevent commercial banks from exactly targeting their required reserves before the closing of the money market (see [Bech and Monnet 2016](#); [Afonso and Lagos 2015](#); [Ennis and Weinberg 2013](#)).

²⁴The commercial bank takes interest rates, reserve balances R_i , deposits D , asset holdings A_i , the distribution of Z , the minimum reserve requirement K , and the supply of debt securities π^{cb} as given.

against the marginal costs of borrowing (the money market rate). Optimal commercial bank behavior requires that these are equal. Optimal commercial bank behavior also implies that lending on the money market is, on the margin, equally attractive as holding a portfolio of size F_i , partly invested in central bank debt securities and partly invested in non-interest-bearing reserves.

3.4 Equilibrium

In equilibrium, a money market rate i_m prevails at which it is beneficial for commercial banks with a relatively scarce (ample) amount of pre-determined reserves R_i to borrow (lend) on the money market. After the closing of the money market, each commercial bank holds the same amount of pre-auction reserves ($F_i = F \forall i$) and thus faces the same probability of a liquidity shortage ($P(X_i > 0) = P(X > 0) \forall i$). Therefore, each bank invests the same share of pre-auction reserves in debt securities ($\pi_i = \pi \forall i$).

Proposition 1 *If each commercial bank maximizes expected profits with respect to B_i and π_i , the money market rate equals $i_m = i_b\pi + (1 - \pi)i_xP(X > 0)$, where $\pi = \min(\pi^{cb}, \bar{\pi})$.*

Proof. See Appendix B, Section B.1.

Proposition 1 establishes the money market equilibrium that prevails if commercial banks can invest in central bank debt securities. If the central bank does not supply debt securities, the money market rate is strictly downward-sloping in reserves as in [Poole \(1968\)](#). If reserves approach infinity, the probability of a liquidity shortage approaches zero. The money market rate then approaches the interest rate floor.

In [Poole \(1968\)](#), the interest rate floor is zero because, in the aggregate, non-interest bearing reserves cannot be invested in interest-bearing assets. In our model, the interest rate floor is strictly positive. Commercial banks can exchange non-interest bearing reserves for interest-bearing debt securities. In addition, our model differs from [Poole \(1968\)](#) in that debt securities drain reserves from the money market.

Commercial banks are willing to invest in debt securities up to some threshold $\bar{\pi}$.²⁵ Accepting an additional unit of debt securities beyond the threshold decreases expected profits through the

²⁵See Appendix B, Section B.3 for a technical discussion.

increased probability of a liquidity shortage. If reserves are ample, the probability of a liquidity shortage is low. Therefore, it is beneficial for commercial banks to exchange a large share of reserves for debt securities. In contrast, if reserves are scarce, commercial banks are not willing to absorb a lot of debt securities. Increasing the supply of debt securities is therefore less effective if reserves are scarce.

Corollary 1.1 *With ample reserves the floor on the money market rate is $\underline{i}_m \equiv \lim_{F \rightarrow \infty} i_m = \pi i_b$.*

Proof. Because $\lim_{F \rightarrow \infty} X = -\infty$, $\lim_{F \rightarrow \infty} P(X > 0) = 0$. The result then follows directly from proposition 1.

Corollary 1.1 establishes that the volume of, and yield on, debt securities jointly determine the interest rate floor.²⁶ Intuitively, the return on a portfolio with a fraction π invested in debt securities and a fraction $1 - \pi$ invested in non-interest-bearing reserves amounts to πi_b . This result suggests that, even with ample reserves, central bank debt securities allow to raise the money market rate.

Corollary 1.2 *The response of the money market rate i_m to an increase in the yield on debt securities i_b is $\frac{di_m}{di_b} = \pi \geq 0$.*

Proof. Follows immediately from proposition 1.

The money market rate strictly increases in the yield on debt securities if commercial banks hold central bank debt securities. A higher yield lowers the cost of holding pre-auction reserves without affecting the amount of post-auction reserves available as a liquidity buffer. Equivalently, a higher yield on debt securities increases the return on a portfolio of size F , partly invested in central bank debt securities and partly invested in non-interest-bearing reserves. Variation in the yield on debt securities therefore affect the money market rate through a cost channel.

Corollary 1.3 *The response of the money market rate to an increase in the supply of debt securities is $\frac{di_m}{d\pi_{cb}} = i_b - i_x P(X > 0) + (1 - \pi) i_x \frac{\partial P(X > 0)}{\partial \pi} > 0$ if $\pi < \bar{\pi}$.*

²⁶The upper limit binds for sufficiently low reserves. The money market rate is constrained by an upper bound because commercial banks would not borrow at a money market rate above the discount window rate. In fact, at sufficiently low F , commercial banks abstain from holding any debt securities ($\bar{\pi} = 0$) such that the upper limit is equal to the discount rate i_x . For more details, see Appendix B, Sections B.3 and B.4.

Proof. Follows from proposition 1 and Appendix B, Sections B.3 and B.4.

The money market rate rises in the supply of debt securities as long as commercial banks' expected profits rise in debt security investments, that is, as long as commercial banks are non-satiated with debt securities ($\pi < \bar{\pi}$). Commercial banks are willing to invest a larger fraction of pre-auction reserves in debt securities if pre-auction reserves are ample.²⁷

In sum, a higher supply of debt securities increases the money market rate through two channels. First, the cost of holding pre-auction reserves falls because reserves can, in part, be invested in interest-bearing debt securities. This investment opportunity translates a greater supply of debt securities into a higher demand for pre-auction reserves (cost channel). Second, debt security investments increase the probability of a liquidity shortage because debt securities drain reserves (reserve-absorbing channel). The reserve-absorbing channel is negligible, however, if reserves are ample. Next, we show that issuing debt securities therefore resembles paying interest on reserves.

3.5 Central bank debt securities and interest on reserves

To establish the equivalence between interest on reserve policies and central bank debt security programs, we derive the money market rate i_m^{ior} that prevails if commercial banks earn positive interest on reserves $i_{ior} > 0$, instead of having access to central bank debt securities.

Proposition 2 *Suppose that commercial banks earn $i_{ior} > 0$ on reserves. If each commercial bank maximizes expected profits with respect to B_i and π_i , the money market rate equals $i_m^{ior} = i_{ior} + i_x P(X^{ior} > 0)$, where $X^{ior} = Z - (F - K)$.*

Proof. See Appendix B, Section B.2.

Proposition 2 establishes the money market equilibrium that prevails if commercial banks earn a strictly positive interest on reserves.²⁸ Issuing debt securities affects the money market rate through the cost channel and the reserve-absorbing channel. In contrast, interest on reserve policies affect the money market rate only through the cost channel.

²⁷The money market rate does not react to an increase in the supply of debt securities if commercial banks are satiated with debt securities. For a more detailed discussion of the level of satiation, see Appendix B, Section B.3.

²⁸Many others have established a similar result (see e.g. Goodfriend 2002). Proposition 2 implicitly assumes that borrowed reserves do not pay interest.

Corollary 2.1 *With ample reserves, the floor on the money market rate is $\underline{i}_m^{ior} \equiv \lim_{F \rightarrow \infty} \dot{i}_m^{ior} = i_{ior}$.*

Proof. Because $\lim_{F \rightarrow \infty} X^{ior} = -\infty$, $\lim_{F \rightarrow \infty} P(X^{ior} > 0) = 0$. The result then follows directly from proposition 2.

From Corollary 1.1 and 2.1, it follows that the central bank can implement the interest rate floor either with an interest on reserves policy or with a debt security program. The interest rate floor in the two operational frameworks is equal if $i_{ior} = i_b \pi$.

3.6 Illustration

To illustrate the qualitative features of the money market model, we calibrate its parameters to match the situation in Switzerland in August 2010.²⁹ We first discuss the impact of changing the volume of debt securities on the money market rate. The left panel of Figure 5 shows the money market rate as a function of pre-auction reserves for various π^{cb} conditional on $i_b = 0.1\%$. The money demand curve is strictly downward sloping in pre-auction reserves, unless commercial banks are satiated with a positive amount of debt securities ($\pi = \bar{\pi} > 0$). The money market rate falls in pre-auction reserves because a greater liquidity buffer decreases the likelihood of a liquidity shortage (the liquidity effect).

If commercial banks are satiated with a positive amount of debt securities, the money demand curve is flat in pre-auction reserves because commercial banks increase their debt security investments if pre-auction reserves rise. Higher investments in debt securities, in turn, increase the return on pre-auction reserves. The resulting upward pressure on the money market rate exactly offsets the liquidity effect.³⁰

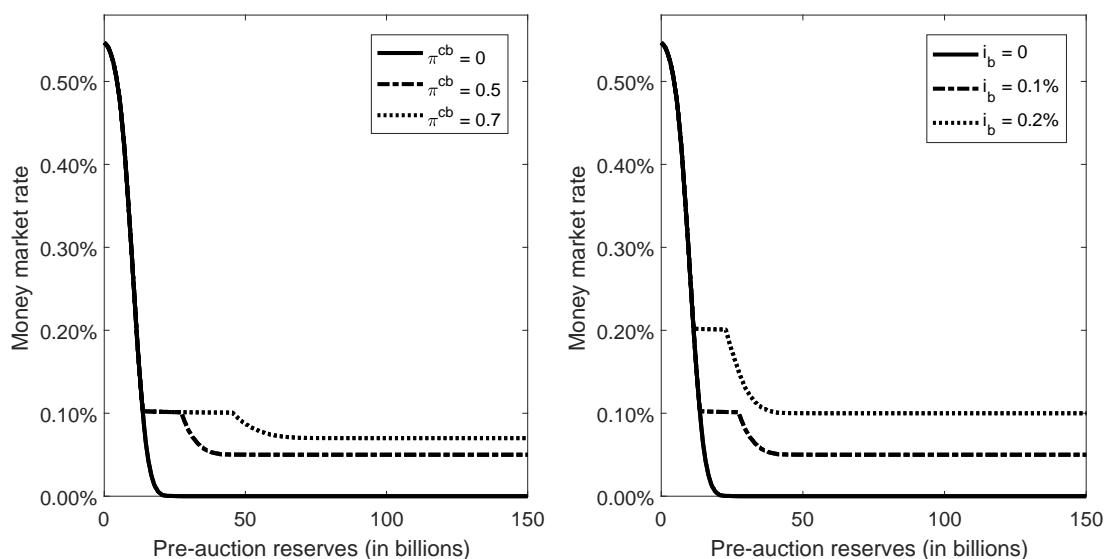
If pre-auction reserves are abundant, the money market rate approaches the interest rate floor. For example, the interest rate floor equals 0.05% if the central bank allows commercial banks to invest up to 50% of their pre-auction reserves in debt securities, and the yield on debt securities amounts to 0.1%. If the central bank supplies debt securities with a positive yield, the floor is strictly positive.

If commercial banks are non-satiated with debt securities ($\pi < \bar{\pi}$), supplying more debt securities raises the money market rate. Increasing the supply of debt securities decreases post-auction reserves available to cushion liquidity shocks (reserve-absorbing channel). Moreover, debt securities provide

²⁹See Appendix B, Section B.5 for details on the calibration.

³⁰See Appendix B, Sections B.1 and Section B.4, for a technical discussion.

Figure 5 — Money demand curves



Notes: Left panel: money demand curves conditional on $i_b = 0.10\%$. Right panel: money demand curves conditional on $\pi^{cb} = 0.5$.

an attractive investment opportunity to commercial banks, which lowers the opportunity cost of holding pre-auction reserves (cost channel). Therefore, increasing π^{cb} from 0 to 0.5 raises the interest rate floor.

If commercial banks are satiated with debt securities ($\pi = \bar{\pi}$), supplying more debt securities does not raise the money market rate. For example, at $F = 25$, commercial banks optimally invest 45% of their pre-auction reserves in debt securities. Thus, increasing π^{cb} from 0.5 to 0.7 does not affect the money market rate.

Next, we examine the impact of changing the yield on debt securities. The right panel of Figure 5 depicts money demand curves, varying the yield on central bank debt securities, conditional on $\pi^{cb} = 0.5$. For a positive yield on debt securities, we see that the floor on the money market rate is strictly positive. In addition, if commercial banks invest in debt securities, increasing the yield on debt securities raises the money market rate through the cost channel, even with ample reserves.

The model's qualitative predictions resonate well with the descriptive analysis. Figure 3 shows that the SNB Bill yield stays below the money market rate up to 2010, when excess reserve balances were small. The model predicts that the money market rate may indeed be higher than the debt security yield in an environment with scarce reserve balances. For large excess reserve balances, however, the money market rate is strictly below the debt security yield. Figure 3 shows that at the end of

the sample period, the share of SNB Bills in pre-auction reserves amounted to 78% and the marginal yield to 0.22%. Our model would predict a money market rate at 0.17%. This close to, but higher than, the SAR 1W (0.05%) and the SAR 3M (0.091%). The higher prediction is consistent with the fact that at the end of the sample, the maturity of outstanding SNB Bills was higher than three months.³¹

4 Empirical strategy

So far, we focused on the partial equilibrium outcomes on the money market. Next, we identify the causal general equilibrium impact of central bank debt securities. We exploit that SNB Bill auctions took place on a pre-determined day of the week to identify their causal impact through heteroscedasticity (see [Rigobon 2003](#); [Rigobon and Sack 2004](#); [Nakamura and Steinsson 2018a](#)). We use sign and zero restrictions to recover two orthogonal dimensions through which SNB Bills affect financial markets: a money market rate shock, in line with the theoretical model, and an expectation shock. To estimate dynamic effects, we combine identification through heteroscedasticity with local projections (see [Jordà 2005](#)).

4.1 Model

Assume that the data are generated by a VAR of order 1 including changes in stock prices (s_t), changes in the money market rate (r_t), and changes the exchange rate (x_t):³²

$$y_t = \Phi y_{t-1} + \Psi e_t ,$$

where $y_t = [r_t \ s_t \ x_t]'$, $e_t = [e_{1t} \ e_{2t} \ e_{3t}]'$ is a vector of i.i.d. structural shocks with $V[e_{1t}] = V[e_{2t}] = V[e_{3t}] = 1$, Φ is a (3×3) matrix of autoregressive coefficients, and Ψ is a (3×3) matrix measuring the immediate impact of the structural shocks.

Assume that shocks 1 and 2 occur only on pre-determined auction days, whereas shock 3 occurs in all periods. Therefore, the auctions have two underlying orthogonal dimensions (see e.g. [Swanson 2017](#)). In addition, shock 3 may be seen as a linear combination of multiple independent shocks as well.

³¹See Appendix D, Figure D.1.

³²For the ease of exposition, we focus on a three-variable VAR of order 1. Importantly, our identification scheme does not depend on whether the data-generating process is well described by a VAR. Appendix C additionally shows how to identify cumulative responses, compute a variance decomposition, and presents a simulation exercise.

Because some shocks occur only on auction days, the variance-covariance matrix of the one-step-ahead forecast error ($\varepsilon_{t|t-1} = \Psi e_t$) is heteroscedastic. Let $\Omega_{t \in A}$ ($\Omega_{t \notin A}$) denote the variance-covariance of $\varepsilon_{t|t-1}$ during auction days (other days), and ψ_{ij} the impact of variable $i \in \{r, s, x\}$ to shock $j \in \{1, 2, 3\}$. It follows that:

$$\begin{aligned} \Omega_{t \in A} &= \begin{bmatrix} \psi_{r1}^2 + \psi_{r2}^2 + \psi_{r3}^2 & \psi_{r1}\psi_{s1} + \psi_{r2}\psi_{s2} + \psi_{r3}\psi_{s3} & \psi_{r1}\psi_{x1} + \psi_{r2}\psi_{x2} + \psi_{r3}\psi_{x3} \\ & \psi_{s1}^2 + \psi_{s2}^2 + \psi_{s3}^2 & \psi_{s1}\psi_{x1} + \psi_{s2}\psi_{x2} + \psi_{s3}\psi_{x3} \\ & & \psi_{x1}^2 + \psi_{x2}^2 + \psi_{x3}^2 \end{bmatrix} \quad (2) \\ \Omega_{t \notin A} &= \begin{bmatrix} \psi_{r3}^2 & \psi_{r3}\psi_{s3} & \psi_{r3}\psi_{x3} \\ & \psi_{s3}^2 & \psi_{s3}\psi_{x3} \\ & & \psi_{x3}^2 \end{bmatrix} \\ \Omega_{t \in A} - \Omega_{t \notin A} &= \begin{bmatrix} \psi_{r1}^2 + \psi_{r2}^2 & \psi_{r1}\psi_{s1} + \psi_{r2}\psi_{s2} & \psi_{r1}\psi_{x1} + \psi_{r2}\psi_{x2} \\ & \psi_{s1}^2 + \psi_{s2}^2 & \psi_{s1}\psi_{x1} + \psi_{s2}\psi_{x2} \\ & & \psi_{x1}^2 + \psi_{x2}^2 \end{bmatrix} = \tilde{\Omega} . \end{aligned}$$

The diagonal of $\tilde{\Omega} = \Omega_{t \in A} - \Omega_{t \notin A}$ comprises the sum of the squared impact coefficients of shock 1 and 2. As [Gürkaynak et al. \(2018\)](#) emphasize, heteroscedasticity-based identification strategies therefore capture the overall impact of all information revealed during an event.

