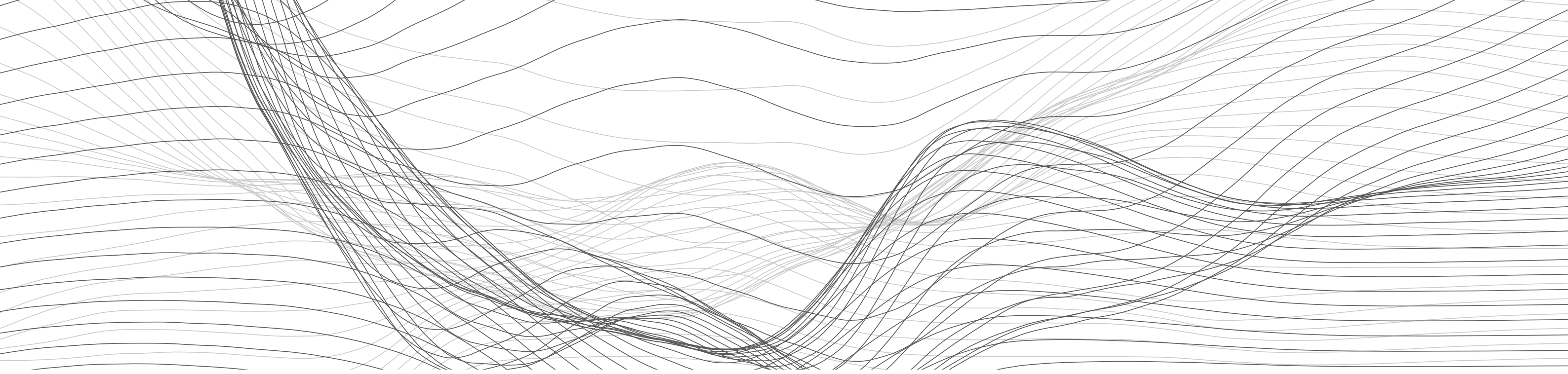

The effect of monetary policy on the Swiss franc: an SVAR approach

Christian Grisse

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The effect of monetary policy on the Swiss franc: an SVAR approach

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Abstract

This paper revisits the effects of monetary policy on the exchange rate, focusing on the Swiss franc. I estimate a structural VAR using Bayesian methods introduced by Baumeister and Hamilton (2015) and identify monetary policy shocks by exploiting the interest rate and stock price comovement they induce. Priors are based on the previous empirical literature, leaving the exchange rate response to monetary policy agnostically open. The results show that increases in Swiss short-term interest rates are associated with a nominal Swiss franc appreciation against the euro and the US dollar within the same week, with the Swiss franc remaining permanently stronger than prior to the interest rate shock.

JEL classification: C32, E43, E58, F31
Keywords: Monetary policy shocks, exchange rates, stock-bond comovement, delayed overshooting, structural vector autoregression, informative priors, sign restrictions

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1 Introduction

What effects do monetary policy shocks have on the exchange rate? This paper revisits this old question, focusing on the Swiss franc. For a small open economy such as Switzerland, the exchange rate is a particularly important channel of monetary policy transmission. Since introducing negative interest rates, the Swiss National Bank (SNB) has emphasized this transmission channel, noting in its press statement that negative interest rates "counteract the attractiveness of Swiss franc investments and thus ease the upward pressure on the currency".[1] Motivated by the key role played by the exchange rate for Swiss monetary policy, this paper aims to quantify the effect of interest rate changes on the Swiss franc.

Estimating this effect is not straightforward because exchange rates and interest rates influence each other. On the one hand, if higher interest rates reflect (expectations of) tighter monetary policy, the exchange rate should appreciate. Similarly, positive economic news should be associated with both higher interest rates and a stronger exchange rate. On the other hand, "risk-off" sentiment may lead to safe-haven capital flows into Switzerland and, thus, to a stronger Swiss franc. This, in turn, may be associated with lower interest rates as markets expect the SNB to loosen monetary policy in response to the appreciation, which places downward pressure on economic activity and inflation. Therefore, the sign of the correlation between exchange rates and interest rates depends on the underlying shocks driving these variables. The challenge is to distinguish monetary policy shocks from other structural shocks that also jointly influence exchange rates and interest rates.

This paper estimates a structural vector autoregression (VAR) relating interest rates, exchange rates and stock prices, and identifies monetary policy shocks by exploiting the correlation they induce between interest rates and stock prices. A tighter monetary policy is associated with higher interest rates and lower stock prices. By contrast, disappointing economic news and "risk-off" sentiment are associated with lower stock prices and with lower interest rates, as central banks are expected to loosen policy in a downturn. This reasoning has been applied in a number of recent papers to distinguish economic news shocks from monetary policy shocks (Matheson and Stavrev (2014)), or to decompose monetary policy shocks into shocks to the outlook for monetary policy and "information" shocks about the economic outlook (Jarociński and Karadi (2019), Cieslak and Schrimpf (2019)). This paper makes use of the same intuition to inform the prior distributions of the structural VAR coefficients, using Bayesian methods introduced by Baumeister and Hamilton (2015). While making use of available prior information, the exchange rate response to interest rates is left unrestricted.

The baseline specification is a 5-variable VAR that relates the bilateral nominal exchange rate to domestic and foreign money market rates and stock prices. The exchange rate response to SNB monetary policy shocks is allowed to differ from that to foreign monetary policy shocks,

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[1] Press release, monetary policy assessment of 12 December 2019. The negative interest rate was introduced in two steps. On 18 December 2014, the SNB announced that it would impose an interest rate of -0.25% on sight deposits at the SNB, which would come into effect on 22 January 2015. On 15 January 2015, the SNB discontinued the minimum exchange rate of CHF 1.20 per euro and simultaneously lowered the interest rate on sight deposits at the SNB to -0.75% (again effective from 22 January 2015).

which might be relevant if, for example, the persistence of central bank policy rates differs across countries. Taking Switzerland as a small open economy, I assume that Swiss variables do not influence foreign variables contemporaneously. The model is estimated using weekly data from January 2000 to August 2011, for Switzerland versus the euro area and the United States. This sample period is chosen to avoid a number of structural breaks, including, in particular, the change in the SNB's monetary policy framework in December 1999 and the SNB's introduction of a minimum exchange rate for the Swiss franc against the euro in September 2011.[2] The data frequency strikes a balance between event studies (which typically look at intraday or daily data) and the structural VAR literature (which typically uses monthly or quarterly data).

The results show that the Swiss franc appreciates on impact in response to increases in Swiss interest rates and remains permanently stronger than prior to the interest rate shock. These findings confirm the theoretical prediction that a tighter monetary policy appreciates the exchange rate immediately and permanently. Quantitatively, in the baseline specification, a positive 1 pp shock to the CHF 3-month Libor is associated with a 4% CHF appreciation against the euro on impact and leaves the CHF approximately 5% stronger in the long run. These effects are statistically significant, in that the 95% credible set of the impulse response of EURCHF to the CHF 3-month Libor never includes zero. Against the US dollar, the effects are estimated to be smaller (3% on impact, 1.5% in the long run). In the precrisis period (2000-2007), the same shock leads to a slightly smaller response against the euro (4%) but a slightly larger response against the US dollar (2%) in the long run.

The standard theory (Dornbusch (1976)) predicts that the exchange rate should overshoot on impact following an interest rate increase; i.e., it should appreciate instantly and gradually depreciate again after the shock, as required by uncovered interest parity (UIP). The empirical literature disagrees about whether this theoretical prediction holds in the data, or whether the exchange rate instead continues to appreciate for a prolonged period of time after a contractionary monetary policy shock, overshooting with a delay. The results presented in the paper concerning this question are not clear-cut. Regarding the response of EURCHF to 3-month Libor shocks, the Swiss franc continues to appreciate for up to a month following an increase in the CHF 3-month Libor, which indicates delayed overshooting (although overshooting still occurs relatively fast compared to some related papers, such as Eichenbaum and Evans (1995) or Scholl and Uhlig (2008)). By contrast, for USDCHF, the evidence is more consistent with the basic overshooting theory.