4.2 Identification

The key assumption of the identification scheme, which we cannot formally test, is that SNB Bill auctions occurred on a deterministic schedule.³³ We are confident that this was indeed the case (see Section 2).

To recover two dimensions of an SNB Bill shock, we impose additional assumptions.³⁴ First, we impose that a money market rate shock (shock 1) increases the short-term interest rate ($\psi_{r1} > 0$). Second, we impose that the expectation shock (shock 2) causes a decline in stock prices, but no change in the money market rate ($\psi_{r2} = 0, \psi_{s2} < 0$).³⁵ After imposing these restrictions, we can use equation (2) to recursively identify the impact of the two shocks on the interest rate, stock prices,

³³We also assume that all parameters except the residual variance-covariance matrix are constant and that the variances of the structural shocks are unity.

³⁴Therefore, the model is overidentified and we could set up a more efficient GMM estimator and test the overidentifying restrictions (see [Rigobon and Sack 2004](#); [Nakamura and Steinsson 2018a](#)).

³⁵Our money market rate shock is similar to what [Gürkaynak et al. \(2005\)](#) and [Altavilla et al. \(2019\)](#) call “target” surprises.

and the exchange rate:

$$\begin{aligned}
\psi_{r1} &= \sqrt{\tilde{\Omega}_{11}} \\
\psi_{s1} &= \tilde{\Omega}_{12}/\psi_{r1} \\
\psi_{x1} &= \tilde{\Omega}_{13}/\psi_{r1} \\
\psi_{r2} &= 0 \\
\psi_{s2} &= -\sqrt{\tilde{\Omega}_{22} - \psi_{s1}^2} \\
\psi_{x2} &= (\tilde{\Omega}_{23} - \psi_{s1}\psi_{x1})/\psi_{s2},
\end{aligned} \tag{3}$$

where $\tilde{\Omega}_{ij}$ denotes the i th row and j th column of $\tilde{\Omega}$. As [Wright \(2012\)](#) suggests, we can test whether the interest rate responds to an SNB Bill shock by examining whether the variance of the money market rate is indeed higher on SNB Bill auction days ($\tilde{\Omega}_{11} > 0$). Similarly, we can test whether, besides the indirect effect via the money market rate, there is an expectation dimension affecting stock prices ($\tilde{\Omega}_{22} - \psi_{s1}^2 > 0$). Therefore, we can verify whether these assumptions are supported by the data.

4.3 Dynamic causal effects

The identification strategy readily extends to dynamic causal effects. For illustration, let $\Psi_h = \Phi^h \Psi_0$ denote the impulse response after h periods from a VAR(1). We can rewrite the VAR as:

$$y_t = \Phi^{h+1} y_{t-h-1} + \Psi_h e_{t-h} + \dots + \Psi_0 e_t.$$

Note that y_t is determined by the h -period-ahead direct forecast, and a forecast error:

$$\begin{aligned}
\mathbb{E}[y_t | y_{t-h-1}] &= \Phi^{h+1} y_{t-h-1} \\
\varepsilon_{t|t-h-1} &= \Psi_h e_{t-h} + \dots + \Psi_0 e_t.
\end{aligned}$$

We use that the change in the direct forecast, when one additional observation becomes available, is only caused by the structural shocks in this period. Equivalently, the change in the forecast error is

only caused by the structural shocks in this period:

$$\begin{aligned}\mathbb{E}[y_t|y_{t-h-1}] - \mathbb{E}[y_t|y_{t-h}] &= \varepsilon_{t|t-h-1} - \varepsilon_{t|t-h} \\ &= \Psi_h e_{t-h}.\end{aligned}$$

Therefore, we can first estimate direct forecasts and forecast revisions with local projections. Second, to identify the dynamic causal effects, we can use equations (2) and (3). That is, we compare the variance-covariance of the forecast revisions, if there was an auction in period $t - h$, to the variance-covariance if there was no auction. Afterwards, we can impose sign and zero restrictions to recursively identify the effects after h periods of the two shocks.

4.4 Data and estimation

The main specification uses a Swiss nominal effective exchange rate index, a Swiss stock price index (Swiss Market Index, SMI), as well as various interest rates.³⁶ We express the exchange rate as one unit of a basket of foreign currencies in terms of Swiss francs. Therefore, a decline in the exchange rate is an effective appreciation of the Swiss franc. The SMI comprises 20 companies with the largest market capitalization on the SIX Exchange.³⁷ The one-week, one-year, and ten-year interest rates are zero coupon yields inferred from interest rate swaps.³⁸ In addition, we control for foreign variables, such as the EUR/USD exchange rate, a European stock market index, and the three-month EUR Libor.³⁹ In some specifications, we extend the model with bilateral exchange rates, and zero coupon yields of government and corporate bonds.

We transform all interest rates to first differences, and all remaining variables to log-changes.⁴⁰ To estimate the forecast errors, we use local projections including a constant and two lags of all variables.

When estimating the variance-covariances, we make sure that no other operations occurred on SNB

³⁶See Appendix A for all data sources.

³⁷See www.six-group.com/exchanges/knowhow/products/shares/indices_en.html (accessed on 6 October 2019).

³⁸The interest rate swaps are based on, SARON, an overnight rate calculated from actual repo transactions and binding quotes. See www.six-group.com/exchanges/indices/data_centre/swiss_reference_rates/reference_rates_en.html (accessed on 6 October 2019). Although there are Swiss Average Rates available for various maturities, the quotes are often missing for periods in which the number of transactions and/or the volume of the transactions were too low. We therefore prefer to use interest rate derivatives in the empirical analysis.

³⁹We also experimented with other exogenous variables, for example, adding the change in the German government bond yield. The results remain qualitatively identical.

⁴⁰We remove all weekends because of missing values. Therefore, our results are measured in weekdays. In addition, there are missing values in stock price data when markets close on holidays. We replace these missing values with the last available observation.

Bill auction days. We assembled information on other monetary and fiscal operations by the SNB. These include (reverse) repo operations (in CHF and USD), foreign exchange swaps, USD SNB Bill auctions, and auctions of bonds and treasury bills on behalf of the Swiss Confederation. To control for these events, we remove them from the estimation of the variance-covariances.⁴¹ In addition, we remove days with official monetary policy decisions by the SNB or by the ECB. We then impose the identifying assumptions on the one-week interest rate and the SMI. For estimating dynamic causal effects, we prefer to impose the restrictions on the cumulative responses because financial market variables likely follow a random walk.⁴² The estimation sample ranges from 20 October 2008 to 28 July 2011. For inference, we use 8,000 samples from a moving block bootstrap as described in ch. 8 by [Efron and Tibshirani \(1993\)](#), with a block size of 5 business days.

5 Empirical results

Table 2 shows the results. Before discussing the responses, it is worth noting that the data support the assumption that there are two independent dimensions. The share identified for the interest rate shock gives the share of bootstrap replications for which the variance during an SNB Bill auction rises ($\tilde{\Omega}_{11} > 0$). Moreover, the share identified for the expectation shock gives the share of bootstrap replications for which there is an effect on stock prices beyond the effect through the money market rate ($\tilde{\Omega}_{22} - \psi_{s1}^2 > 0$). The first test therefore provides evidence on whether SNB Bill shocks affect the money market rate. The second test provides evidence on whether there is an additional dimension unrelated to the money market rate. The shares are indeed close to unity for both shocks.

The shocks yield qualitatively and quantitatively different responses. For the expectation shock, we find an appreciation of the Swiss franc (-0.4%), and decline in stock prices (-1.2%). At the upper end of the 95% confidence interval, we still find a 0.4% decline in stock prices and a 0.08% appreciation. In addition, long-term interest rates decline. By contrast, the money market rate shock yields responses in line with monetary policy surprises before the crisis (see e.g. [Gürkaynak et al. 2005](#)). The increase in the money market rate leads to a small increase in the long-term interest rate. Stock prices decline by 0.3% and the Swiss franc appreciates by 0.1%. These responses are imprecisely estimated, however.

To assess the relative importance of the shocks, we provide a forecast-error variance decomposition.

⁴¹For reverse repo operations and foreign exchange swaps, we remove them only if no SNB Bill auction occurred.

⁴²See C for a discussion.

Table 2 — Impact of SNB Bills shocks

	Effects of orthogonalized shocks		Variance share explained by		
	Expectation	Interest rate	Expectation	Interest rate	Total
1W interest rate (in pp)	0.000 [0.000, 0.000] (0.000, 0.000)	0.059 [0.033, 0.085] (0.029, 0.089)	0.00 [0.00, 0.00] (0.00, 0.00)	0.71 [0.47, 0.86] (0.39, 0.87)	0.71 [0.47, 0.86] (0.39, 0.87)
1Y interest rate (in pp)	0.007 [-0.058, 0.068] (-0.082, 0.085)	-0.040 [-0.122, 0.021] (-0.144, 0.032)	0.24 [0.00, 0.48] (0.00, 0.76)	0.11 [0.00, 0.34] (0.00, 0.45)	0.35 [0.02, 0.65] (0.01, 0.95)
10Y interest rate (in pp)	-0.034 [-0.050, -0.015] (-0.054, -0.011)	0.014 [-0.006, 0.035] (-0.009, 0.039)	0.62 [0.14, 0.91] (0.08, 1.20)	0.12 [0.00, 0.36] (0.00, 0.42)	0.75 [0.20, 1.03] (0.13, 1.28)
Stock prices (in %)	-1.176 [-1.751, -0.520] (-1.845, -0.400)	-0.296 [-0.923, 0.255] (-1.047, 0.363)	0.51 [0.17, 0.73] (0.11, 0.75)	0.08 [0.00, 0.31] (0.00, 0.39)	0.58 [0.29, 0.75] (0.22, 0.77)
Exchange rate (in %)	-0.352 [-0.594, -0.121] (-0.668, -0.082)	-0.116 [-0.250, 0.019] (-0.274, 0.046)	0.72 [0.07, 1.14] (0.03, 1.62)	0.08 [0.00, 0.23] (0.00, 0.28)	0.79 [0.16, 1.21] (0.12, 1.70)
Share identified	0.97	1.00			
N overall	724	724			
N auctions	52	52			
N without auctions	207	207			

Notes: Impact of one standard deviation SNB Bill shocks identified with sign and zero restrictions. The expectation shock leads to a decline in stock prices but no change in the one-week interest rate. The interest rate shock leads to an increase in the one-week interest rate. The third and fourth column give a variance decomposition. All specifications control for two lags of all dependent variables, as well as, the EUR/USD exchange rate, the 3M EUR Libor, and a European stock price index. 90% and 95% confidence intervals in brackets and parentheses, respectively. Inference is based on 8,000 draws from a block bootstrap algorithm. We also report the share of bootstrap replications for which $\tilde{\Omega}_{11} > 0$ or $\tilde{\Omega}_{22} - \psi_{s1}^2 > 0$ (share identified), the overall number of observations to estimate the parameters (N auctions), the number of observations to estimate $\Omega_{t \in A}$ (N auctions), and $\Omega_{t \notin A}$ (N without events).

The expectation shock explains a large share of fluctuations in long-term interest rates (60%), the exchange rate (70%), and stock prices (50%). We therefore corroborate that this shock mostly affects forward-looking variables. Meanwhile, the money market rate shock explains 70% of the one-week interest rate. But, it explains less than 10% of forward-looking variables. The last column shows that the two SNB Bill shocks account for up to 80% of the forecast-error variance on an auction day.

The fall in long-term interest rates after a contractionary expectation shock contrasts with research on large-scale asset purchases. To shed more light on this finding, we extend the model with measures for the future expected real interest rate, corporate bond risk premia, and inflation expectations. We approximate these measures using eight-year zero coupon yields of bonds from Swiss manufacturing firms, banks, the Swiss Confederation, as well as foreign companies issuing bonds in Swiss franc. We compute risk premia as the spread between eight-year corporate, and government bond yields. Then, we assume that foreign risk premia and foreign real interest rates are not affected by an SNB Bill shock. This allows us to interpret the effect on Swiss franc denominated corporate bond yields of foreign companies as the effect on inflation expectations. Finally, we approximate the expected real interest rate as the difference of government bond yields and inflation expectations.

Table 3 suggests that an SNB Bill shock causes expectations about future economic activity to deteriorate. An expectation shock leads to a decline in expected real interest rates by 0.02 pp. In addition, we observe an increase of corporate bond risk premia for manufacturing firms and banks by 0.01 pp. Although the point estimate suggests that inflation expectations declined somewhat, the effect is imprecisely estimated. The variance decomposition confirms that the expectation shock was important. It explains 60% of the variance in the real interest rate, and up to 55% of the variance in risk premia. Meanwhile, it explains less of the variance in inflation expectations. This is not surprising, however, because most fluctuations of foreign corporate bond yields are unrelated to Swiss developments.

Next, we analyze whether the responses depend on the maturity of SNB Bills. Table 4 shows the effect of short-term SNB Bill auctions. On the one hand, short-term SNB Bills may have little effect because they soak up reserves only for a brief period. On the other hand, the impact may be large if financial market participants expect that the SNB systematically rolls over newly created Bills when they mature. For brevity, we only report the expectation shock. We see that short-term SNB

Table 3 — Impact of SNB Bill shocks on corporate bond yields

(a) Manufacturing

	Effects of orthogonalized shocks		Variance share explained by		
	Expectation	Interest rate	Expectation	Interest rate	Total
8Y real rate (in pp)	-0.022 [-0.034, -0.010] (-0.038, -0.007)	0.002 [-0.008, 0.011] (-0.010, 0.012)	0.60 [0.16, 1.01] (0.10, 1.38)	0.04 [0.00, 0.14] (0.00, 0.19)	0.63 [0.21, 1.06] (0.14, 1.41)
8Y risk premium (in pp)	0.012 [0.002, 0.022] (-0.001, 0.025)	0.000 [-0.008, 0.008] (-0.010, 0.010)	0.39 [0.02, 0.80] (0.00, 1.05)	0.05 [0.00, 0.18] (0.00, 0.25)	0.43 [0.06, 0.83] (0.03, 1.12)
8Y inflation exp. (in pp)	-0.005 [-0.017, 0.006] (-0.021, 0.008)	0.005 [-0.006, 0.014] (-0.008, 0.016)	0.11 [0.00, 0.30] (0.00, 0.49)	0.06 [0.00, 0.20] (0.00, 0.24)	0.16 [0.01, 0.39] (0.00, 0.55)
Share identified	0.96	1.00			
N overall	724	724			
N auctions	52	52			
N without auctions	207	207			

(b) Banks

	Effects of orthogonalized shocks		Variance share explained by		
	Expectation	Interest rate	Expectation	Interest rate	Total
8Y real rate (in pp)	-0.022 [-0.034, -0.010] (-0.038, -0.007)	0.002 [-0.008, 0.010] (-0.010, 0.012)	0.63 [0.14, 0.98] (0.08, 1.35)	0.04 [0.00, 0.14] (0.00, 0.18)	0.67 [0.19, 1.02] (0.12, 1.42)
8Y risk premium (in pp)	0.012 [0.002, 0.022] (-0.000, 0.027)	0.002 [-0.004, 0.008] (-0.005, 0.010)	0.55 [0.02, 1.13] (0.01, 1.64)	0.04 [0.00, 0.16] (0.00, 0.21)	0.59 [0.07, 1.16] (0.03, 1.69)
8Y inflation exp. (in pp)	-0.004 [-0.016, 0.006] (-0.021, 0.009)	0.005 [-0.005, 0.014] (-0.008, 0.016)	0.11 [0.00, 0.28] (0.00, 0.46)	0.05 [0.00, 0.19] (0.00, 0.23)	0.16 [0.01, 0.36] (0.00, 0.53)
Share identified	0.96	1.00			
N overall	724	724			
N auctions	52	52			
N without auctions	207	207			

Notes: Responses of 8Y corporate bond yields decomposed into the real interest rate, a risk premium, and inflation expectations. Impact of one standard deviation SNB Bill shocks identified with sign restrictions and zero restrictions. The expectation shock leads to a decline in stock prices but no change in the one-week interest rate. The interest rate shock leads to an increase in the one-week interest rate. The third and fourth column give a variance decomposition. All specifications control for two lags of all dependent variables, as well as, the EUR/USD exchange rate, the 3M EUR Libor, and a European stock price index. 90% and 95% confidence intervals in brackets and parentheses, respectively. Inference is based on 8,000 draws from a block bootstrap algorithm. We also report the share of bootstrap replications for which $\tilde{\Omega}_{11} > 0$ or $\tilde{\Omega}_{22} - \psi_{s1}^2 > 0$ (share identified), the overall number of observations to estimate the parameters (N auctions), the number of observations to estimate $\Omega_{t \in A}$ (N auctions), and $\Omega_{t \notin A}$ (N without events).