This paper builds on and extends a large empirical literature on the effects of monetary policy on exchange rates (see the next section for a literature review) and is, in particular, related to earlier structural VAR studies that have used sign restrictions to identify monetary policy shocks. I confirm the finding of the previous literature that the exchange rate appreciates following an increase in the central bank policy rate, in line with economic theory, for Swiss data.

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[2] The minimum exchange rate was discontinued in January 2015. The period since 2015 is not suitable for estimating the effects of CHF interest rate changes on the Swiss franc, however. First, since 2015, the SNB has regularly stated its willingness to intervene on the foreign exchange rate "as necessary". This willingness to intervene influences market expectations and, hence, exchange rates. This would distort the estimation over the post-2015 sample. Second, there were no SNB policy rate changes after the discontinuation of the minimum rate.

To the best of my knowledge, this paper is the first to apply Bayesian methods suggested by Baumeister and Hamilton (2015) to study the effects of monetary policy on the exchange rate. This approach has a number of advantages; it allows informative priors to be specified based on the existing empirical evidence and is transparent about the influence that the priors have on the posterior results. This paper also contributes to the literature by using sign restrictions on stock-bond comovements to identify interest rate shocks in weekly data, which is in contrast to most related papers that use restrictions on the response of output and prices to interest rates in monthly or quarterly data.

2 Related literature

This paper is related to a large literature that investigates the effects of monetary policy shocks on the exchange rate. The key challenge is that interest rates – and monetary policy decisions – both influence and respond to exchange rates. This is particularly the case for market interest rates, which contain expectations about future interest rates and a term premium, both of which are driven by the same shocks that also drive the exchange rate. This is also the case for policy interest rates, because monetary policy responds to the exchange rate, except perhaps when looking at very short windows around monetary policy decisions. Because of this endogeneity of exchange rates and interest rates, a simple regression of the exchange rate on interest rates will give a biased estimate of the causal effect of interest rate changes on the exchange rate. The literature, therefore, focuses on exogenous monetary policy or, more generally, interest rate "shocks". This section briefly reviews the various identification strategies that have been employed in previous studies and highlights the contribution of this paper relative to the existing literature.

One popular identification approach is using an event study, i.e., looking at short windows (typically ranging from a few minutes to one day) around monetary policy announcements where exchange rate movements reflect only the effects of monetary policy. Using this approach, a number of papers (e.g., Ehrmann and Fratzscher (2005), Kearns and Manners (2006), Faust et al. (2007), Ranaldo and Rossi (2010)) document that exchange rates appreciate in response to tighter policy, in line with economic theory. Rogers et al. (2018) and Inoue and Rossi (2019) aggregate high-frequency interest rate movements around monetary policy announcements and include them as "external instruments" in a monthly VAR model. This allows them to estimate the longer-term impact of monetary policy on the exchange rate based on shocks obtained from an event study.

An alternative approach that has been used in a few papers is to exploit the heteroskedasticity of the data for identification. This method is typically implemented using a sample of monetary policy assessment days versus days around these assessments (Fink et al. (2020)), or by classifying regimes of high and low volatility based on the changing variance (estimated over moving windows) of the residuals of a reduced-form VAR (Ehrmann et al. (2011)).

This paper belongs to the large literature that uses structural VARs to identify monetary policy shocks. Most of the literature estimates models relating exchange rates and interest rates to output and prices, along with other variables, at a monthly or quarterly frequency. Monetary policy shocks are then identified from assumptions about the feedback effects between interest rates and macroeconomic variables. By contrast, the empirical approach proposed in this paper relates exchange rates and interest rates to stock prices at a weekly frequency and identifies monetary policy shocks based on assumptions about their effects on interest rates and stock prices, following Matheson and Stavrev (2014) and others. In their seminal paper, Eichenbaum and Evans (1995) use exclusion restrictions with recursive ordering for identification, particularly the key assumption that the monetary policy instrument does not respond to the exchange rate within the same month. Later, papers using zero restrictions have employed more realistic nonrecursive ordering schemes (e.g., Cushman and Zha (1997), Kim and Roubini (2000), Faust and Rogers (2003) and Kim (2005)). An alternative route to identification has been the assumption that monetary policy does not influence the real exchange rate in the long run (Bjørnland (2009), Lenz and Savioz (2009)). More recently, researchers have used structural VARs identified with sign restrictions (e.g., Scholl and Uhlig (2008), Kim et al. (2017), Kim and Lim (2018)). The key idea is to only impose signs on impulse responses where the researcher has a strong belief, motivated from economic theory or prior empirical evidence, about the signs of certain effects. Sign restrictions are imposed on contemporaneous or lagged effects of shocks, while the effects that the researcher is interested in – here, the response of the exchange rate to monetary policy – are left unrestricted. This approach is attractive in that only minimal and economically plausible assumptions are imposed. The drawback is that it yields only a set of models that are consistent with the imposed restrictions, which often imply a wide range of values for the parameters of interest.

Baumeister and Hamilton (2015, 2018) criticize the canonical sign restrictions approach. They argue that, given the algorithms used to implement these restrictions in practice, researchers have actually not been as agnostic about the effects of interest as they claim. Moreover, they show that the priors influence the posterior, even in the limit where the number of observations tends to infinity. Therefore, the results that have been reported based on this approach may reflect priors that were neither chosen carefully nor openly acknowledged. Baumeister and Hamilton (2015) instead propose a method that allows the flexible specification of prior assumptions for the structural parameters and argue that priors should be chosen based on the existing empirical evidence and economic theory.[3] To the best of my knowledge, this paper is the first to apply the Baumeister and Hamilton (2015) approach to study the effects of monetary policy on the exchange rate. I specify priors based on the empirical results from Ehrmann et al. (2011), which were obtained for a different currency pair, estimation period, and identification scheme.

This paper adds to and complements a number of previous papers that study the effect of interest rates on the Swiss franc (see Table 1 for an overview). These papers differ in the identification strategy used, estimation sample, data frequency, as well as the time horizon over which the exchange rate response is estimated. Given these differences, it is not surprising that

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[3] Baumeister and Hamilton (2015) illustrate their method with an application to the labor market. Baumeister and Hamilton (2018) use this method to study the effects of monetary policy on output and inflation, while Baumeister and Hamilton (2019) apply it study oil demand and supply shocks.

Table 1: Overview of studies on the response of the Swiss franc to monetary policy

Study	Exchange rate	Data frequency	Period	Identification
Cuche-Curti et. al (2009)	EUR	quarterly	1975-2006	calibrated DSGE model
Ferrari et al. (2017)	USD	25 minutes	2010-2015	event study
Fink et al. (2020)	EUR, USD	daily	2000-2011	ItH
Kugler (2020)	EUR, USD	daily	2000-2011	instrumental variables
Lenz and Savioz (2009)	EUR	monthly	1981-2008	long-run restrictions
Ranaldo and Rossi (2010)	USD	20 minutes	2000-2005	event study
Rudolf and Zurlinden (2014)	NEER-2	quarterly	1983-2013	estimated DSGE model
This paper	EUR, USD	weekly	2000-2011	sign restrictions

Notes: NEER = CHF nominal effective exchange rate published by the SNB. NEER-2 = CHF nominal effective exchange rate computed as 0.7×EURCHF + 0.3×USDCHF. ItH = identification through heteroskedasticity.

the quantitative assessment of the effect of monetary policy on the Swiss franc also varies across studies. For example, studying short windows around SNB policy meetings, Ferrari et al. (2017) find that the Swiss franc appreciates by 25% in response to a one percentage point increase in CHF interest rates, while by contrast, the corresponding estimate in Ranaldo and Rossi (2010) is only 0.7%. All studies agree, however, that the Swiss franc appreciates in response to an increase in Swiss interest rates, in line with theory.