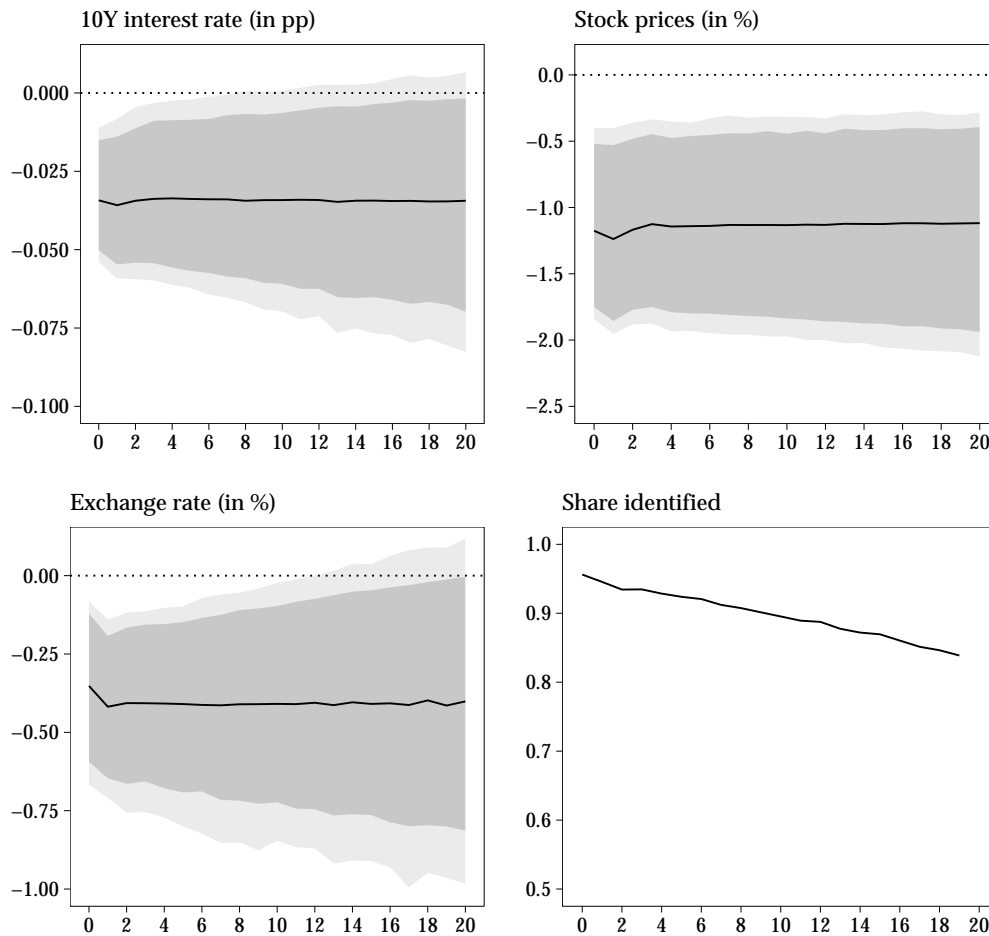
Table 4 — Impact of SNB Bill shocks according to maturity

	Expectation shock			
	1M SNB Bills	3M SNB Bills	6M SNB Bills	12M SNB Bills
1W interest rate (in pp)	0.000 [0.000, 0.000] (0.000, 0.000)	0.000 [0.000, 0.000] (0.000, 0.000)	0.000 [0.000, 0.000] (0.000, 0.000)	0.000 [0.000, 0.000] (0.000, 0.000)
1Y interest rate (in pp)	0.014 [-0.051, 0.082] (-0.068, 0.101)	-0.103 [-0.288, 0.005] (-0.395, 0.022)	-0.110 [-0.318, 0.017] (-0.433, 0.041)	-0.066 [-0.201, 0.017] (-0.264, 0.045)
10Y interest rate (in pp)	-0.033 [-0.050, -0.012] (-0.053, -0.007)	-0.101 [-0.247, -0.033] (-0.339, -0.027)	-0.049 [-0.153, -0.002] (-0.213, 0.004)	-0.036 [-0.110, 0.027] (-0.164, 0.053)
Stock prices (in %)	-1.163 [-1.777, -0.465] (-1.863, -0.350)	-0.341 [-0.622, -0.102] (-0.660, -0.075)	-0.332 [-0.608, -0.094] (-0.695, -0.065)	-0.480 [-0.867, -0.123] (-0.950, -0.089)
Exchange rate (in %)	-0.367 [-0.670, -0.086] (-0.762, -0.045)	-0.047 [-0.963, 0.677] (-1.267, 1.018)	-1.692 [-4.337, -0.522] (-6.032, -0.368)	-0.759 [-2.003, -0.126] (-2.710, -0.021)
Share identified	0.94	0.08	0.04	0.16
N overall	724	724	724	724
N auctions	49	18	12	12
N without auctions	210	208	211	211

Notes: Impact of one standard deviation SNB Bill shocks identified with sign and zero restrictions. The analysis is limited to auction days with securities of a maturity of 1M and less, or, 3M and less. The expectation shock leads to a decline in stock prices but no change in the one-week interest rate. The interest rate shock leads to an increase in the one-week interest rate. The third and fourth column give a variance decomposition. All specifications control for two lags of all dependent variables, as well as, the EUR/USD exchange rate, the 3M EUR Libor, and a European stock price index. 90% and 95% confidence intervals in brackets and parentheses, respectively. Inference is based on 8,000 draws from a block bootstrap algorithm. We also report the share of bootstrap replications for which $\tilde{\Omega}_{11} > 0$ or $\tilde{\Omega}_{22} - \psi_{s1}^2 > 0$ (share identified), the overall number of observations to estimate the parameters (N auctions), the number of observations to estimate $\Omega_{t \in A}$ (N auctions), and $\Omega_{t \notin A}$ (N without events).

Bill auctions were mainly responsible for the effects we identify. Separately estimating models for maturities of three months and more leaves us with less than 20 auctions days. The table shows that the share of bootstrap replications with satisfied identifying assumption is very low for longer maturities. Therefore, these results are not reliable. By contrast, the results for shorter maturities are reliable, and in line with our main specification.

Figure 6 — Dynamic impact of an expectation shock

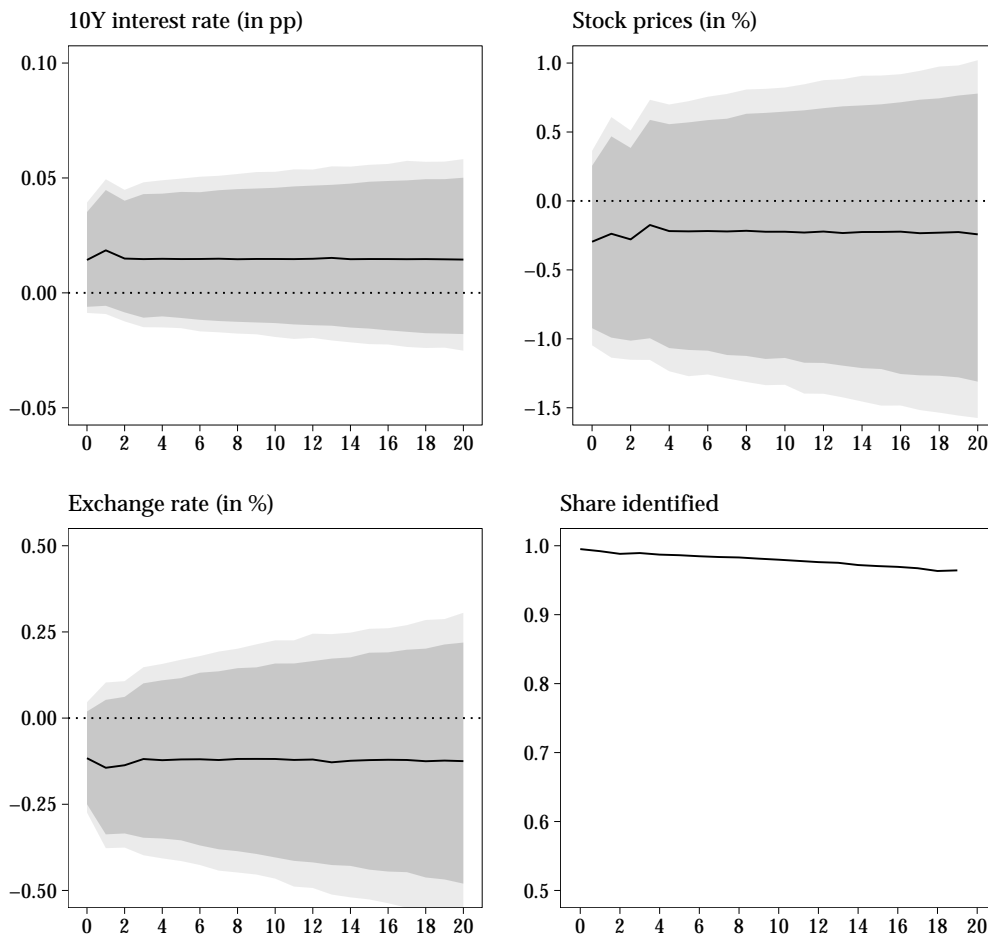


Notes: Dynamic impact of a one standard deviation expectation shock identified with sign and zero restrictions. All specifications control for two lags of all dependent variables, as well as, the EUR/USD exchange rate, the 3M EUR Libor, and a European stock price index. Shaded areas give 90% and 95% confidence intervals. Inference is based on 8,000 draws from a block bootstrap algorithm. We also report the the share of bootstrap replications for which $\tilde{\Omega}_{22} - \psi_{s1}^2 > 0$ (share identified).

Did an SNB Bill shock have a persistent effect on financial market variables?⁴³ To shed light on this question, we estimate dynamic causal effects with local projections. Figure 6 shows that an expectation shock caused a persistent decline in stock prices, the exchange rate, and long-term

⁴³Studies on US large-scale asset purchases do not agree whether they had a persistent effect (Wright 2012; Swanson 2017).

Figure 7 — Dynamic impact of an interest rate shock



Notes: Dynamic impact of a one standard deviation money market rate shock identified with sign and zero restrictions. All specifications control for two lags of all dependent variables, as well as, the EUR/USD exchange rate, the 3M EUR Libor, and a European stock price index. Shaded areas give 90% and 95% confidence intervals. Inference is based on 8,000 draws from a block bootstrap algorithm. We also report the share of bootstrap replications for which $\tilde{\Omega}_{11} > 0$ (share identified).

interest rates.⁴⁴ Up to 20 business days, we still find a significant appreciation and decline in long-term interest rates at the 10% level. However, the share of identified bootstrap replications clearly declines as we estimate longer horizons.⁴⁵

Figure 7 shows the corresponding responses for the money market rate shock. Although the shock is well identified, the effect on forward-looking variables is imprecisely estimated and economically small. Therefore, the local projections corroborate our findings of the main specification

5.1 Placebo tests

We performed various placebo tests to see whether our identification scheme picks up effects of other events, for which we expect the effect to be zero. We focus on the expectation shock. The tests confirm that actual SNB Bill auction days systematically differ from other days without an auction.

Table 5 — Impact of random auction days

(a) Random auction day before SNB Bill program

	Stock prices	Exchange rate	10Y interest rate
Average impact	-0.24	0.09	0.00
Share rejected	1.00	0.05	0.15
Share identified	0.00	0.00	0.00

(b) Random auction day during SNB Bill program (excluding actual auctions)

	Stock prices	Exchange rate	10Y interest rate
Average impact	-0.39	-0.09	-0.02
Share rejected	1.00	0.10	0.23
Share identified	0.00	0.00	0.00

Notes: Results of two placebo simulations using 170 auction dummies generated on random days. Identification with sign restriction on stock prices. Panel (a) uses a sample from 2005 to 2008, when no SNB Bills were issued, with random auctions occurring on Tuesdays or Wednesdays. Panel (b) uses the actual sample, when SNB Bills were issued, with random auctions occurring on days without an SNB Bill auction. We generate 200 placebo samples. The first row reports the average of the immediate impact (averaged over all bootstrap replications and placebo samples). The second row reports the share of placebo samples rejecting the null hypothesis of no response at the 10% level. We test the null against the one-sided alternative of a drop in the SMI, an appreciation of the exchange rate, and a decline in the long-term interest rate. The last row shows the share of placebo samples with at least 90% of the bootstrapped impulse responses for which $\tilde{\Omega}_{22} - \psi_{s1}^2 > 0$ (share identified).

First, we estimate the model on a sample from January 2005 to January 2008. During this period, no SNB Bill auctions took place. Instead, we generate a placebo dummy variable with 170 random

⁴⁴The persistent impact is in line with Baurle and Kaufmann (2018), using a structural VAR to show that exchange rate movements became much more persistent during the post-crisis period episode.

⁴⁵In Figure D.2, in Appendix D, we show the responses identified only with a sign restriction on stock prices. This identifying assumption is less restrictive, strongly supported by the data, and, confirms that an SNB Bill shock had a persistent effect on financial market variables.

auctions occurring on either Tuesday or Thursday. We then estimate the immediate impulse responses on 200 different placebo samples. Based on these placebo estimates, we can compute various statistics. The average impact indicates whether we find the same sign and magnitude of the effect as in the actual sample. Then, we compute the share of placebo samples in which we reject the null hypothesis of no response at the 10% level. We test the null against the one-sided alternative of a drop in the SMI, an appreciation of the exchange rate, and a decline in the long-term interest rate. The share of rejections indicates how often we would falsely draw the same conclusion as in our main analysis. Finally, we compute the share of placebo samples where at least 90% of the bootstrapped impulse responses are consistent with our identifying assumption. This share indicates how often we wrongly conclude that the identifying assumption is satisfied.

Panel (a) of Table 5 shows the results. The summary statistics suggest that there was no impact of the placebo auctions on the exchange rate. In fact, the average coefficient on the exchange rate is positive and we reject the null hypothesis only in 5% of all cases. For the interest rate, we find no effect on average. But, we reject the null hypothesis in 15% of all cases. Because we use a 10% significance level, however, this share still appears small. In addition, these responses condition on a decline in stock prices. As a consequence, the negative coefficient on the SMI and the high rejection rate reflect our identifying assumption. To show whether this conditioning is supported by the data we can investigate how many of the bootstrap samples fulfill this restriction. The last row shows that this is almost never the case; therefore we conclude that, before the SNB Bills program was in place, Tuesdays and Thursdays did not systematically differ from other days.

Second, we perform a placebo test using the original sample during which the SNB Bills program was in place. We randomly select placebo days on which no SNB Bill auction occurred. Panel (b) shows that there is some evidence that, conditional on a decline in stock prices, the Swiss franc appreciates and the long-term interest rate declines during these random auction days. However, the rejection rates are still relatively small (10% and 23%). Most importantly, the identifying assumption almost never holds.

Third, we examine whether other events had an impact on financial market variables (the payment day, auctions of SNB Bills in USD, and treasury bill auctions). The payment day should not matter if all information about the auction was already revealed on the auction day. Then, SNB Bill auctions

in USD should not affect the Swiss money market rate because they do not increase demand for reserves in Swiss franc. Finally, we expect that treasury bill auctions have no impact because the SNB issues these bills on behalf of the Swiss Confederation, that is, without the intention of draining reserves. We focus on the expectation shock; the results are shown in Appendix D. The exchange rate appreciates on treasury bill auction days, whereas, long-term interest rates decline on payment days and treasury bill auction days. Note, however, that the share of bootstrap replications supporting the identifying assumption ranges only from 12% to 70%. We therefore have only limited support that these operations indeed had an effect on financial market variables.

5.2 Robustness tests

We perform a range of robustness tests, focusing on the expectation shock.⁴⁶ Appendix D shows the results. Changing the number of lags to four or zero, and increasing the block size in the bootstrap algorithm does not change the results. We also use different stock market indexes to identify the impulse responses (i.e. the MSCI Switzerland and the SPI, both including a broader range of Swiss companies). In both cases, the results remain qualitatively the same. Then, we estimate models including bilateral exchange rates. We find an appreciation of the Swiss franc against the euro and the US dollar. But, the latter is less precisely estimated. We also varied the definition of days without an event from broad—excluding only official monetary policy assessments—to narrow—excluding daily operations in USD, treasury and government bond auctions, and foreign exchange swaps. For the narrow definition, we therefore have more auction days and days without an auction. The effects on stock prices and the exchange rate are qualitatively robust across all specifications. Using the narrow definition, we do not find a decline in long-term interest rates. Generally, the effects are less precisely estimated when we control for fewer other events. We also split the sample in June 2010, when the SNB started to issue SNB Bills with a longer term to maturity. Because there are fewer auctions in the two samples, we use a narrower definition of other events. In the second sample, when the SNB issued longer maturities, our identifying assumptions are not well supported by the data. In the first sample, we find qualitatively similar results. But the effects are less precisely estimated. Finally, we used a more efficient VAR approach to estimate dynamic effects.

⁴⁶We also experimented with other identification schemes. A point identification scheme along the lines of Nakamura and Steinsson (2018a) yields qualitatively identical results. Moreover, we identified a forward guidance shock by assuming that the 1Y-1W interest rate spread increases. The effect on other financial market variables was small, however. We therefore do not report these results in the Appendix.

Not surprisingly, the results are qualitatively identical, but, more precisely estimated using a VAR.

6 Concluding remarks

This paper analyzes the effects of novel exit strategies on money and financial markets. We use a theoretical model to show that the money market rate increases in the volume of, and yield on, debt securities even if commercial banks hold large excess reserve balances. Similar to interest on reserves, central bank debt therefore determines the interest rate floor.

The empirical analysis confirms that central bank debt securities affect money market rates in practice. We identify a money market rate shock that raises short-term interest rates and explains almost 70% of the variation in the one-week interest rate. Meanwhile, this shock has modest effects on forward-looking financial market variables.

In addition, we identify an expectation shock, which explains an important share of the forecast-error variance in forward-looking financial variables. This shock causes a decline in stock prices, a persistent appreciation of the Swiss franc, as well as a decline in long-term interest rates. Moreover, it leads to an increase in corporate bond risk premia for manufacturing firms and banks.

Our results suggest that novel exit strategies work, in the sense that they raise the money market rate even with large excess reserves. However, such exit strategies can be surprisingly contractionary because they affect financial market participants' expectations.

References

- Afonso, Gara and Ricardo Lagos (2015) "Trade dynamics in the market for federal funds," *Econometrica*, Vol. 83, pp. 263–313.
- Altavilla, Carlo, Luca Brugnolini, Refet S. Gürkaynak, Roberto Motto, and Giuseppe Ragusa (2019) "Measuring euro area monetary policy," *Journal of Monetary Economics*, DOI: <http://dx.doi.org/doi.org/10.1016/j.jmoneco.2019.08.016>.
- Armenter, Roc and Benjamin Lester (2017) "Excess reserves and monetary policy implementation," *Review of Economic Dynamics*, Vol. 23, pp. 212–235.
- Bauer, Michael D. and Glenn D. Rudebusch (2014) "The signaling channel for Federal Reserve bond purchases," *International Journal of Central Banking*, Vol. 10, pp. 233–289.
- Bäurle, Gregor and Daniel Kaufmann (2018) "Measuring exchange rate, price, and output dynamics at the effective lower bound," *Oxford Bulletin of Economics and Statistics*, Vol. 80, pp. 1243–1266.
- Bech, Morten and Todd Keister (2017) "Liquidity regulation and the implementation of monetary policy," *Journal of Monetary Economics*, Vol. 92, pp. 64–77.
- Bech, Morten and Cyril Monnet (2016) "A search-based model of the interbank money market and monetary policy implementation," *Journal of Economic Theory*, Vol. 164, pp. 32–67.
- Berentsen, Aleksander, Sébastien Kraenzlin, and Benjamin Müller (2018) "Exit strategies for monetary policy," *Journal of Monetary Economics*, Vol. 99, pp. 20–40.
- Bernanke, Ben S. and Ilian Mihov (1998) "The liquidity effect and long-run neutrality," *Carnegie-Rochester Conference Series on Public Policy*, Vol. 49, pp. 149 – 194.
- Boutros, Michael and Jonathan Witmer (2019) "Monetary policy implementation in a negative rate environment," *Journal of Money, Credit and Banking*, DOI: <http://dx.doi.org/doi:10.1111/jmcb.12605>.
- Bundesrat (2004) "Verordnung zum Bundesgesetz über die Schweizerische Nationalbank vom 18. März 2004, SR 951.131.," Verordnung, Der Schweizerische Bundesrat.
- Cieslak, Anna and Andreas Schrimpf (2019) "Non-monetary news in central bank communication," *Journal of International Economics*, Vol. 118, pp. 293–315.
- Dziobek, Claudia H. and John W. Dalton (2005) "Central bank losses and experiences in selected countries," IMF Working Papers 05/72, International Monetary Fund.
- Efron, Bradley and Robert J. Tibshirani (1993) *An Introduction to the Bootstrap*, New York: Chapman & Hall/CRC.
- Ennis, Huberto M. and John A. Weinberg (2013) "Over-the-counter loans, adverse selection, and stigma in the interbank market," *Review of Economic Dynamics*, Vol. 16, pp. 601–616.
- Federal Reserve Board (2019) "Federal Reserve to offer seven-day term deposits on May 30 (23 May 2019)," press release, Federal Reserve Board.
- Friedman, Milton (1968) "The role of monetary policy," *American Economic Review*, Vol. 58, pp. 1–17.
- Gagnon, Joseph E. and Brian Sack (2014) "Monetary policy with abundant liquidity: a new operating framework for the Federal Reserve," Policy Brief 14-4, Peterson Institute for International Economics.
- Gertler, Mark and Peter Karadi (2015) "Monetary policy surprises, credit costs, and economic activity," *American Economic Journal: Macroeconomics*, Vol. 7, pp. 44–76.

- Goodfriend, Marvin (2002) "Interest on reserves and monetary policy," *Economic Policy Review*, Vol. 8, pp. 77–84.
- Gray, Simon T. and Runchana Pongsaparn (2015) "Issuance of central bank securities; International experiences and guidelines," IMF Working Papers 15/106, International Monetary Fund.
- Gürkaynak, Refet S., Burçin Kisacikoğlu, and Jonathan H. Wright (2018) "Missing events in event studies: Identifying the effects of partially-measured news surprises," NBER Working Papers 25016, National Bureau of Economic Research.
- Gürkaynak, Refet S., Brian Sack, and Eric Swanson (2005) "Do actions speak louder than words? The response of asset prices to monetary policy actions and statements," *International Journal of Central Banking*, Vol. 1, pp. 55–93.
- Gürkaynak, Refet S. and Jonathan H. Wright (2013) "Identification and inference using event studies," *The Manchester School*, Vol. 81, pp. 48–65, URL: <https://doi.org/10.1111/manc.12020>.
- Hamilton, James D. (2019) "Perspectives on U.S. monetary policy tools and instruments," NBER Working Papers 25911, National Bureau of Economic Research.
- Hendrickson, Joshua R. (2017) "Interest on reserves, settlement, and the effectiveness of monetary policy," *Journal of Macroeconomics*, Vol. 54, pp. 208 – 216.
- Ireland, Peter N. (2014) "The macroeconomic effects of interest on reserves," *Macroeconomic Dynamics*, Vol. 18, pp. 1271–1312.
- Jarociński, Marek and Peter Karadi (2018) "Deconstructing monetary policy surprises - The role of information shocks," CEPR Discussion Papers 12765, Center for Economic Policy Research.
- Jordà, Òscar (2005) "Estimation and inference of impulse responses by local projections," *American Economic Review*, Vol. 95, pp. 161–182.
- Jordan, Thomas J. (2009) "10 Jahre Franken-Repomarkt - eine Erfolgsgeschichte (2 July 2009)," speech, Swiss National Bank.
- Kraenzlin, Sébastien and Thomas Nellen (2015) "Access policy and money market segmentation," *Journal of Monetary Economics*, Vol. 71, pp. 1–12.
- Kuttner, Kenneth N. (2001) "Monetary policy surprises and interest rates: Evidence from the Fed funds futures market," *Journal of Monetary Economics*, Vol. 47, pp. 523–544.
- Lütkepohl, Helmut (2012) "Identifying structural vector autoregressions via changes in volatility," DIW Berlin Discussion Papers 1259, DIW Berlin, German Institute for Economic Research.
- Lütkepohl, Helmut, Mika Meitz, Aleksei Netunajev, and Pentti Saikkonen (2018) "Testing identification via heteroskedasticity in structural vector autoregressive models," DIW Berlin Discussion Papers 1764, DIW Berlin, German Institute for Economic Research.
- Moser, Dewet (2011) "Die neue Umsetzung der Geldpolitik und ihre Auswirkungen auf den Geldmarkt (Zusammenfassung, 24 March 2011)," speech, Swiss National Bank.
- (2012) "Umsetzung der Geldpolitik im Wandel der Zeit (22 March 2012)," speech, Swiss National Bank.
- Müller, Robert (2017) "The new SNB exchange rate index," Economic Studies 2017-11, Swiss National Bank.
- Nakamura, Emi and Jón Steinsson (2018a) "High frequency identification of monetary non-neutrality: The information effect," *Quarterly Journal of Economics*, Vol. 133, pp. 1283–1330.

- Nakamura, Emi and Jón Steinsson (2018b) "Identification in macroeconomics," *Journal of Economic Perspectives*, Vol. 32, pp. 59–86.
- Nyawata, Obert (2012) "Treasury bills and/or central bank bills for absorbing surplus liquidity; the main considerations," IMF Working Papers 12/40, International Monetary Fund.
- Poole, William (1968) "Commercial bank reserve management in a stochastic model: implications for monetary policy," *The Journal of Finance*, Vol. 23, pp. 769–791.
- Quarles, Randal K. (2019) "The future of the Federal Reserve's balance sheet (22 February 2019)," speech, Federal Reserve.
- Rigobon, Roberto (2003) "Identification through heteroskedasticity," *The Review of Economics and Statistics*, Vol. 85, pp. 777–792.
- Rigobon, Roberto and Brian Sack (2004) "The impact of monetary policy on asset prices," *Journal of Monetary Economics*, Vol. 51, pp. 1553–1575.
- Rule, Garreth (2011) "Issuing central bank securities," Centre for Central Banking Studies Handbook 30, Bank of England.
- SNB (2008) "Swiss National Bank issuing SNB Bills to steer money market liquidity (15 October 2008)," press release, Swiss National Bank.
- (2009a) "Swiss National Bank takes decisive action to forcefully relax monetary conditions (12 March 2009)," press release, Swiss National Bank.
- (2009b) "Swiss National Bank to issue SNB Bills in US dollars (2 February 2009)," press release, Swiss National Bank.
- (2010a) "Geldpolitisch wichtige Daten für die Woche zum 27. August 2010," press release, Swiss National Bank.
- (2010b) "Geldpolitisch wichtige Daten für die Woche zum 29. Oktober 2010," press release, Swiss National Bank.
- (2016) "SNB Bills – Issue Conditions (1 March 2016)," press release, Swiss National Bank.
- Stock, James H. and Mark W. Watson (2018) "Identification and estimation of dynamic causal effects in macroeconomics using external instruments," *The Economic Journal*, Vol. 128, pp. 917–948.
- Swanson, Eric T. (2017) "Measuring the effects of Federal Reserve forward guidance and asset purchases on financial markets," Working Paper 23311, National Bureau of Economic Research.
- Williamson, Stephen D. (2018) "Interest on reserves, interbank lending, and monetary policy," *Journal of Monetary Economics*, Vol. 101, pp. 14 – 30.
- Woodford, Michael (2012) "Methods of policy accommodation at the interest-rate lower bound," *Proceedings - Economic Policy Symposium - Jackson Hole*, pp. 185–288.
- Wright, Jonathan H. (2012) "What does monetary policy do to long-term interest rates at the zero lower bound?" *The Economic Journal*, Vol. 122, pp. F447–F466.

A Data

Table A.1 — Data and sources

Name	Time stamp	Source	Links
CHF SNB Bills		SNB	www.snb.ch/en/mmr/reference/snb_bills_res/source/snb_bills_res.en.pdf and www.snb.ch/en/mmr/reference/snb_bills_new/source/snb_bills_new.en.pdf
USD SNB Bills		SNB	www.snb.ch/en/mmr/reference/snb_usd_bills_20100621/source/snb_usd_bills_20100621.en.pdf
CHF repo auctions		SNB	www.snb.ch/en/mmr/reference/repo_mb23/source/repo_mb23.en.pdf and www.snb.ch/en/iabout/stat/statrep/statpubdis/id/statpub_statmon_arch
USD repo auctions		SNB	www.snb.ch/en/mmr/reference/snb_usd_repo_results_20191002/source/snb_usd_repo_results_20191002.en.pdf
Reverse repos and FX swaps		SNB	www.snb.ch/en/iabout/stat/statrep/statpubdis/id/statpub_statmon_arch
Government bond auctions		Federal Finance Administration	www.admin.ch/gov/de/start/dokumentation/medienmitteilungen.msg-id-16132.html
Treasury bill auctions		Federal Finance Administration	www.news.admin.ch/news/message/attachments/54842.pdf
Weekly reserves		SNB	www.snb.ch/de/iabout/stat/statrep/id/statpub_impdata
Monthly liabilities		SNB	data.snb.ch/en/topics/snb#!/cube/snbbipo
Stock market data (SMI, SPI, MSCI, VSTOXX, EURO STOXX 50)	Trade close	Datastream	
Effective exchange rate	11:00 am	SNB	data.snb.ch/en/topics/ziredev#!/cube/devwkieffid and Müller (2017)
Bilateral exchange rates	2:15 am	ECB	www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/index.en.html
Swiss Average Rates (SAR)	4:00 pm	SNB	data.snb.ch/de/topics/ziredev#!/cube/zirepo
Zero coupon yields based on IRS on SARON	4:00 pm	Reuters/Datastream	
Government bond yields	Morning	SNB	data.snb.ch/en/topics/ziredev#!/cube/rendoblid
Corporate bond yields	Morning	SNB	data.snb.ch/en/topics/ziredev#!/cube/rendoblid
Libor interest rates	12:00 am	Federal Reserve Bank of St. Louis	fred.stlouisfed.org/categories/33003

Notes: If the information stems from press releases the links give only one example of the information obtained. All URLs accessed on 6 October 2019.