More recently, Fink et al. (2020) estimate these effects over the same time period (2000-2011) studied in this paper, but focus on the days of SNB monetary policy meetings, as well as on the days prior to these meetings. The identification exploits the fact that the volatility of monetary policy shocks is higher on days of SNB policy meetings than on the preceding days. By contrast, this paper looks at the weekly comovements between the Swiss franc and interest rates over the entire 2000-2011 sample. Therefore, in this paper, "monetary policy shocks" include interest rate movements both due to monetary policy communication and actions, as well as due to *expected* monetary policy actions. Moreover, I identify monetary policy shocks as shocks that move interest rates and stock prices in opposite directions. In doing so, I classify interest rate changes that reflect a market-perceived monetary policy reaction to economic developments as "economic news" rather than "monetary policy" shocks. This is consistent with a number of recent papers, including Miranda-Agrippino and Ricco (2017), Cieslak and Schrimpf (2019), and Jarociński and Karadi (2019). These papers argue that monetary policy announcements convey information about both the central bank's economic outlook and the future path for monetary policy, and thus, in a sense, can be thought of as representing a combination of economic news and monetary policy shocks (which likely differ in their effect on the exchange rate). Kugler (2020) also studies the effect of CHF interest rates on the Swiss franc, using daily data from 2000 to 2011. In his model, the identification rests on the plausible assumption that CHF interest rates do not affect EURUSD. Like this paper, both Fink et al. (2020) and Kugler (2020) confirm the theoretical prediction that increases in CHF interest rates strengthen the Swiss franc.

3 Theoretical motivation

This section presents a theoretical motivation for the empirical model relating exchange rates, interest rates, and stock prices. Uncovered interest parity (UIP) states that[4],

$$\mathbb{E}_t(\Delta s_{t+1}) = (i_t - i_t^*) - \xi_t \tag{1}$$

where s_t is the log nominal exchange rate (CHF per foreign currency), i_t is a Swiss short-term interest rate, i_t^* the corresponding foreign interest rate, and ξ_t is a risk premium. Assuming the risk premium is sufficiently small, this equation says that when the CHF interest rate is higher than the foreign interest rate (when $i_t - i_t^* > 0$), the CHF should be expected to depreciate ($\Delta s_{t+1} > 0$) to make investments in CHF and foreign currency equally attractive. Rearranging and solving forward using the law of iterated expectations, one obtains the following after k substitutions:

$$s_t \quad = \quad -\sum_{j=0}^{k} \mathbb{E}_t\left(i_{t+j} - i_{t+j}^*\right) + \sum_{j=0}^{k} \mathbb{E}_t\left(\xi_{t+j}\right) + \mathbb{E}_t\left(s_{t+k+1}\right) \tag{2}$$

This equation says that the exchange rate today reflects market expectations of future interest rate differentials, market expectations of future risk premia, and market expectations of the future exchange rate. If k is large, one can think of $\mathbb{E}_t\left(s_{t+k+1}\right)$ as being pinned down by purchasing power parity (PPP), i.e., by market views about the real equilibrium exchange rate and future inflation differentials.

Equation (2) suggests that monetary policy can potentially influence the exchange rate through three distinct channels, as follows: first, by affecting market expectations about the future path of policy rates; second, (potentially) by affecting market expectations of future risk premia, for example, by reducing uncertainty and, thus, affecting risk aversion and/or expected exchange rate volatility; and third, by affecting market expectations of future nominal exchange rate levels. For example, tighter policy should be associated with lower inflation; therefore, given an exogenous equilibrium real exchange rate, the nominal equilibrium exchange rate would be expected to be stronger. Consequently, tighter monetary policy should appreciate the exchange rate at least via the first and third channels. Monetary policy's effect through the second channel is unclear and is likely to be small.

Taking first differences of (2), we see that upon impact, an increase in CHF interest rates should be associated with a CHF appreciation. Once interest rates have reached their new level, (1) implies that the exchange rate must depreciate. Together, we arrive at the theoretical prediction (Dornbusch, 1976) that when the domestic interest rate increases, the exchange rate must overshoot on impact so that it can depreciate thereafter as required to make investors indifferent between domestic and foreign bonds. If PPP holds, the increase in CHF interest rates leaves the CHF stronger in nominal terms in the long-run, because a lower price level due to the contractionary monetary policy shock requires a stronger nominal exchange rate to

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[4] The following discussion is based on Engel (2014).

give the same PPP-implied long-run real exchange rate. The empirical literature (as surveyed in the previous section) has provided a large body of evidence showing that the exchange rate indeed appreciates upon impact following an interest rate increase. Many studies, however, find that overshooting is delayed, i.e., that the exchange rate continues to appreciate for some time following the interest rate increase. Some studies do not find any evidence for (1); often the data instead suggest that high-interest rate currencies continue to appreciate, thus violating UIP and giving rise to profitable carry trade opportunities.[5]

In the empirical model, the exchange rate determination equation is

$$s_t = \gamma_i i_t + \gamma_{i^*} i_t^* + \gamma_p p_t + \gamma_{p^*} p_t^* + u_t^s \tag{3}$$

This equation is motivated by (2), but implicitly assumes that expected future short-term interest rates are a linear function of current short-term rates. Equation (2) implies that $\gamma_i < 0$ and $\gamma_{i^*} > 0$, so that an interest rate increase is associated with an exchange rate appreciation upon impact. As I discuss in a moment, I also include domestic and foreign log stock prices p_t and p_t^* in the empirical model to help identify monetary policy shocks. In (2), I allow for the possibility that the exchange rate may respond to stock price movements. Intuitively, one might expect higher stock prices to be associated with a stronger exchange rate, so that $\gamma_p < 0$ and $\gamma_{p^*} > 0$. The structural shock u_t^s can be interpreted as a "risk" shock. For example, $u_t^s < 0$ would be a CHF appreciation that is unrelated to changes in monetary policy or growth prospects and could be interpreted as reflecting safe-haven capital inflows into Switzerland.

For the identification of the empirical model, it will be useful to consider stock markets as well. The ex-post stock market return R_{t+1} is defined as

$$R_{t+1} \equiv \frac{P_{t+1} + D_{t+1}}{P_t}$$

where P_t is the stock price and D_t is the dividend. Campbell and Shiller's (1988) log-linearization of this identity around the sample mean of the dividend-price ratio gives

$$r_{t+1} \simeq \rho p_{t+1} - p_t + \kappa + (1-\rho) d_{t+1}$$

where r_t and d_t are log returns and log dividends, and $\kappa > 0$ and ρ, with $0 < \rho < 1$, are parameters.[6] Rearranging and solving forward, we have

$$\begin{aligned} p_t &\simeq \rho^k p_{t+k} + \sum_{j=1}^{k} \rho^{j-1} \left(\kappa - r_{t+j} + (1-\rho) d_{t+j}\right) \\ &= \frac{1-\rho^k}{1-\rho}\kappa + \rho^k (p_{t+k} - d_{t+k}) - \sum_{j=1}^{k} \rho^{j-1} r_{t+j} + (1-\rho) \sum_{j=1}^{k} \rho^{j-1} d_{t+j} + \rho^k d_{t+k} \end{aligned}$$

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[5] See, for example, Engel (1996) for a survey on this "UIP puzzle".

[6] The parameters are defined as $\rho \equiv \left(1 + \exp(\bar{d} - \bar{p})\right)^{-1}$ and $\kappa \equiv -\ln(\rho) + (1-\rho)\ln(1/\rho - 1)$.

The ex-post return can be decomposed into the risk-free short-term interest rate i_t and an excess return $er_t \equiv r_t - i_t$. Taking expectations on both sides and rearranging, we get

$$p_t \simeq \frac{1-\rho^k}{1-\rho}\kappa + \rho^k \mathbb{E}_t(p_{t+k} - d_{t+k}) - \sum_{j=1}^{k} \rho^{j-1} \mathbb{E}_t\left(i_{t+j} - er_{t+j}\right) + (1-\rho)\sum_{j=1}^{k} \rho^{j-1}\mathbb{E}_t\left(d_{t+j}\right) + \rho^k \mathbb{E}_t\left(d_{t+k}\right) \tag{4}$$

This is the log approximation of the standard present value equation. For a large enough k, one can assume that the expected price-dividend ratio k periods ahead, $p_{t+k} - d_{t+k}$, equals some equilibrium value that is unaffected by monetary policy. Equation (4) then suggests that expectations of tighter monetary policy – i.e., increases in $\mathbb{E}_t(i_{t+k})$ – are associated with lower stock prices, through two channels. First, given future dividends, higher interest rates imply that the present discounted value of dividends is lower (the third term in (4)). Second, higher interest rates may be associated with lower growth and, hence, lower future dividends (the final two terms in (4)).