B Theoretical appendix

This appendix provides proofs of propositions, further theoretical insights, and the calibration used for illustrating the model.

B.1 Proof of proposition 1

Optimization with respect to $\pi_i \in [0, \pi^{cb}]$ of

$$\mathbb{L} = i_a A_i + i_b \pi_i (R_i + B_i) - i_m B_i - i_d \mathbb{E}(D - Z) - i_x \int_{\hat{z}_i}^{\infty} X_i f(Z) dZ - \lambda_{1,i} (\pi_i - \pi^{cb}) + \lambda_{2,i} \pi_i$$

yields the following first order condition

$$\begin{aligned} F_i \left(i_b - i_x \int_{\hat{z}_i}^{\infty} f(Z) dZ \right) - \lambda_{1,i} + \lambda_{2,i} &= 0 \\ F_i \left(i_b - i_x (1 - F(Z < (1 - \pi_i) F_i - K)) \right) - \lambda_{1,i} + \lambda_{2,i} &= 0 \\ F_i \left(i_b - i_x P(X_i > 0) \right) - \lambda_{1,i} + \lambda_{2,i} &= 0 \end{aligned}$$

together with the complementary slackness conditions

$$\begin{aligned} \lambda_{1,i} (\pi_i - \pi^{cb}) &= 0 \\ \lambda_{2,i} \pi_i &= 0. \end{aligned}$$

Therefore, $\lambda_{1,i} > 0$ if $\pi_i = \pi^{cb}$ and $\lambda_{2,i} > 0$ if $\pi_i = 0$. Thus, a commercial bank optimally holds $\pi_i = \pi^{cb}$ if $i_b - i_x P(X_i > 0) > 0$, $\pi_i = 0$ if $i_b - i_x P(X_i > 0) < 0$, and $\pi_i \in (0, \pi^{cb})$ if $i_b - i_x P(X_i > 0) = 0$.⁴⁷ If expected profits do not change in π_i (i.e. if $i_b - i_x P(X_i > 0) = 0$), commercial bank i is indifferent between holding an additional unit of debt securities and an additional unit of reserves. Therefore, $i_b - i_x P(X_i > 0) = 0$ defines the indifference fraction $\bar{\pi}_i$.

$$\begin{aligned} i_b &= i_x P(X_i(\bar{\pi}_i) > 0) \\ \frac{i_b}{i_x} &= P(Z > (1 - \bar{\pi}_i) F_i - K) \\ \bar{\pi}_i &= 1 - \frac{P^{-1} \left(1 - \frac{i_b}{i_x} \right) + K}{F_i} \end{aligned}$$

⁴⁷ Expected commercial bank profits strictly increase in π_i if $i_b - i_x P(X_i > 0) > 0$. A commercial bank is willing to hold any π^{cb} up to the point at which a marginal increase in π_i does no longer increase expected profits. Formally,

$$\begin{aligned} \frac{d\mathbb{E}(\Pi_i)}{d\pi_i} &= i_b F_i - i_x \left[\int_{\hat{z}_i}^{\infty} \frac{\partial X_i}{\partial \pi_i} f(Z) dZ + X_i(\hat{z}_i) f(\hat{z}_i) \frac{\partial(\hat{z}_i)}{\partial \pi_i} \right] \\ \frac{d\mathbb{E}(\Pi_i)}{d\pi_i} &= F_i \left(i_b - i_x P(X_i > 0) \right). \end{aligned}$$

where $P^{-1}(\cdot)$ is the inverse cumulative distribution function of X_i . Because we assume that the central bank is the only institution that offers central bank debt securities, we impose $\min(\bar{\pi}_i) = 0$.

$$\bar{\pi}_i = \min \left(0, 1 - \frac{P^{-1} \left(1 - \frac{i_b}{i_x} \right) + K}{F_i} \right)$$

In sum, $\pi_i = \min(\pi^{cb}, \bar{\pi}_i)$. Optimization with respect to $B_i \geq -R_i$ of

$$\mathbb{L} = i_a A_i + i_b \pi_i (R_i + B_i) - i_m B_i - i_d \mathbb{E}(D - Z) - i_x \int_{\hat{z}_i}^{\infty} X_i f(Z) dZ + \mu_i (B_i + R_i)$$

yields the following first order condition

$$\begin{aligned} i_b \min(\pi^{cb}, \bar{\pi}_i) + i_b \frac{\partial \min(\pi^{cb}, \bar{\pi}_i)}{\partial B_i} - i_m - i_x \left[\int_{\hat{z}_i}^{\infty} \frac{\partial X_i}{\partial B_i} f(Z) dZ + X_i(\hat{z}_i) f(\hat{z}_i) \frac{\partial(\hat{z}_i)}{\partial B_i} \right] + \mu_i &= 0 \\ i_m = i_b \left(\min(\pi^{cb}, \bar{\pi}_i) + \frac{\partial \min(\pi^{cb}, \bar{\pi}_i)}{\partial B_i} \right) - i_x \int_{\hat{z}_i}^{\infty} \frac{\partial X_i}{\partial B_i} f(Z) dZ + \mu_i, \end{aligned}$$

where $X_i = Z - (1 - \pi_i)(B_i + R_i) + K$, $X_i(\hat{z}_i) = 0$, and

$$\frac{\partial X_i}{\partial B_i} = -(1 - \min(\pi^{cb}, \bar{\pi}_i)) + \frac{\partial \min(\pi^{cb}, \bar{\pi}_i)}{\partial B_i}.$$

Using that $\hat{z}_i = (1 - \min(\pi^{cb}, \bar{\pi}_i))(B_i + R_i) - K$ it follows that

$$i_m = i_b \left(\min(\pi^{cb}, \bar{\pi}_i) + \frac{\partial \min(\pi^{cb}, \bar{\pi}_i)}{\partial B_i} \right) + \left((1 - \min(\pi^{cb}, \bar{\pi}_i)) - \frac{\partial \min(\pi^{cb}, \bar{\pi}_i)}{\partial B_i} \right) i_x P(X_i > 0) + \mu_i.$$

More transparently

$$i_m = \begin{cases} i_b \pi_i + (1 - \pi_i) i_x P(X_i > 0) + \mu_i, & \text{if } \pi^{cb} < \bar{\pi}_i \\ i_b \pi_i + (1 - \pi_i) i_x P(X_i > 0) + \frac{\partial \bar{\pi}_i}{\partial B_i} (i_b - i_x P(X_i > 0)) + \mu_i, & \text{if } \pi^{cb} \geq \bar{\pi}_i \end{cases}$$

Use that, if $\pi^{cb} > \bar{\pi}_i$, we have $\pi_i = \bar{\pi}_i$ which, by construction, implies $i_b - i_x P(X_i > 0) = 0$.

Furthermore, the complementary slackness condition requires

$$\mu_i (B_i + R_i) = 0.$$

Hence, if $B_i > -R_i$ (which is true in equilibrium), then

$$i_m = i_b \pi_i + (1 - \pi_i) i_x P(X_i > 0).$$

Guess the solution to be $B_i + R_i = \zeta_1 \forall i$ and $\pi_i = \pi \forall i$. Then

$$i_m = i_b \pi + (1 - \pi) i_x P(X(\zeta_1) > 0) .$$

To check if the guess is compatible with the market clearing condition, combine the (integrated) guess $\int_0^1 (B_i + R_i) di = \zeta_1$ with the market clearing condition $\int_0^1 B_i di = 0$ to obtain

$$\int_0^1 R_i di = \zeta_1 . \quad (4)$$

Furthermore, by definition, $\int_0^1 (B_i + R_i) di = \int_0^1 F_i di$. In combination with the market clearing condition $\int_0^1 B_i di = 0$, it follows that

$$\int_0^1 R_i di = F . \quad (5)$$

Combining equations (4) and (5) yields $\zeta_1 = F$. Thus, in equilibrium, the money market rate is equal to

$$i_m = i_b \pi_i + (1 - \pi) i_x P(X > 0) ,$$

where $X = Z - (1 - \pi)F + K$.

B.2 Proof of proposition 2

Optimization with respect to $B_i \geq -R_i$ of

$$\mathbb{L} = i_a A_i + i_{ior}(B_i + R_i) - i_m^{ior} B_i - i_d \mathbb{E}(D - Z) - i_x \int_{\hat{z}_i^{ior}}^{\infty} X_i^{ior} f(Z) dZ + \mu_i (B_i + R_i)$$

yields the following first order condition

$$i_{ior} - i_m^{ior} - i_x \left[\int_{\hat{z}_i^{ior}}^{\infty} \frac{\partial X_i^{ior}}{\partial B_i} f(Z) dZ + X_i^{ior}(\hat{z}_i^{ior}) f(\hat{z}_i^{ior}) \frac{\partial(\hat{z}_i^{ior})}{\partial B_i} \right] + \mu_i = 0$$

$$i_m^{ior} = i_{ior} - i_x \int_{\hat{z}_i^{ior}}^{\infty} \frac{\partial X_i^{ior}}{\partial B_i} f(Z) dZ + \mu_i ,$$

where $X_i^{ior} = Z - (B_i + R_i) + K$, and

$$\frac{\partial X_i^{ior}}{\partial B_i} = -1 .$$

Using that $\hat{z}_i^{ior} = (B_i + R_i) - K$, it follows that

$$\begin{aligned} i_m^{ior} &= i_{ior} + i_x \int_{\hat{z}_i^{ior}}^{\infty} f(Z) dZ + \mu_i \\ i_m^{ior} &= i_{ior} + i_x P(X_i^{ior} > 0) + \mu_i . \end{aligned}$$

Furthermore, the complementary slackness condition requires

$$\mu_i(B_i + R_i) = 0 .$$

Hence, if $B_i > -R_i$ (which is true in equilibrium), then

$$i_m^{ior} = i_{ior} + i_x P(X_i^{ior} > 0) .$$

Guess the solution to be $B_i + R_i = \zeta_2 \forall i$ and $\pi_i = \pi \forall i$. Then,

$$i_m^{ior} = i_{ior} + i_x P(X^{ior}(\zeta_2) > 0) .$$

To check if the guess is compatible with the market clearing condition, combine the (integrated) guess $\int_0^1 (B_i + R_i) di = \zeta_2$ with the market clearing condition $\int_0^1 B_i di = 0$ to obtain

$$\int_0^1 R_i di = \zeta_2 . \quad (6)$$

Furthermore, by definition, $\int_0^1 (B_i + R_i) di = \int_0^1 F_i di$. In combination with the market clearing condition $\int_0^1 B_i di = 0$, it follows that

$$\int_0^1 R_i di = F . \quad (7)$$

Combining equation (6) and (7) yields $\zeta_2 = F$. Thus, in equilibrium, the money market rate is equal to

$$i_m^{ior} = i_{ior} + i_x P(X^{ior} > 0) ,$$

where $X^{ior} = Z - F + K$.

B.3 The maximum fraction of pre-auction reserves invested in debt securities

If pre-auction reserves are relatively scarce, the commercial bank may find it optimal not to absorb the entire supply of central bank debt securities π^{cb} . Therefore, for any amount of pre-auction reserves, we determine a $\bar{\pi}_i$ which denotes the maximum fraction of pre-auction reserves that a commercial

bank is willing to hold. In other words, at $\bar{\pi}_i$, the commercial bank holds its desired level of central bank debt. As a consequence, expected commercial bank profits neither rise nor fall in the fraction of pre-auction reserves invested in debt securities (π_i). Because the commercial bank cannot hold negative amounts of central bank debt, $\bar{\pi}_i$ cannot fall below zero.

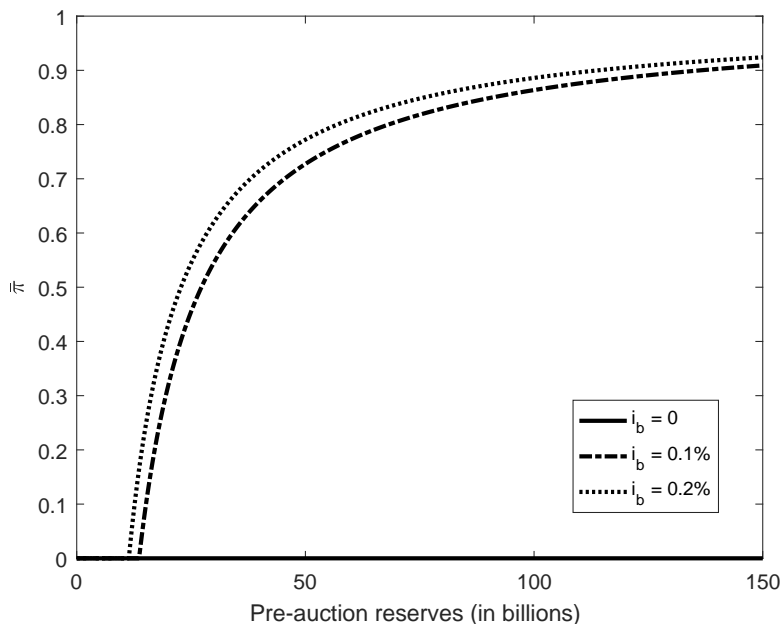
Proposition 3 *The maximum fraction of pre-auction reserves invested in debt securities is $\bar{\pi}_i = \max\left(0, 1 - \frac{P^{-1}\left(1 - \frac{i_b}{i_x}\right) + K}{F_i}\right)$.*

Proof. Solve $\frac{d\mathbb{E}(\Pi_i)}{d\pi_i} = 0 \Leftrightarrow i_b - i_x P(X_i > 0) = 0$ for $\tilde{\pi}_i$. Thereafter, determine $\bar{\pi}_i$ with $\bar{\pi}_i = \min(\tilde{\pi}_i, 0)$. More explicitly,

$$\begin{aligned}
 i_b - i_x(1 - P(X_i < 0)) &= 0 \\
 P(X_i < 0) &= 1 - \frac{i_b}{i_x} \\
 P(Z < (1 - \tilde{\pi}_i)F_i - K) &= 1 - \frac{i_b}{i_x} \\
 (1 - \tilde{\pi}_i)F_i - K &= P^{-1}\left(1 - \frac{i_b}{i_x}\right) \\
 \tilde{\pi}_i &= 1 - \frac{P^{-1}\left(1 - \frac{i_b}{i_x} + K\right)}{F_i}
 \end{aligned}$$

Figure B.1 presents $\bar{\pi}_i \forall i$ conditional on i_b and F . A lower supply of pre-auction reserves leads to lower desired debt security holdings (lower $\bar{\pi}_i$). The reason is that the probability of a liquidity shortage rises if pre-auction reserves fall. Therefore, to maintain the the ex-ante probability of a liquidity shortage, desired investments in debt securities fall when pre-auction reserves fall.

Figure B.1 — The maximum fraction of F_i invested in debt securities ($\bar{\pi}_i$)



If pre-auction reserves F_i become sufficiently scarce, the commercial bank abstain from investing in debt securities ($\lim_{F_i \rightarrow 0} \bar{\pi}_i = 0$). In contrast, if pre-auction reserves go to infinity, the commercial bank is willing to hold any fraction of reserves in debt securities ($\lim_{F_i \rightarrow \infty} \bar{\pi}_i = 1$).

B.4 The probability of a liquidity shortage

As discussed in Section 3.6, money market rates are constant in pre-auction reserves if $\pi_i = \bar{\pi}_i$. The reason is that the probability of a liquidity shortage is constant (strictly declining) in pre-auction reserves if $\pi_i = \bar{\pi}_i$ ($\pi_i < \bar{\pi}_i$).

Proposition 4 *The probability of a liquidity shortage weakly decreases in pre-auction reserves. Formally, $\frac{\partial P(X_i > 0)}{\partial F_i} = \mathbb{I}_{\pi_i < \bar{\pi}_i} \left(-\phi \left((1 - \pi_i)F_i - K \right) \left[1 - \pi_i \right] \right) \leq 0$, where $\phi \left((1 - \pi_i)F_i - K \right) > 0$ is the probability density function of Z evaluated at $(1 - \pi_i)F_i - K$ and $\mathbb{I}_{\pi_i < \bar{\pi}_i}$ is an indicator function taking on the value 1 if $\pi_i < \bar{\pi}_i$ and zero otherwise.*

Proof. Take the partial derivative of $P(X_i > 0) = 1 - P(Z < \hat{z}_i)$ with respect to F_i and use $\hat{z}_i = (1 - \pi_i)F_i - K$. More explicitly,

$$\begin{aligned} \frac{\partial P(X_i > 0)}{\partial F_i} &= \frac{\partial [1 - P(X_i < 0)]}{\partial F_i} \\ \frac{\partial P(X_i > 0)}{\partial F_i} &= \frac{\partial [1 - P(Z < (1 - \pi_i)F_i - K)]}{\partial F_i} \\ \frac{\partial P(X_i > 0)}{\partial F_i} &= - \frac{\partial P(Z < (1 - \pi_i)F_i - K)}{\partial F_i} \\ \frac{\partial P(X_i > 0)}{\partial F_i} &= - \left[\phi \left((1 - \pi_i)F_i - K \right) (1 - \pi_i) - (1 - \mathbb{I}_{\pi_i < \bar{\pi}_i}) \phi \left((1 - \pi_i)F_i - K \right) \frac{\partial \bar{\pi}_i}{\partial F_i} F_i \right] \\ \frac{\partial P(X_i > 0)}{\partial F_i} &= -\phi \left((1 - \pi_i)F_i - K \right) \left[(1 - \pi_i) - (1 - \mathbb{I}_{\pi_i < \bar{\pi}_i}) \frac{\partial \bar{\pi}_i}{\partial F_i} F_i \right] \end{aligned}$$

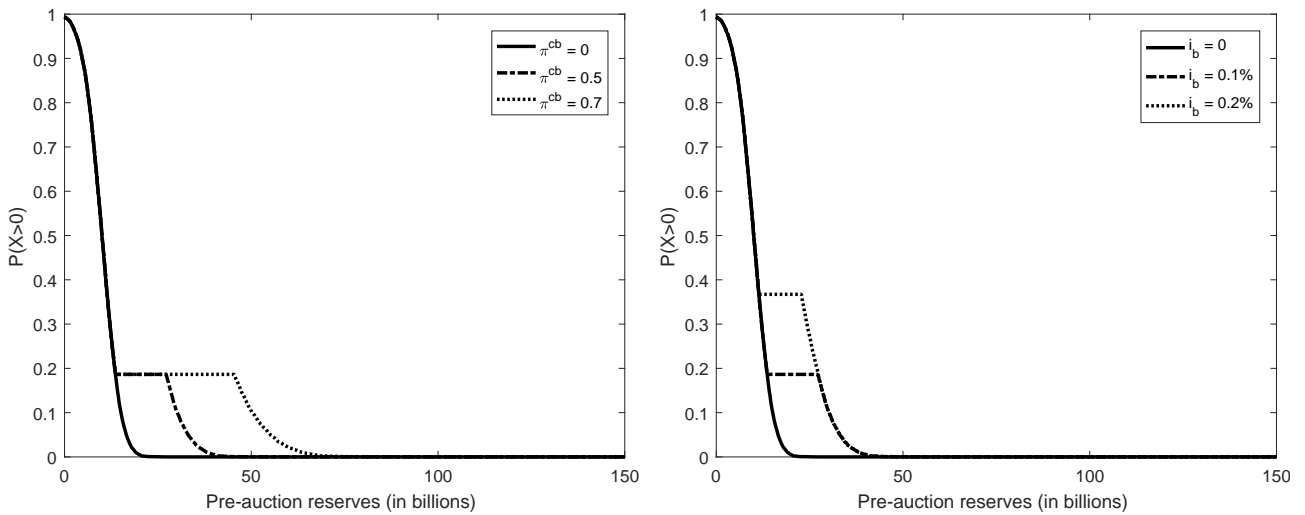
Use that $\bar{\pi}_i = 1 - \frac{P^{-1} \left(1 - \frac{i_b}{i_x} \right) + K}{F_i}$ if $\bar{\pi}_i > 0$ and $\frac{\partial \bar{\pi}_i}{\partial F_i} = \frac{P^{-1} \left(1 - \frac{i_b}{i_x} \right) + K}{F_i^2}$.

$$\frac{\partial P(X_i > 0)}{\partial F_i} = \begin{cases} -\phi \left((1 - \pi_i)F_i - K \right) \left[1 - \pi_i \right] < 0, & \text{if } \pi_i < \bar{\pi}_i \\ -\phi \left((1 - \pi_i)F_i - K \right) \left[\bar{\pi}_i - \bar{\pi}_i \right] = 0, & \text{if } \pi_i = \bar{\pi}_i \end{cases}$$

The left panel in Figure B.2 displays the probability of a liquidity shortage, $P(X_i > 0)$, as a function of pre-auction reserves, F_i , conditional on $i_b = 0.10\%$. The probability of a liquidity shortage is constant in pre-auction reserves if the commercial bank holds its desired amount of debt securities $\bar{\pi}_i$. For example, the commercial bank holds its desired amount of debt securities if the central bank supplies $\pi_i^{cb} = 0.7$ between about $F_i = 20$ and $F_i = 50$.

The probability of a liquidity shortage is constant in pre-auction reserves if the commercial bank

Figure B.2 — The probability of a liquidity shortage



Notes: Left panel: probability of a liquidity shortage conditional on $i_b = 0.10\%$. Right panel: probability of a liquidity shortage conditional on $\pi^{cb} = 0.5$.

holds $\pi_i = \bar{\pi}_i > 0$ because $\bar{\pi} > 0$ holds the probability of a liquidity shortage constant at any F_i by definition. For $F_i > 50$ ($F_i < 20$), the commercial bank would want to hold more than $\pi_i^{cb} = 0.7$ (less than $\bar{\pi} = 0$) in debt securities, i.e. $\pi_i < \bar{\pi}_i$ ($\pi_i = 0$). In these cases, an increase in pre-auction reserves decreases the probability of a liquidity shortage.

The right panel in Figure B.2 plots the probability of a liquidity shortage conditional on $\pi = 0.50$. The probability of a liquidity shortage increases in the yield of the debt securities because in relative terms, liquidity shortages become less costly in i_b . In other words, the commercial bank is willing to hold less post-auction reserves if the yield on central bank debt is high.

B.5 Calibration

To illustrate the qualitative features of the money market model, we calibrate its parameters to match the situation in Switzerland in August 2010. At the time, Swiss commercial banks held approximately CHF 10 billion as minimum reserves ($K = 10$). The minimum reserve requirement was 2.5%, implying $D = 400$.⁴⁸ The discount rate was $i_x = 0.55\%$.⁴⁹ We assume a rather arbitrary distribution of the liquidity shock $Z \sim N(0, 4)$. The marginal SNB Bill yield ranged from 0.05% to 1.25%, exceeding 0.55% only before the 3M Libor target range fell to [0% 0.75%] in March 2009.⁵⁰ At the peak of the program, SNB Bills accounted for 80% of pre-auction reserves. We compute pre-auction reserves as the sum of the volume of SNB Bills outstanding and reserves of domestic counterparties. Consequently, we vary i_b and π^{cb} between $[0, i_x]$ and $[0, 1]$, respectively. Pre-auction reserves reached CHF 140 billion in August 2010. For pre-auction reserves, we thus consider values between 0 and

⁴⁸See SNB (2010b) and Bundesrat (2004).

⁴⁹See SNB (2010a).

⁵⁰The SNB targeted the lower end of the range at approximately 0.25% (see SNB 2009a).

150 billion.⁵¹

C Dynamic event study estimator

This appendix derives some additional results of the a dynamic event study estimator. Unless otherwise stated, we assume that the data is generated by a VAR(1):

$$y_t = \Phi y_{t-1} + \Psi_0 e_t ,$$

where y_t is an N -dimensional vector of financial market variables, Φ is an $(N \times N)$ matrix of autoregressive coefficients, Ψ_0 is an $(N \times R)$ matrix of impact coefficients, and e_t is an R -dimensional vector of structural shocks.

C.1 Cumulative impulse responses

To identify the cumulative response, we can add lagged y_t to the left-hand-side of the local projection (see [Stock and Watson 2018](#)). First, note that for a VAR(1), the cumulative response amounts to:

$$\Psi_0 + \Psi_1 = (I + \Phi)\Psi_0 ,$$

where I is a conformable identity matrix. If we add y_{t-1} on both sides of the equation of the VAR iterated one period backwards we obtain:

$$y_t + y_{t-1} = \Phi^2 y_{t-2} + \Psi_1 e_{t-1} + \Psi_0 e_t + y_{t-1} .$$

Replacing y_{t-1} with $\Phi y_{t-2} + \Psi_0 e_{t-1}$ yields

$$\begin{aligned} y_t + y_{t-1} &= \Phi^2 y_{t-2} + \Psi_1 e_{t-1} + \Psi_0 e_t + \Phi y_{t-2} + \Psi_0 e_{t-1} \\ &= (\Phi + \Phi^2) y_{t-2} + (\Psi_0 + \Psi_1) e_{t-1} + \Psi_0 e_t . \end{aligned}$$

The two-step-ahead forecast error comprises a linear combination of past (period $t - 1$) and current (period t) shocks. We can remove period t shocks by subtracting the one-step-ahead forecast error.

$$\varepsilon_{t|t-2} - \varepsilon_{t|t-1} = (\Psi_0 + \Psi_1) e_{t-1}$$

and proceed as before to estimate the response.

⁵¹The value of i_a is irrelevant for the money market rate because, in the aggregate, commercial banks cannot exchange reserves for private assets.

More generally, let $\varepsilon_{t|t-h-1}$ be the $h - 1$ step-ahead forecast error in

$$\sum_{j=0}^h y_{t-j} = \Phi^{h+1} y_{t-h-1} + \varepsilon_{t|t-h-1} .$$

It follows that

$$\varepsilon_{t|t-h-1} - \varepsilon_{t|t-h} = \left(\sum_{j=0}^h \Psi_j \right) e_{t-h} .$$

We can therefore estimate local projections using the cumulative sum as the dependent variable. Then, we can apply the heteroscedasticity-based identification scheme as before.

C.2 Variance decomposition

If we have estimated the impulse responses, we can compute the relative importance of the two shocks as:

$$\text{Rel. importance}_{ij} = \frac{\psi_{ij}^2}{\psi_{i1}^2 + \psi_{i2}^2} ,$$

which is a variance decomposition of the shock occurring on an event day into its two components. A variance decomposition to the overall variance on an event day can be similarly calculated as

$$\text{Var. decomposition}_{ij} = \frac{\psi_{ij}^2}{\Omega_{t \in A, ii}} .$$

C.3 Impulse responses using a VAR

Having computed the initial response, we can recursively compute the impulse responses using the VAR parameters (see also [Wright 2012](#); [Lütkepohl 2012](#); [Lütkepohl et al. 2018](#), for similar approaches).

For a VAR(1) we can compute the dynamic impact after h periods as:

$$\Psi_h = \Phi^h \Psi_0 .$$

To estimate the dynamic impact for a VAR(p), we can use the recursion:

$$\begin{aligned} \Psi_1 &= \Phi_1 \Psi_0 \\ \Psi_2 &= \Phi_1 \Psi_1 + \Phi_2 \Psi_0 \\ &\vdots \\ \Psi_h &= \Phi_1 \Psi_{h-1} + \Phi_2 \Psi_{h-2} + \dots + \Phi_p \Psi_{h-p} \text{ for } h \geq p . \end{aligned}$$

C.4 Simulations

To show under which circumstances the identification scheme works and illustrate potential pitfalls, we first simulate 1,000,000 observations from a VAR(2):

$$y_t = B^{-1}\Gamma_1 y_{t-1} + B^{-1}\Gamma_2 y_{t-2} + B^{-1}e_t ,$$

with

$$B^{-1} = \begin{bmatrix} 0.7 & 0.8 & 0.5 \\ 0.5 & -0.9 & 0.4 \\ 0.3 & 0.1 & 0.2 \end{bmatrix} \quad \Gamma_1 = \begin{bmatrix} 0.3 & 0.2 & 0.4 \\ 0.7 & 0.2 & 0.5 \\ 0.1 & 0.2 & -0.4 \end{bmatrix} \quad \Gamma_2 = \begin{bmatrix} 0.1 & 0.2 & 0.2 \\ 0.2 & 0.3 & 0.3 \\ 0.05 & 0.1 & 0.1 \end{bmatrix} \quad E[e_t e_t'] = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 3 & 0 \\ 0 & 0 & 2 \end{bmatrix}$$

When simulating the data we impose that shock 1 happens every 5th period while the other shocks occur every period. To estimate the impact of shock 1 we restrict the response of the first variable to be positive.

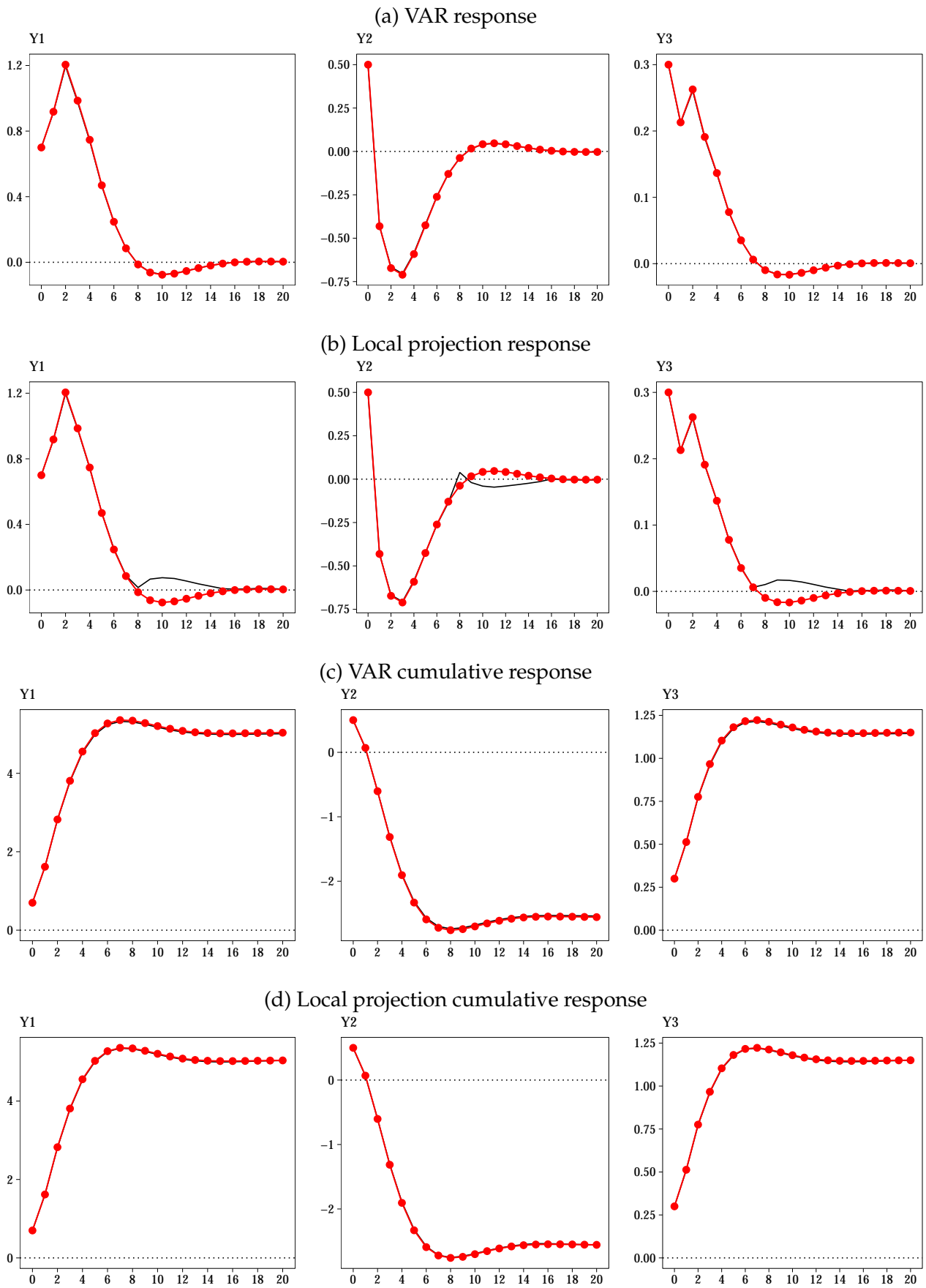
The black lines in Figure C.1 show the estimates of the impulse response functions.⁵² The red lines are the actual impulse response functions. Not surprisingly, the VAR approach identifies the responses (panels a and c).