Motivated by (4), I model domestic and foreign stock prices as a linear function of current interest rates and exchange rates:

$$\begin{aligned} p_t &= \beta_i i_t + \beta_s s_t + \beta_{p^*} p_t^* + \beta_{i^*} i_t^* + u_t^p && (5) \\ p_t^* &= \beta_i^* i_t^* + u_t^{p*} && (6) \end{aligned}$$

Based on (4), higher interest rates should be associated with lower stock prices ($\beta_i, \beta_i^* < 0$), both through a higher discount factor and through dampening economic growth and, hence, firms' profits. An exchange rate depreciation could also be expected to be associated with higher stock prices ($\beta_s > 0$) because it boosts export performance. The structural shocks u_t^p and u_t^{p*} can be interpreted as "economic news shocks" that are related to growth prospects. Due to Switzerland being a small open economy, and positive business cycle comovement across countries, Swiss stock prices are assumed to increase with foreign stock prices, $\beta_{p^*} > 0$. By contrast, foreign stock prices are assumed not to respond to Swiss stock prices.

I assume that markets expect central bank policy rates to follow a Taylor-type rule; i.e., market interest rates are increasing in an environment of rising output and inflation. I model domestic and foreign interest rates as follows:

$$\begin{aligned} i_t &= \alpha_p p_t + \alpha_s s_t + \alpha_{i^*} i_t^* + \alpha_{p^*} p_t^* + u_t^i && (7) \\ i_t^* &= \alpha_p^* p_t^* + u_t^{i*} && (8) \end{aligned}$$

An increase in domestic stock prices signals a better than expected economic outlook and/or improved risk sentiment. Both should be associated with higher economic growth and inflation and, hence, tighter monetary policy, i.e., $\alpha_p, \alpha_p^* > 0$. Moreover, an exchange rate depreciation boosts exports and import prices and, hence, economic growth and inflation. Therefore, I assume that $\alpha_s > 0$. I also assume that $\alpha_{i^*} > 0$, as CHF interest rates have historically moved closely with foreign (especially euro area) interest rates. This is intuitive, since economic conditions in a small open economy such as Switzerland tend to follow economic conditions of important trading partners. In the baseline specification, I will assume that $\alpha_{p^*} = 0$. Because Switzerland is a small open economy, Swiss stock prices as well as the Swiss franc exchange rate are assumed not to affect foreign interest rates. The structural shocks u_t^i and u_t^{i*} are exogenous interest rate shocks, although I will often refer to them as “monetary policy shocks”. These shocks could reflect either a monetary policy action (policy rate change, communication) that markets interpret as a deviation from their perceived monetary policy reaction function or a market expectation that the central bank will deviate from their perceived rule in the future.

Equations (3) and (5) to (8) form the basis for the 5-variable VAR model estimated below. The prior distributions for the parameters in these equations will be specified based on the above discussion, as well as based on estimates in the previous literature. The identification of monetary policy shocks is achieved by imposing sign restrictions on the comovement of interest rates and stock prices.

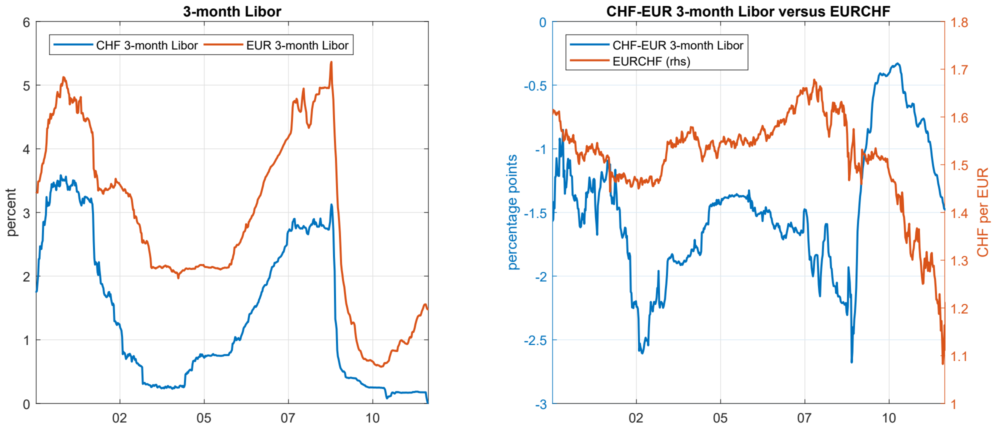
4 Data

The baseline empirical model is estimated using nominal data on CHF, EUR and USD 3-month Libor interest rates, EURCHF and USDCHF exchange rates (i.e., CHF per foreign currency), and MSCI stock price indices for Switzerland, the euro area and the U.S. In a robustness check, I additionally include the Citi economic surprise indices to control for economic data announcements that may drive financial market movements. I use weekly data based on the final trading day of the week. The main motivation for using weekly rather than daily data is that with daily data, the time stamps at which the data are measured do not match up perfectly (see appendix A for details). The weekly frequency perhaps also has the advantage that it filters out some of the noise inherent in daily data.

There are a number of structural breaks that limit the sample period over which one may reasonably expect constant parameters. The baseline specification includes data from January 2000 to August 2011. The sample starts in 2000 to avoid structural breaks due to the introduction of the euro and due to the change in the SNB’s monetary policy framework in December 1999. The sample ends in August 2011 due to the SNB’s introduction of a minimum exchange rate for the Swiss franc against the euro in September 2011. The minimum exchange rate was in place between September 2011 and January 2015. After 2015, the SNB’s “willingness to intervene in the foreign exchange market as necessary” influences the exchange rate and, therefore, makes it problematic to estimate the link between interest rates and Swiss franc exchange rates in this period. Moreover, there have been no SNB policy rate changes after the discontinuation of the minimum exchange rate.

The 3-month Libor is chosen as a baseline interest rate measure because it was the reference rate for Swiss monetary policy during the period studied. The CHF 3-month Libor reflects both the current monetary policy stance, as well as expectations about monetary policy changes within the next three months. Libor has the drawback, however, that it contains a risk premium due to the unsecured nature of the underlying interbank loans. This risk premium became

Figure 1: CHF interest rates, EUR interest rates and EURCHF



Notes: Weekly data.

important during the global financial crisis. For example, Libor-OIS spreads in CHF, EUR and USD increased strongly in August 2007, before easing again in early 2009 after central banks took measures against money market stress. In the baseline specification, I examine the 3-month Libor during the sample from 2000 to 2011, because this seems to be the most relevant measure for the stance of the SNB's monetary policy in this period, and because I want to include in the estimation the effects of the sharp changes in central bank policy rates that occurred at the beginning of the financial crisis. As a robustness check, the model is estimated up to July 2007, ending the sample before the Libor-OIS spreads increased. Ending in 2007 also has the advantage that the period after 2009, when the SNB started to intervene in the foreign exchange market and foreign central banks introduced quantitative easing, is excluded.

The left panel in Figure 1 shows that interest rates in the euro area and in Switzerland are highly correlated. The right panel plots the 3-month Libor interest rate differential between Switzerland and the euro area against EURCHF. In episodes where exchange rates and interest rates are mainly driven by monetary policy, we expect a negative correlation. However, no stable correlation pattern is apparent. The lack of a stable correlation pattern does not imply that monetary policy has had no influence on the exchange rate. Rather, it suggests that there have been other factors besides monetary policy – such as, potentially, news about the economic outlook or capital flows driven by risk sentiment – that have, at times, dominated the comovement of interest rates and exchange rates.

5 Empirical model

The empirical model builds on equations (3) to (7). By rearranging and adding constants and m lags of the variables, this system of equations can be written in terms of a structural autoregression (structural VAR),

$$\mathbf{A}\mathbf{y}_t = \mathbf{b}_0 + \sum_{\ell=1}^{m} \mathbf{B}_\ell \mathbf{y}_{t-\ell} + \mathbf{u}_t \tag{9}$$

where $\mathbf{y}_t$ is an $n \times 1$ vector of endogenous variables, $\mathbf{u}_t$ is an $n \times 1$ vector of structural shocks, $\mathbf{b}_0$ is an $n \times 1$ vector of constants and $\mathbf{A}$ and $\mathbf{B}_\ell$ are $n \times n$ matrices of parameters, with

$$\begin{aligned}
\mathbf{y}_t &\equiv \begin{pmatrix} i_t^* & p_t^* & i_t & p_t & s_t \end{pmatrix}' \\
\mathbf{u}_t &\equiv \begin{pmatrix} u_t^{i*} & u_t^{p*} & u_t^{i} & u_t^{p} & u_t^{s} \end{pmatrix}' \\
\mathbf{A} &\equiv \begin{pmatrix} 1 & -\alpha_p^* & 0 & 0 & 0 \\ -\beta_i^* & 1 & 0 & 0 & 0 \\ -\alpha_{i^*} & 0 & 1 & -\alpha_p & -\alpha_s \\ 0 & -\beta_{p^*} & -\beta_i & 1 & -\beta_s \\ -\gamma_{i^*} & -\gamma_{p^*} & -\gamma_i & -\gamma_p & 1 \end{pmatrix}
\end{aligned}$$

Here, i_t and i_t^* are the CHF and foreign currency interest rates, p_t and p_t^* are the Swiss and foreign log stock prices and s_t is the log CHF nominal exchange rate (CHF per foreign currency). The vector of structural shocks is assumed to be normally distributed $\mathbf{u}_t \sim N(\mathbf{0}, \mathbf{D})$, where the $n \times n$ covariance matrix $\mathbf{D}$ is diagonal. I estimate (9) in first differences.

Without further assumptions, the structural model in (9) is not identified.[7] The model is estimated using Bayesian methods, following the approach proposed by Baumeister and Hamilton (2015), to achieve (set) identification. In summary, this approach proceeds by specifying a full prior distribution – rather than just sign and zero restrictions – for all structural parameters. The prior information is imposed on the elements in $\mathbf{A}$, rather than on the impulse response functions (on $\mathbf{A}^{-1}$), as in most of the literature on structural VARs.[8] This approach has the advantage that it is both flexible and explicit about how the prior information is imposed and affects the results. The estimation yields a posterior distribution for the structural parameters and other objects of interest, such as the impulse response functions, that is consistent with the imposed sign restrictions.

Priors for the structural parameters. Following Baumeister and Hamilton (2015), I specify t-distributions with 3 degrees of freedom as the priors for the parameters in $\mathbf{A}$. The details can be found in Table 2.

As discussed above, the priors reflect the assumption that Switzerland is a small open economy; I assume that euro area variables do not respond within the same week to the Swiss franc, Swiss interest rates and Swiss stock prices. This is reflected in the zeros in the upper right block of matrix $\mathbf{A}$.

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[7] One way to see this is to note that the 5×5 variance-covariance matrix of the residuals has 15 unique elements, from which 17 parameters need to be estimated, i.e., the 12 parameters in matrix $\mathbf{A}$, and the 5 diagonal elements in the covariance matrix $\mathbf{D}$ of the structural shocks. Therefore, one needs to impose two further equality restrictions to identify the model.

[8] Baumeister and Hamilton (2018, 2019) show that this Bayesian approach also lends itself to using information on $\mathbf{A}^{-1}$, in addition to information about $\mathbf{A}$.

Table 2: Priors for the contemporaneous coefficients

Parameter	Meaning	Prior mode	Prior scale	Sign restriction
α_p, α_p^*	Effect of p, p^* on i, i^*	0.006	0.01	+
α_s	Effect of s on i	0.048	0.04	+
β_i, β_i^*	Effect of i, i^* on p, p^*	-1.423	1.60	$-$
β_s	Effect of s on p	0.625	0.40	none
$\gamma_i, -\gamma_i^*$	Effect of i, i^* on s	-3.698	1.20	none
$\gamma_p, -\gamma_p^*$	Effect of p, p^* on s	-0.034	0.40	none
α_{i^*}	Effect of i^* on i	0.256	0.40	+
β_{p^*}	Effect of p^* on p	0.308	0.40	+

Notes: This table provides details on the assumed prior distributions for the parameters in matrix **A** in equation (9). All priors are student's t distributions with 3 degrees of freedom.

The prior modes are chosen based on the previous literature and consistent with the economic intuition outlined earlier. In particular, I make use of the results reported in Ehrmann, Fratzscher and Rigobon (2005), who estimate a structural VAR for spillover effects between the U.S. and the euro area, using identification through heteroskedasticity, based on data from 1989 to 2008. Relative to other studies, theirs, for the purposes of this paper, has the advantage of also reporting an estimate for the parameters in **A**, rather than only $\mathbf{A}^{-1}$.[9] For the stock price reaction to the exchange rate, Ehrmann, Fratzscher and Rigobon (2005) estimate that a depreciation is associated with a decrease in stock prices. For Switzerland, with its export-oriented economy, this does not seem plausible; a CHF depreciation likely boosts exports and economic performance over time and, thus, increases stock prices on impact. Moreover, many large, export-oriented companies listed on the stock exchange likely profit directly from a CHF depreciation, as their stock price increases when the Swiss franc depreciates. To quantify the effect of the Swiss franc on Swiss stock prices, I proceed as follows. On September 6, 2011, the SNB introduced a minimum exchange rate of 1.20 for EURCHF. From September 5 to September 6, 2011, CHF depreciated by 8%, while stock prices increased by 4% in Switzerland but fell by approximately 1% in the euro area and the U.S. Based on these numbers, I take as the prior mode for the response of stock prices to the exchange rate an estimate of $(4-(-1))/8 = 0.625$.

I set sign restrictions for the effects of monetary policy on stock markets and for the response of monetary policy to stock markets. This follows the approach of Matheson and Stavrev (2014) and others, but with restrictions applied to **A** rather than $\mathbf{A}^{-1}$. These sign restrictions are consistent with a large body of empirical evidence, such as Thorbecke (1997), Bernanke and

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[9] Their model is estimated using 2-day returns, rather than weekly returns, and additionally includes long-term government bond yields. For a given coefficient in **A**, I set the prior mode by taking the average of Ehrmann et al. (2005)'s estimates for the U.S. and euro area coefficients. I do not use the results of the published version of Ehrmann et al. (2011) because there, a VAR including asset price changes but interest rate *levels* (rather than changes) is considered.

Kuttner (2005), Rigobon and Sack (2003, 2004) and Bjørnland and Leitemo (2009). I also assume that the *direct* effect of an exchange rate appreciation cannot be an increase in expected interest rates – that would seem incompatible with central banks' mandates and the effects of the exchange rate on inflation and growth. Moreover, to the extent that an exchange rate appreciation is driven by capital inflows, these inflows would need to be invested in the Swiss financial markets and would likely put upward pressure on longer-term government bond yields (via higher term premia). The effects of interest rates and stock prices on the exchange rate are left unrestricted. The effect of the exchange rate on Swiss stock prices – where the prior mode differs in sign from the results in Ehrmann et al. (2005) – is also left unrestricted.

The prior scale parameters control the width of the priors around the modes and are chosen to generate "reasonable" prior distributions. This will become clearer below, where the priors are plotted against the posteriors. For example, for the response of interest rates to stock prices (α_p^*, α_p), the priors put a positive probability on the larger estimate of 0.0214 in Rigobon and Sack (2003), as well as on the much smaller values found in Furlanetto (2011). Similarly, Rigobon and Sack (2004) estimate β_i^*, β_i at -6.81 for US data, and the prior scale ensures a small but positive probability for this value. For the response of Swiss stock prices to the Swiss franc (β_s), the prior scale ensures that a positive weight is placed on the negative point estimate in Ehrmann et al. (2005). Finally, for the response of the Swiss franc to interest rates (γ_i^*, γ_i), the chosen prior scale implies a probability of approximately 2% on the possibility that the direct effect of an interest rate increase is an exchange rate depreciation (which would contradict the theory and all available empirical evidence). It is in this sense that the priors are agnostic about the exchange rate response to interest rates.

The reduced-form VAR includes $m = 8$ lags with weekly data (i.e., approximately 2 months), using a Minnesota prior with standard hyperparameter choices. Full details on the priors can be found in appendix B.