Panels (b) and (d) show the estimates using local projections. In panel (b) the identifying assumption requires that the response of variable 1 is always positive. We have an identification problem when the red line crosses the zero line. Because of our identification scheme, the response of variable 1 has to remain positive, leading to a wrong sign in the responses of all other variables. Panel (d) shows that we avoid this problem when identifying the response by restricting the cumulative response. Because the cumulative response of variable 1 is always positive, we also identify the responses of all other variables.

Next, we illustrate the empirical implementation of our two approaches by simulating a smaller number of observations (2,000) and estimate confidence intervals using a moving block bootstrap approach (see [Efron and Tibshirani 1993](#), section 8.6). We set the block size to 50 and draw 5,000 bootstrap samples. Figure C.2, panel (a) shows that we can estimate the impulse response using the VAR and restricting the initial response. Panel (b) shows, however, that the local projections do not allow to estimate the response because of the identification problem. However, panels (c) and (d) show that both approaches allow to estimate the cumulative response. Therefore, we face the following trade-off in practice. Either we choose a particular model to estimate the dynamic effects.

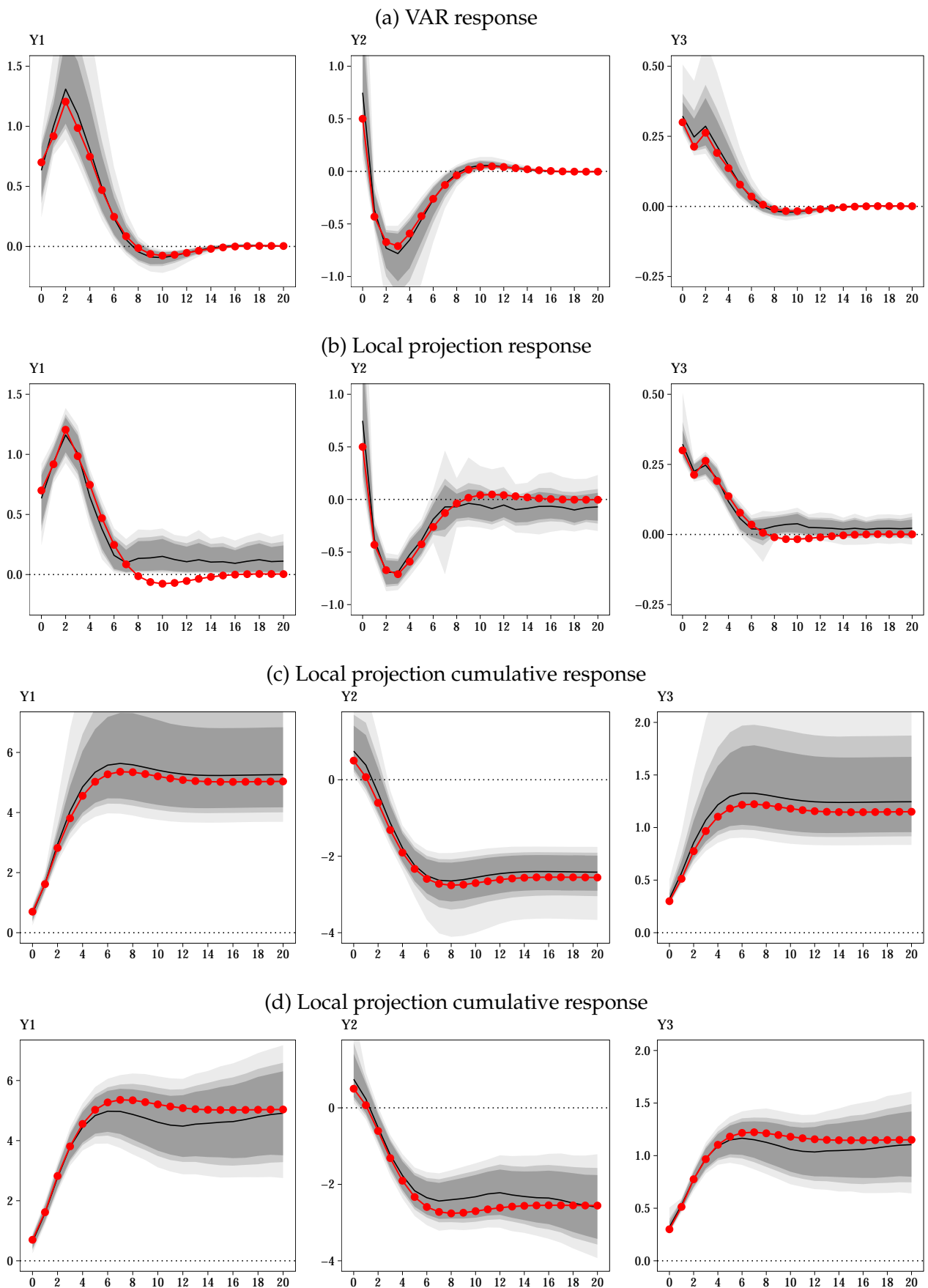
⁵²We scaled the impulse response using the inverse standard deviation of structural shock 1 so that it matches the actual impulse response. In practice, as noted before, we are not able to separately identify the scale of the impulse response and the standard deviation of the structural shock.

Figure C.1 — Estimates based on 1,000,000 observations



Notes: Actual response (red line with dots) and estimated response (black line).

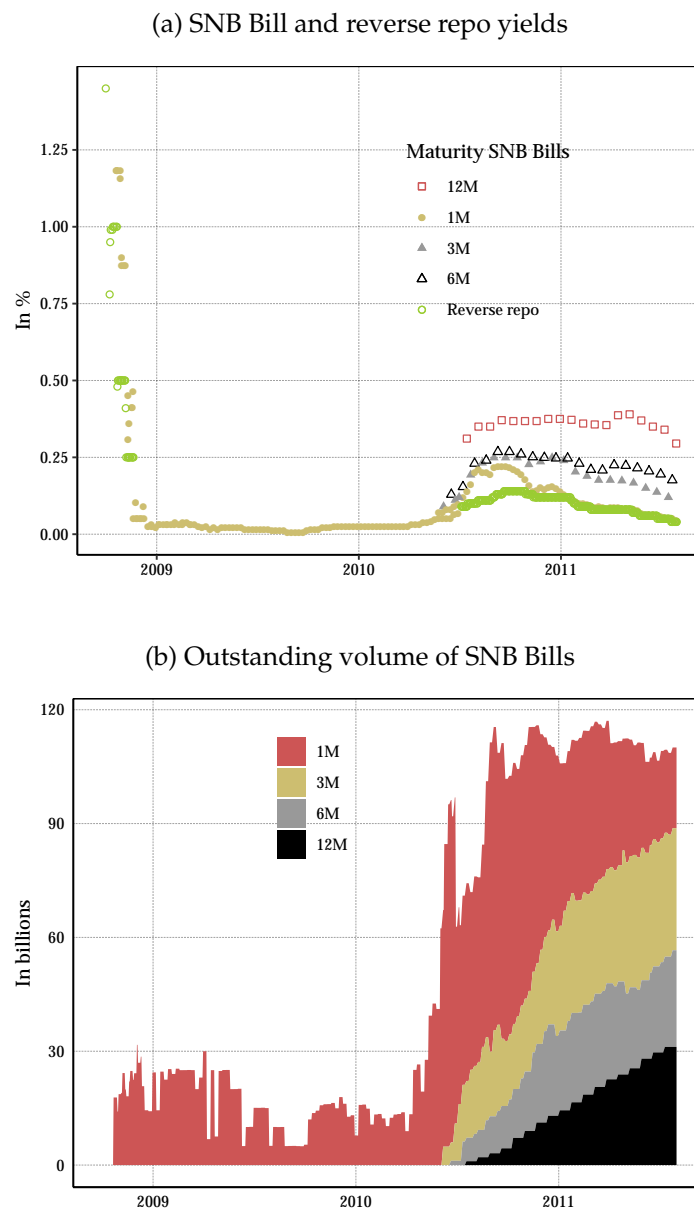
Figure C.2 — Estimates based on 2,000 observations



These estimates will be precise but biased if the VAR is misspecified. Or, we use local projections which are more robust with respect to model misspecification. This comes at the cost, however, that these responses are less precisely estimated and we have to impose a plausible sign restriction at every horizon.

D Additional results

Figure D.1 — Yields, volume, and maturity over time



Notes: Panel (a): SNB Bill marginal yields for various maturities, and reverse repo yields. All reverse repos had a maturity of 2 weeks or less. Panel (b): Outstanding volume of SNB Bills by maturity in buckets of approximately one month and less, three months, six months, and twelve months.

D.1 Placebo tests

Table D.1 — Effect of other events

	Expectation shock		
	Payment day	USD SNB Bill auction	Treasury bill auction
1W interest rate (in pp)	0.000 [0.000, 0.000] (0.000, 0.000)	0.000 [0.000, 0.000] (0.000, 0.000)	0.000 [0.000, 0.000] (0.000, 0.000)
1Y interest rate (in pp)	0.062 [-0.111, 0.257] (-0.154, 0.387)	-0.029 [-0.146, 0.073] (-0.208, 0.112)	-0.053 [-0.197, 0.043] (-0.296, 0.064)
10Y interest rate (in pp)	-0.056 [-0.144, -0.012] (-0.199, -0.007)	-0.013 [-0.041, 0.020] (-0.050, 0.032)	-0.036 [-0.090, -0.005] (-0.120, 0.000)
Stock prices (in %)	-0.310 [-0.562, -0.094] (-0.614, -0.070)	-0.686 [-1.095, -0.241] (-1.171, -0.175)	-0.415 [-0.734, -0.118] (-0.809, -0.085)
Exchange rate (in %)	0.002 [-0.623, 0.764] (-0.912, 0.977)	-0.095 [-0.356, 0.200] (-0.478, 0.311)	-1.224 [-2.955, -0.438] (-4.227, -0.383)
Share identified	0.12	0.73	0.22
N overall	724	724	724
N auctions	114	34	57
N without auctions	148	207	219

Notes: Impact of other events identified with sign restrictions. All specifications control for two lags of all dependent variables, as well as, the EUR/USD exchange rate, the 3M EUR Libor, and a European stock price index. 90% and 95% confidence intervals in brackets and parentheses, respectively. Inference is based on 8,000 draws from a block bootstrap algorithm. We also report the share of bootstrap replications for which $\tilde{\Omega}_{11} > 0$ or $\tilde{\Omega}_{22} - \psi_{s1}^2 > 0$ (share identified), the overall number of observations to estimate the parameters (N auctions), the number of observations to estimate $\Omega_{t \in A}$ (N auctions), and $\Omega_{t \notin A}$ (N without events).

D.2 Robustness tests

Table D.2 — Robustness tests (continued)

	Expectation shock				
	No lags	Four lags	Block size = 20	SPI stock prices	MSCI stock prices
1W interest rate (in pp)	0.000 [0.000, 0.000] (0.000, 0.000)	0.000 [0.000, 0.000] (0.000, 0.000)	0.000 [0.000, 0.000] (0.000, 0.000)	0.000 [0.000, 0.000] (0.000, 0.000)	0.000 [0.000, 0.000] (0.000, 0.000)
1Y interest rate (in pp)	0.009 [-0.053, 0.070] (-0.072, 0.089)	0.022 [-0.039, 0.088] (-0.055, 0.110)	0.019 [-0.041, 0.088] (-0.058, 0.123)	0.015 [-0.046, 0.081] (-0.063, 0.102)	0.015 [-0.046, 0.081] (-0.063, 0.102)
10Y interest rate (in pp)	-0.033 [-0.048, -0.015] (-0.052, -0.011)	-0.035 [-0.049, -0.017] (-0.053, -0.013)	-0.037 [-0.054, -0.015] (-0.059, -0.009)	-0.035 [-0.051, -0.015] (-0.055, -0.010)	-0.035 [-0.051, -0.015] (-0.055, -0.010)
Stock prices (in %)	-1.112 [-1.653, -0.481] (-1.738, -0.351)	-1.308 [-1.992, -0.526] (-2.111, -0.403)	-1.179 [-1.870, -0.391] (-1.978, -0.274)	-1.085 [-1.647, -0.438] (-1.736, -0.333)	-1.085 [-1.647, -0.438] (-1.736, -0.333)
Exchange rate (in %)	-0.353 [-0.633, -0.087] (-0.730, -0.045)	-0.357 [-0.626, -0.141] (-0.703, -0.107)	-0.381 [-0.679, -0.118] (-0.864, -0.073)	-0.359 [-0.643, -0.091] (-0.743, -0.052)	-0.359 [-0.643, -0.091] (-0.743, -0.052)
Share identified	0.96	0.97	0.92	0.95	0.95
N overall	724	724	724	724	724
N auctions	52	52	52	52	52
N without auctions	207	207	207	207	207

Notes: Impact of a one standard deviation expectation shock identified with sign and zero restrictions. Each column shows results for a different model specification. All specifications control for two lags of all dependent variables, as well as, the EUR/USD exchange rate, the 3M EUR Libor, and a European stock price index. 90% and 95% confidence intervals in brackets and parentheses, respectively. Inference is based on 8,000 draws from a block bootstrap algorithm. We also report the share of bootstrap replications for which $\tilde{\Omega}_{11} > 0$ or $\tilde{\Omega}_{22} - \psi_{s1}^2 > 0$ (share identified), the overall number of observations to estimate the parameters (N auctions), the number of observations to estimate $\Omega_{t \in A}$ (N auctions), and $\Omega_{t \notin A}$ (N without events).

Table D.2 — Robustness tests (continued)

	Expectation shock		
	CHF/EUR	CHF/USD	CHF/JPY
1W interest rate (in pp)	0.000 [0.000, 0.000] (0.000, 0.000)	0.000 [0.000, 0.000] (0.000, 0.000)	0.000 [0.000, 0.000] (0.000, 0.000)
1Y interest rate (in pp)	0.014 [-0.047, 0.077] (-0.061, 0.095)	0.014 [-0.047, 0.077] (-0.061, 0.095)	0.013 [-0.048, 0.077] (-0.066, 0.099)
10Y interest rate (in pp)	-0.034 [-0.051, -0.015] (-0.054, -0.011)	-0.034 [-0.051, -0.015] (-0.054, -0.011)	-0.037 [-0.053, -0.018] (-0.057, -0.013)
Stock prices (in %)	-1.155 [-1.747, -0.476] (-1.831, -0.353)	-1.155 [-1.747, -0.476] (-1.831, -0.353)	-1.163 [-1.762, -0.478] (-1.850, -0.351)
Exchange rate (in %)	-0.360 [-0.655, -0.095] (-0.771, -0.056)	-0.234 [-0.797, 0.121] (-1.052, 0.162)	-0.017 [-0.704, 0.420] (-1.093, 0.479)
Share identified	0.96	0.96	0.95
N overall	724	724	724
N auctions	52	52	52
N without auctions	207	207	207

Notes: Impact of an SNB Bill shock identified with sign restrictions. Each column shows results for a different bilateral exchange rate. All specifications control for two lags of all dependent variables, as well as, the EUR/USD exchange rate, the 3M EUR Libor, and a European stock price index. 90% and 95% confidence intervals in brackets and parentheses, respectively. Inference is based on 8,000 draws from a block bootstrap algorithm. We also report the share of bootstrap replications for which $\tilde{\Omega}_{11} > 0$ or $\tilde{\Omega}_{22} - \psi_{s1}^2 > 0$ (share identified), the overall number of observations to estimate the parameters (N auctions), the number of observations to estimate $\Omega_{t \in A}$ (N auctions), and $\Omega_{t \notin A}$ (N without events).