Implications of the priors for impulse response functions. Ultimately, the focus of this paper is on the impulse response functions. The responses on impact (i.e., within the same week) are given by $\mathbf{A}^{-1}$. In general, the elements in $\mathbf{A}^{-1}$ are nonlinear functions of all elements in $\mathbf{A}$. Nevertheless, it is worth noting at this stage that the prior assumptions do not restrict the sign of the exchange rate response to monetary policy shocks. The impact impulse responses are

$$\mathbf{A}^{-1} = \begin{pmatrix} \begin{pmatrix} 1 & -\alpha_p^* \\ -\beta_i^* & 1 \end{pmatrix}^{-1} & \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \\ -\mathbf{A}_{3:5,3:5}^{-1}\mathbf{A}_{3:5,1:2}\mathbf{A}_{1:2,1:2}^{-1} & \begin{pmatrix} 1 & -\alpha_p & -\alpha_s \\ -\beta_i & 1 & -\beta_s \\ -\gamma_i & -\gamma_p & 1 \end{pmatrix}^{-1} \end{pmatrix} \tag{10}$$

with

$$\begin{pmatrix} 1 & -\alpha_p & -\alpha_s \\ -\beta_i & 1 & -\beta_s \\ -\gamma_i & -\gamma_p & 1 \end{pmatrix}^{-1} = \frac{1}{\det(\mathbf{A}_{3:5,3:5})} \begin{pmatrix} 1-\beta_s\gamma_p & \alpha_p+\alpha_s\gamma_p & \alpha_s+\alpha_p\beta_s \\ \beta_i+\beta_s\gamma_i & 1-\alpha_s\gamma_i & \beta_s+\alpha_s\beta_i \\ \gamma_i+\beta_i\gamma_p & \gamma_p+\alpha_p\gamma_i & 1-\alpha_p\beta_i \end{pmatrix} \tag{11}$$

The response of the exchange rate to a unit (1 percentage point) CHF interest rate shock u_t^i is given by the bottom left entry of this matrix, $(\gamma_i + \beta_i\gamma_p)/\det(\mathbf{A}_{3:5,3:5})$. This is unrestricted a priori since $\det(\mathbf{A}_{3:5,3:5})$, γ_i and γ_p are unrestricted. It also does not depend on foreign stock-bond spillover parameters α_p^* and β_i^*.

Note that a 1 pp CHF interest rate shock, $u_t^i = 1$, may not, in fact, increase the CHF interest rate by 1 pp, because the shock also moves stock prices and the exchange rate, which, in turn, contemporaneously influence the interest rate. The response to a CHF interest rate shock that moves the CHF interest rate by 1 percentage point is given by $(\gamma_i + \beta_i\gamma_p)/(1-\beta_s\gamma_p)$, which, again, is not restricted in sign. Intuitively, a positive interest rate shock lowers stock prices and appreciates the exchange rate, both of which dampen the initial interest rate increase. Therefore, a positive 1 pp interest rate shock increases interest rates by (slightly) less than 1 pp on impact.

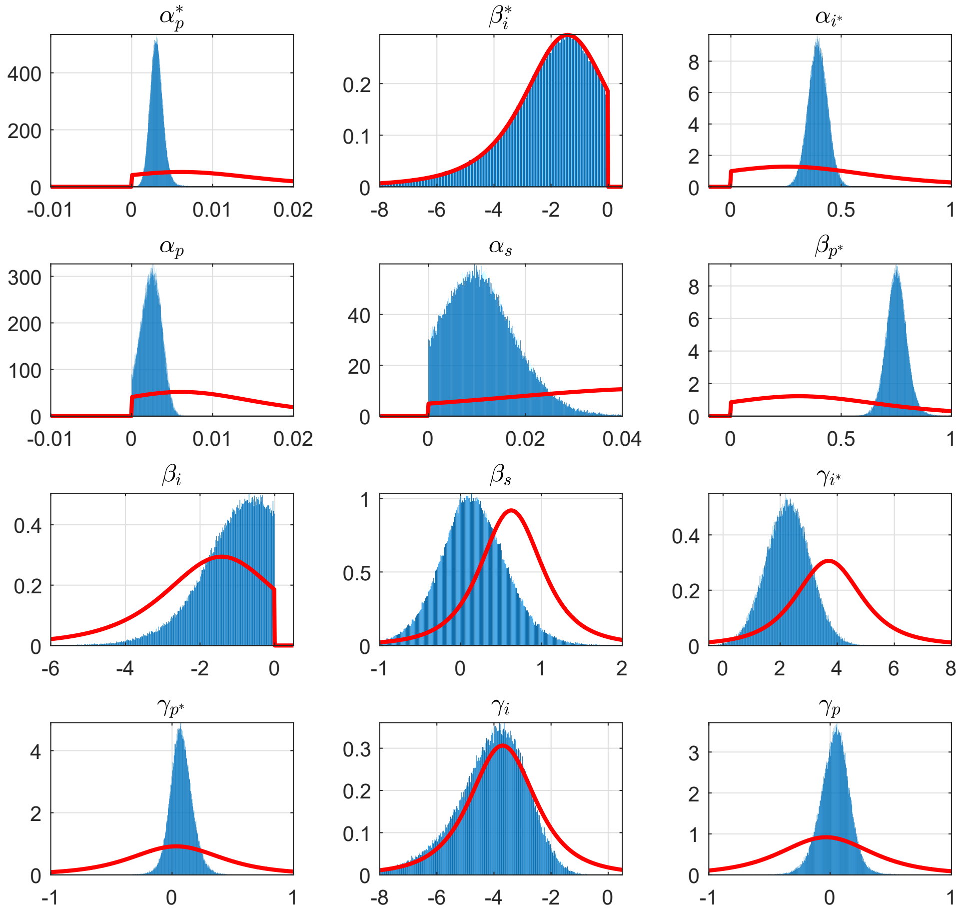
6 Results

This section presents the baseline results. I first report the results for the VAR estimated for EURCHF and Swiss and euro area data before turning briefly to the VAR estimated for USDCHF and Swiss versus U.S. data.

Figure 2 reports the prior and posterior distributions for the parameters in matrix $\mathbf{A}$, with the density on the vertical axis and the parameter values on the horizontal axis. The units are percent (exchange rate, stock prices) and percentage points (interest rates). Most parameters are well identified in the sense that the posteriors move away from the priors and that the posterior distributions are typically narrower than the prior distributions. The only exception is the response of euro area stock prices to euro interest rates, β^*, which however, as equation (11) shows, is not relevant for the main result, namely, the impulse response of the exchange rate to CHF interest rates. The prior puts a nonzero weight on the possibility that the exchange rate response to interest rates has the "wrong" sign, $\gamma_i > 0, \gamma_i^* < 0$. Nevertheless, for γ_i, the posterior has zero mass in the positive territory, thus providing strong evidence for the theoretical prediction that the direct effect of an increase in CHF interest rates – i.e., before accounting for indirect feedback effects via stock prices – will strengthen the Swiss franc against the euro. Regarding the effect of the EUR 3-month Libor on EURCHF, the posterior also has essentially zero weight on negative values for γ_i^*, again in line with the theory.

The posterior median implies that the direct effect of a 1 pp increase in the CHF 3-month Libor is to appreciate the Swiss franc by 4%. The estimated direct effect of the EUR 3-month Libor on EURCHF is smaller, with a posterior median of 2.3. Why do changes in euro interest rates appear to have smaller effects on EURCHF than changes in CHF interest rates? One

Figure 2: Structural parameters, EURCHF model



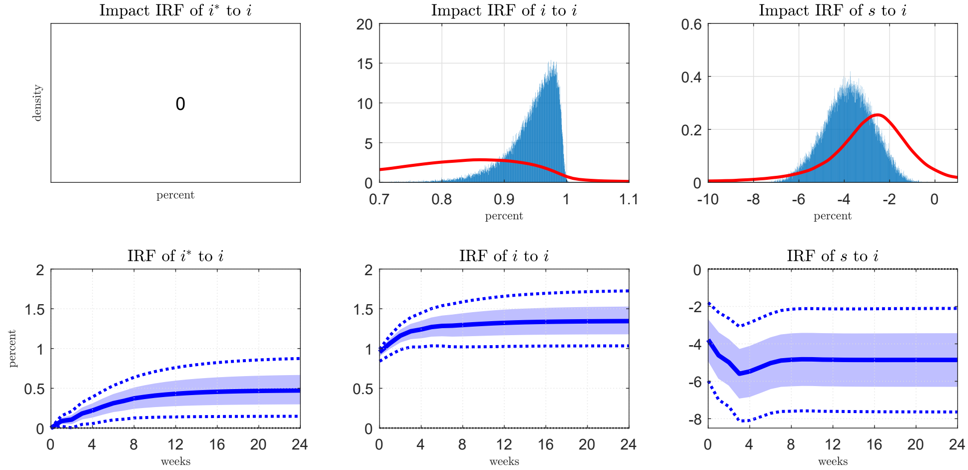
Notes: Posterior distributions (blue histograms) and prior distributions (red lines) for the parameters in matrix **A** for the VAR estimated using CHF and EUR 3-month Libor, Swiss and euro area stock prices, and EURCHF.

speculative interpretation is based on the observation that Swiss and euro area interest rates have tended to move together over the 2000-2011 sample (cf. Figure 1). Indeed, an EUR interest rate increase is found to increase CHF interest rates; the posterior for β_{i^*} is sharply peaked at approximately 0.4, with the sign restriction apparently nonbinding. Beyond this spillover via short-term rates, it is possible that markets expect an ECB policy hike, for example, to be followed by an SNB policy hike, but with a delay of more than 3 months. In this case, the spillover would not be captured in β_{i^*} but would be visible in longer-term interest rates, as well as priced into the exchange rate. Consequently, it is intuitive that γ_i is estimated to be larger than γ_i^* in absolute value.

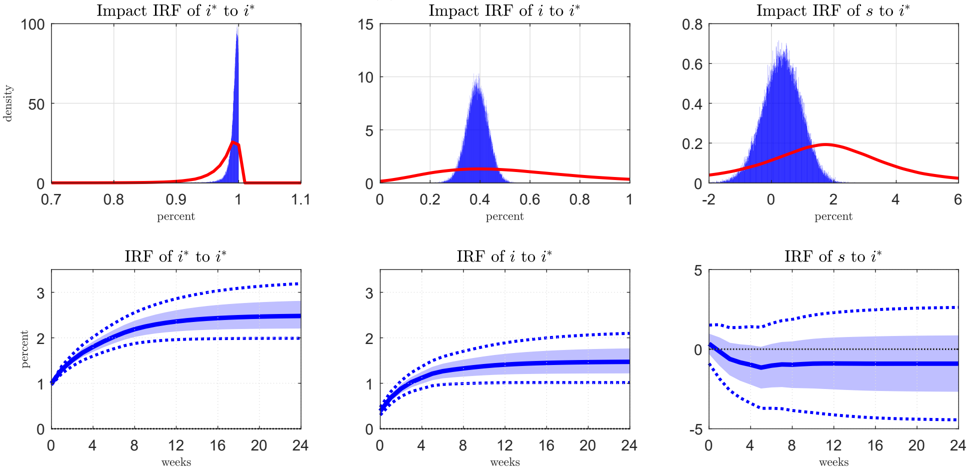
Selected impulse response functions for CHF and EUR interest rate shocks are reported in Figure 3 (for additional results, see appendix C). The responses are shown for unit (positive 1 pp) shocks. Both the responses on impact (prior and posterior distribution) and the longer-term

Figure 3: Impulse response functions, EURCHF model

(a) Shock to CHF interest rates



(b) Shock to EUR interest rates



Notes: IRFs to 1 pp interest rate shocks. For the impact IRFs, the blue histograms denote the posterior and the red lines denote the prior. For longer-horizon cumulated IRFs, the median (solid line), 68% credible set (blue area) and 95% credible sets (dashed lines) are reported. Results for the VAR estimated using CHF and EUR 3-month Libor, Swiss and U.S. stock prices, and EURCHF.

responses (median, 68% and 95% credible sets) are shown, for the responses of EUR interest rates (i^*), CHF interest rates (i) and EURCHF (s). The posterior distributions are narrower than the prior, indicating that the data are informative about these effects.

The top 6 panels show responses to a CHF interest rate shock. Despite the sign restrictions on some elements of $\mathbf{A}$, the impulse responses of the exchange rate to interest rate shocks are unrestricted in sign. In particular, the prior places a probability of 7% on the possibility that a positive shock to the CHF 3-month Libor is associated with a CHF depreciation against the euro within the same week. However, all posterior draws turn out to have the negative impact response predicted by theory (top right panel), with a posterior median of -3.8%. The exchange rate appreciates upon impact and for the following four weeks before depreciating again briefly and quickly converging to its long-term equilibrium value, which is approximately 5% stronger than prior to the shock. The 95% credibility set of the EURCHF response to CHF interest rates never includes zero. While the contemporaneous response of euro area interest rates to a CHF interest rate shock is zero by construction, euro area interest rates increase with a lag. Therefore, even though CHF interest rates continue to increase for some time following the initial shock, the CHF-EUR interest rate differential widens only by approximately 0.9 pp in the long run. These results confirm the theoretical prediction that an increase in CHF short-term interest rates persistently appreciates the Swiss franc against the euro.

The bottom six panels report the effects of a euro area interest rate shock. A 1 pp increase in the EUR 3-month Libor spills over to CHF interest rates, which increase both on impact and over time. As a result, the interest rate differential only widens by approximately 0.6 pp in the short run and by approximately 1 pp in the long run. The Swiss franc response to the EUR interest rate shock is never statistically significant, with the 68% credible set always including zero and even having the wrong sign after an initial positive impact.

Why should ECB policy rate changes have no effect on EURCHF, in stark contrast to SNB policy rate changes? First, recall from Figure 2 that the *direct* effect of higher euro area interest rates is a EURCHF increase, $\gamma_i^* > 0$, as expected. It is only with a lag and once all feedback effects are taken into account, the effect turns negative. One potential explanation is again that markets expect the SNB to follow ECB interest rate changes, though with a substantial delay. While within the first 24 weeks following the EUR interest rate shock, the CHF-EUR interest rate differential remains increased relative to before the shock, markets may expect the SNB to increase interest rates (with some probability) with a delay of more than half a year. This interest rate comovement seems plausible based on the historically observed correlation of economic activity and inflation in Switzerland and the euro area. From equation (2), this should be immediately priced into EURCHF, which as a result is little changed after the shock.[10]

Turning to the US dollar, Figure 4 shows that the posterior medians for the direct effects of interest rates on the Swiss franc have the right sign ($\gamma_i < 0, \gamma^* > 0$). Again, although the effects are unrestricted in sign, the posterior places essentially zero weight on the possibility that these effects might have a sign at odds with the theory.

Figure 5 shows that the Swiss franc appreciates approximately 3% on impact against the US dollar after a positive 1 pp shock to CHF 3-month Libor and remains 1.4% stronger in the long run. Here, the response is consistent with the prediction of Dornbusch (1976), i.e., the exchange overshoots on impact and depreciates in the following weeks to its new equilibrium value. In line with the results for the EURCHF VAR, a USD interest rate increase leads to an immediate and permanent, though smaller, increase in CHF interest rates. The Swiss franc depreciates 2% on impact in response to a 1 pp USD interest rate shock and remains approximately 3.4% weaker in the long run, with the 95% credible set mostly (just) excluding zero.