Table D.2 — Robustness tests (continued)

	Expectation shock			
	(1)	(2)	(3)	(4)
1W interest rate (in pp)	0.000 [0.000, 0.000] (0.000, 0.000)	0.000 [0.000, 0.000] (0.000, 0.000)	0.000 [0.000, 0.000] (0.000, 0.000)	0.000 [0.000, 0.000] (0.000, 0.000)
1Y interest rate (in pp)	-0.005 [-0.056, 0.050] (-0.070, 0.068)	0.013 [-0.028, 0.059] (-0.037, 0.073)	0.020 [-0.036, 0.082] (-0.054, 0.107)	0.019 [-0.033, 0.075] (-0.049, 0.093)
10Y interest rate (in pp)	-0.011 [-0.026, 0.005] (-0.029, 0.009)	-0.012 [-0.026, 0.003] (-0.029, 0.007)	-0.030 [-0.048, -0.009] (-0.051, -0.003)	-0.030 [-0.046, -0.009] (-0.049, -0.004)
Stock prices (in %)	-0.881 [-1.213, -0.477] (-1.264, -0.375)	-0.883 [-1.212, -0.507] (-1.263, -0.422)	-1.160 [-1.747, -0.481] (-1.832, -0.358)	-1.213 [-1.796, -0.536] (-1.884, -0.407)
Exchange rate (in %)	-0.141 [-0.305, 0.008] (-0.349, 0.039)	-0.145 [-0.293, 0.002] (-0.323, 0.029)	-0.281 [-0.551, -0.025] (-0.611, 0.025)	-0.276 [-0.522, -0.038] (-0.567, 0.010)
Share identified	0.99	0.99	0.96	0.97
N overall	724	724	724	724
N auctions	148	127	52	52
N without auctions	530	475	393	364

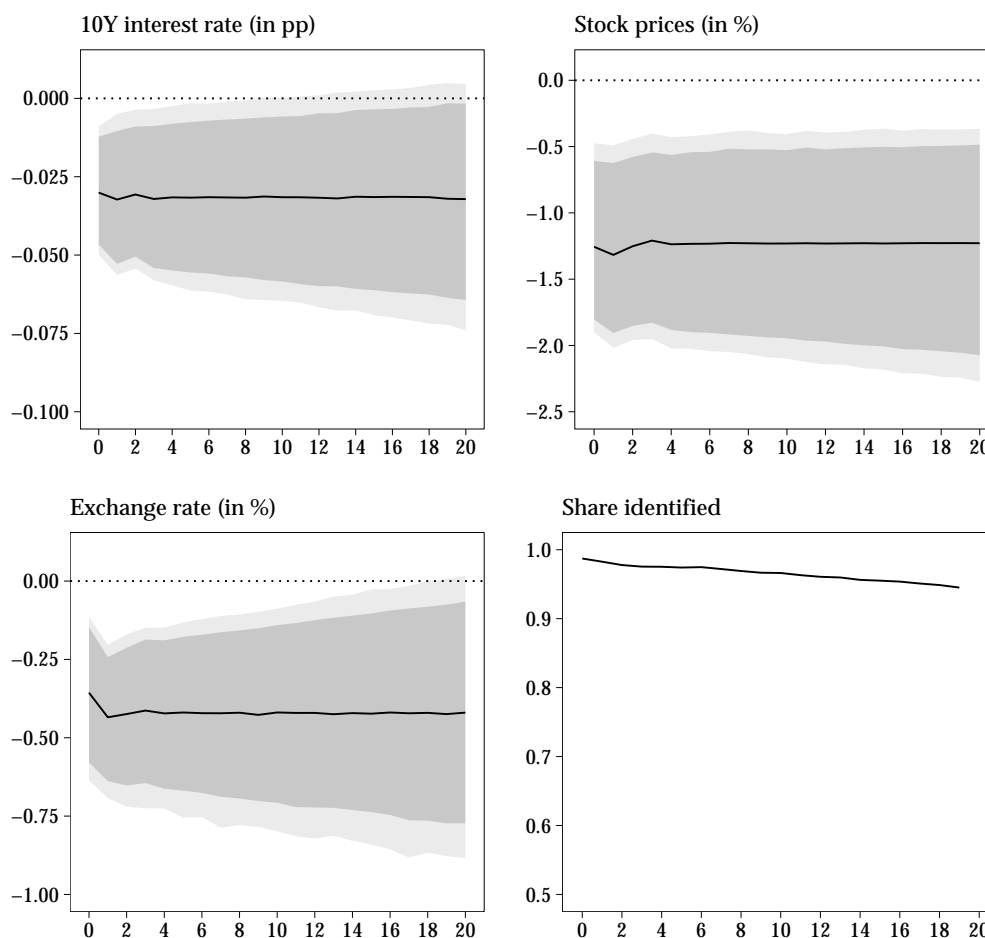
Notes: Impact of a one standard deviation expectation shock identified with sign and zero restrictions. Each column shows a different definition of days without an event. (1) excluding official monetary policy assessment of the SNB and ECB; (2) additionally excluding USD repo and USD SNB Bills; (3) additionally excluding treasury bill and government bond auctions; (4) additionally excluding foreign exchange swap auctions. All specifications control for two lags of all dependent variables, as well as, the EUR/USD exchange rate, the 3M EUR Libor, and a European stock price index. 90% and 95% confidence intervals in brackets and parentheses, respectively. Inference is based on 8,000 draws from a block bootstrap algorithm. We also report the share of bootstrap replications for which $\tilde{\Omega}_{11} > 0$ or $\tilde{\Omega}_{22} - \psi_{s1}^2 > 0$ (share identified), the overall number of observations to estimate the parameters (N auctions), the number of observations to estimate $\Omega_{t \in A}$ (N auctions), and $\Omega_{t \notin A}$ (N without events).

Table D.2 — Robustness tests (continued)

	Effects of orthogonalized shocks			
	After June 2010		Before June 2010	
	Expectation	Interest rate	Expectation	Interest rate
1W interest rate (in pp)	0.000 [0.000, 0.000] (0.000, 0.000)	0.030 [0.010, 0.048] (0.007, 0.051)	0.000 [0.000, 0.000] (0.000, 0.000)	0.047 [0.026, 0.069] (0.022, 0.072)
1Y interest rate (in pp)	-0.003 [-0.012, 0.011] (-0.015, 0.016)	-0.003 [-0.013, 0.004] (-0.018, 0.005)	0.002 [-0.090, 0.080] (-0.128, 0.101)	-0.076 [-0.183, 0.008] (-0.209, 0.018)
10Y interest rate (in pp)	-0.010 [-0.031, 0.012] (-0.039, 0.021)	-0.004 [-0.023, 0.011] (-0.031, 0.015)	-0.014 [-0.031, 0.007] (-0.034, 0.013)	0.016 [-0.000, 0.032] (-0.003, 0.035)
Stock prices (in %)	-0.460 [-0.748, -0.159] (-0.795, -0.112)	-0.150 [-0.530, 0.223] (-0.723, 0.347)	-0.960 [-1.393, -0.440] (-1.468, -0.346)	0.054 [-0.433, 0.499] (-0.535, 0.590)
Exchange rate (in %)	-0.259 [-0.570, 0.067] (-0.737, 0.165)	-0.155 [-0.376, 0.096] (-0.479, 0.173)	-0.133 [-0.322, 0.051] (-0.376, 0.090)	-0.014 [-0.114, 0.084] (-0.145, 0.105)
Share identified	0.56	0.83	0.97	1.00
N overall	302	302	421	421
N auctions	46	46	80	80
N without auctions	233	233	242	242

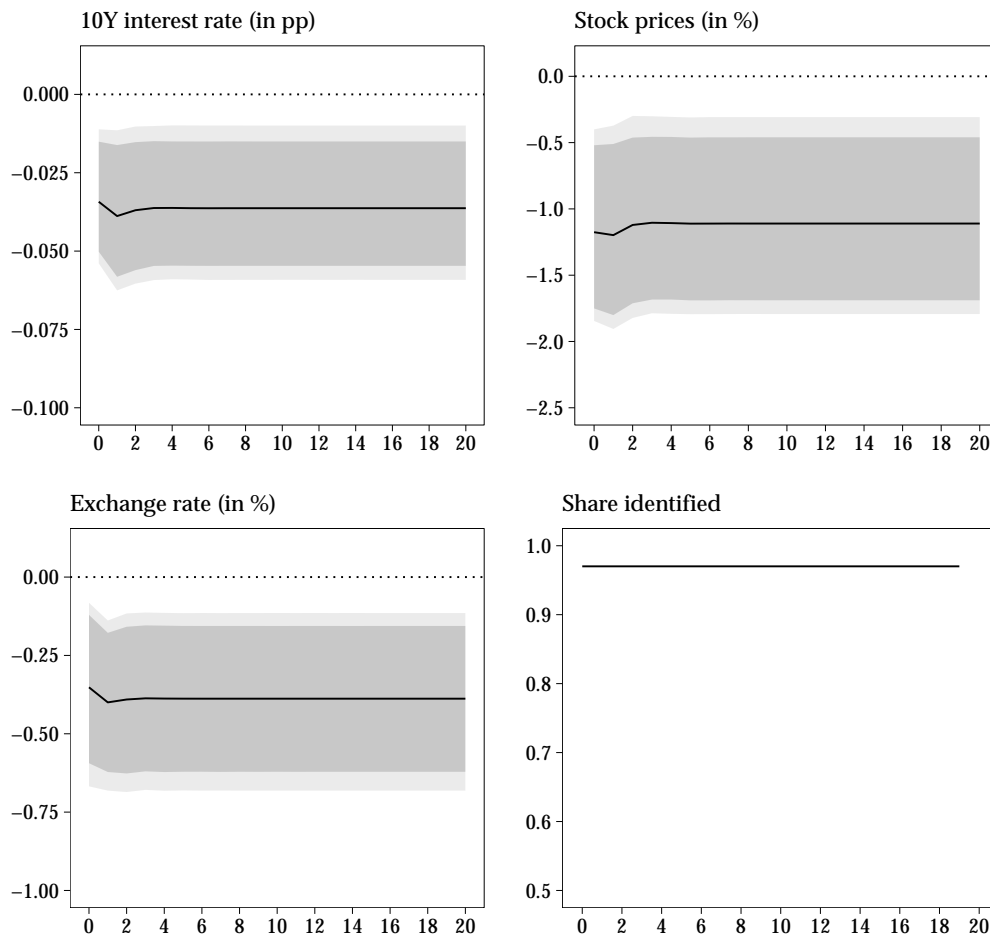
Notes: Impact of one standard deviation SNB Bill shocks identified with sign and zero restrictions. The expectation shock leads to a decline in stock prices but no change in the one-week interest rate. The interest rate shock leads to an increase in the one-week interest rate. The third and fourth column give a variance decomposition. All specifications control for two lags of all dependent variables, as well as, the EUR/USD exchange rate, the 3M EUR Libor, and a European stock price index. 90% and 95% confidence intervals in brackets and parentheses, respectively. Inference is based on 8,000 draws from a block bootstrap algorithm. We also report the share of bootstrap replications for which $\tilde{\Omega}_{11} > 0$ or $\tilde{\Omega}_{22} - \psi_{s1}^2 > 0$ (share identified), the overall number of observations to estimate the parameters (N auctions), the number of observations to estimate $\Omega_{t \in A}$ (N auctions), and $\Omega_{t \notin A}$ (N without events).

Figure D.2 — Dynamic impact of shock identified with a sign restriction on stock prices



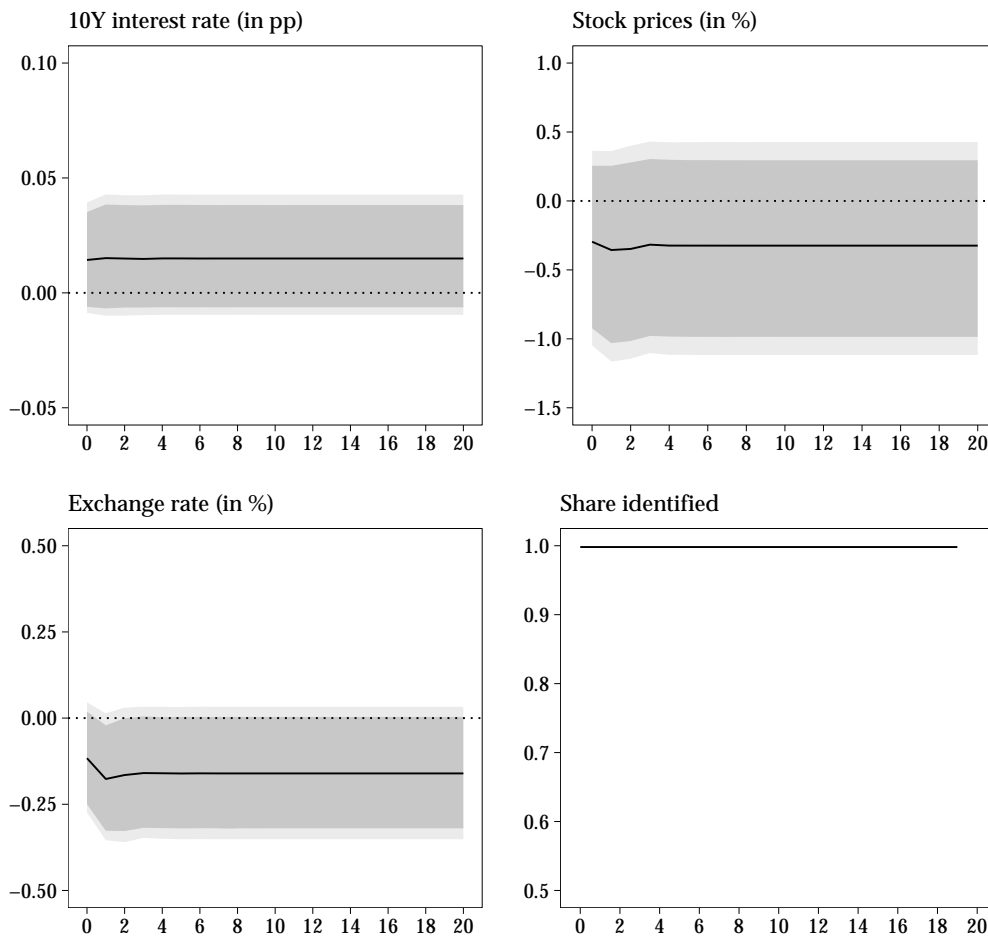
Notes: Dynamic impact of a one standard deviation SNB Bill shock identified with a sign restriction on stock prices. All specifications control for two lags of all dependent variables, as well as, the EUR/USD exchange rate, the 3M EUR Libor, and a European stock price index. Shaded areas give 90% and 95% confidence intervals. Inference is based on 8,000 draws from a block bootstrap algorithm. We also report the share of bootstrap replications for which $\tilde{\Omega}_{11} > 0$ (share identified).

Figure D.3 — VAR impulse response to an expectation shock



Notes: Dynamic impact of a one standard deviation expectation shock identified with sign and zero restrictions. All specifications control for two lags of all dependent variables, as well as, the EUR/USD exchange rate, the 3M EUR Libor, and a European stock price index. Shaded areas give 90% and 95% confidence intervals. Inference is based on 8,000 draws from a block bootstrap algorithm. We also report the share of bootstrap replications for which $\tilde{\Omega}_{11} > 0$ (share identified).

Figure D.4 — VAR impulse response to a money market rate shock



Notes: Dynamic impact of a one standard deviation money market rate shock identified with sign and zero restrictions. All specifications control for two lags of all dependent variables, as well as, the EUR/USD exchange rate, the 3M EUR Libor, and a European stock price index. Shaded areas give 90% and 95% confidence intervals. Inference is based on 8,000 draws from a block bootstrap algorithm. We also report the share of bootstrap replications for which $\tilde{\Omega}_{11} > 0$ (share identified).