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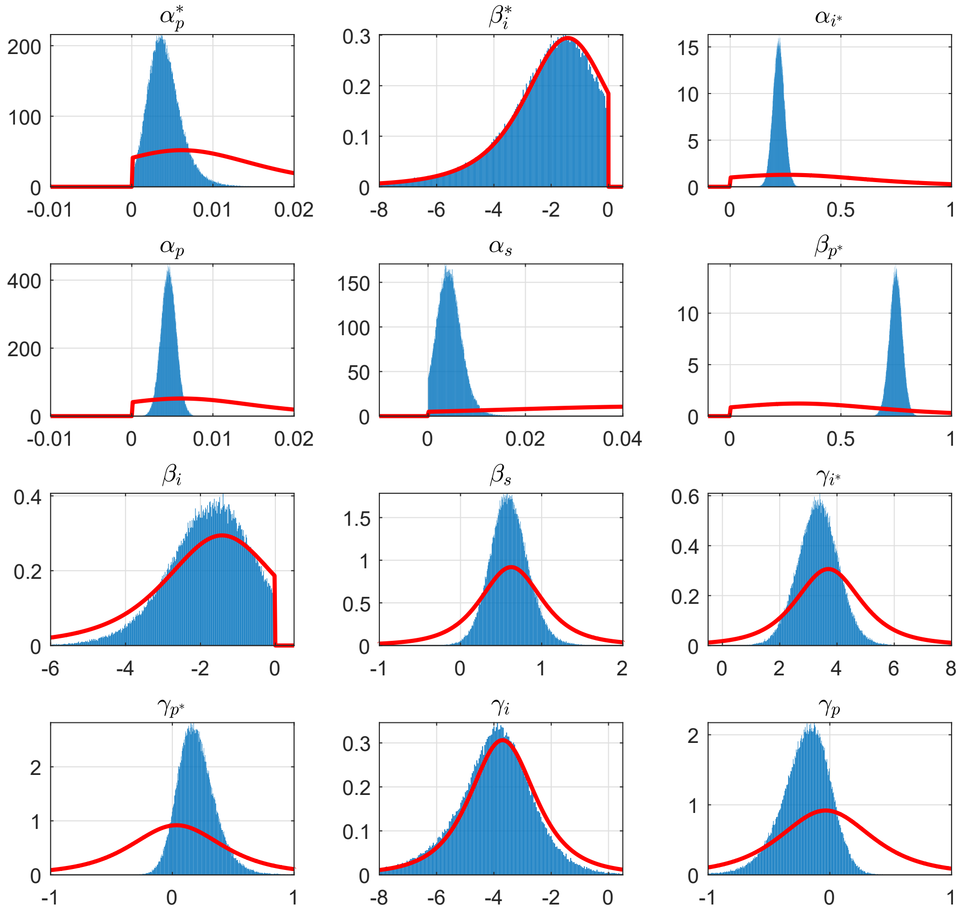
[10] Note, however, that when longer-term government bond yields are used as interest rate measures instead of 3-month Libor in the VAR (9), increases in foreign yields are always associated with a Swiss franc depreciation, both on impact and in the long run, while increases in the Swiss yields are associated with a Swiss franc appreciation.

Figure 4: Structural parameters, USDCHF model

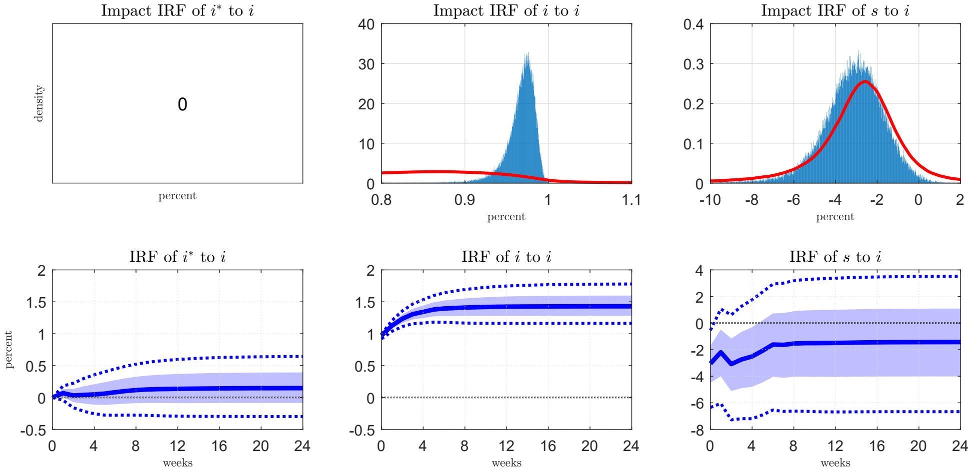


Notes: Posterior distributions (blue histograms) and prior distributions (red lines) for the parameters in matrix **A** for the VAR estimated using CHF and USD 3-month Libor, Swiss and U.S. stock prices, and USDCHF.

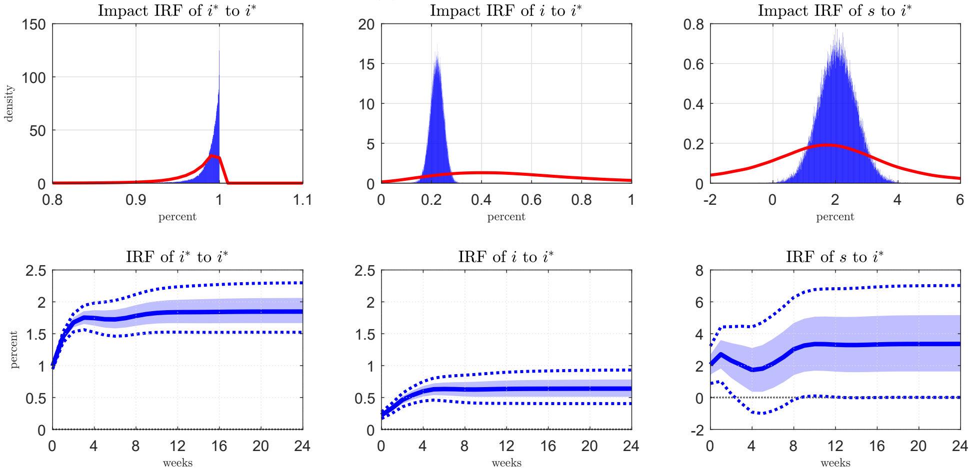
The results from the VARs estimated separately for EURCHF and USDCHF seem to indicate that the effect of an increase in CHF interest rates differs for EURCHF and USDCHF. This seems implausible, given that it would imply that Swiss monetary policy can influence the exchange rate of the euro against the US dollar. Note, however, that the median of the direct effects of CHF interest rates on EURCHF and USDCHF, γ_i, is very similar in Figures 2 and 4. It is only once feedback effects via stock prices are taken into account in the impulse responses that the effects differ. Moreover, the impulse response of USDCHF to CHF interest rate shocks is rather imprecisely estimated, with 95% credibility sets in Figure 5 that overlap those for the corresponding EURCHF response shown in Figure 3. Therefore, in a sense one cannot reject the hypothesis that the responses of EURCHF and USDCHF to CHF interest rate shocks are identical.

Figure 5: Impulse response functions, USDCHF model

(a) Shock to CHF interest rates



(b) Shock to USD interest rates



Notes: IRFs to 1 pp interest rate shocks. For the impact IRFs, the blue histograms denote the posterior and the red lines denote the prior. For longer-horizon cumulated IRFs, the median (solid line), 68% credible set (blue area) and 95% credible sets (dashed lines) are reported. Results for the VAR estimated using CHF and the USD 3-month Libor, Swiss and U.S. stock prices, and USDCHF.

7 Robustness

This section explores the robustness of the baseline results along several dimensions: (1) limiting the sample to the precrisis period; (2) controlling for macroeconomic news announcements; and (3) relaxing some zero restrictions imposed in the baseline specification on the contemporaneous feedback effects. Throughout, the same priors as in Table 2 are used, except where stated otherwise. Selected results are shown in Figure 6 for EURCHF and in Figure 7 for USDCHF. For brevity, I report only the implications for the response of the exchange rate to Swiss franc interest rates, which is the main focus of this paper.

Precrisis sample. The baseline specification includes the 3-month Libor as the interest rate measure, because this was the reference rate for Swiss monetary policy during the period studied. One problem with using the 3-month Libor as a measure of the current and expected monetary policy stance, however, is that the risk premia contained in Libor rates spiked during the financial crisis. During the crisis, changes in the 3-month Libor might therefore give a distorted picture depiction of the (expected) monetary policy stance. To check whether this influences the results, I end the sample in July 2007, just before the Libor-OIS spreads increased. The results are reported in panel (a) of Figures 6 and 7. The long-run response of the Swiss franc to a 1 pp increase in the CHF 3-month Libor is slightly smaller in absolute value than in the baseline specification (4.3%) for EURCHF and slightly larger (2.1%) for USDCHF. One difference to the baseline results for EURCHF, however, is that for the shorter sample, there is no evidence of delayed overshooting. Following an increase in CHF interest rates, the Swiss franc appreciates on impact and continues to appreciate for 2 weeks. After that, EURCHF quickly settles at its new long-term equilibrium value. For the USDCHF, the exchange rate response is immediate.

Controlling for macroeconomic news surprises. A second robustness check is to control for possible common shocks that may jointly drive exchange rates, stock prices and interest rates. To do so, I follow Ehrmann et al. (2011) and others and add macroeconomic news announcements as control variables in the VAR. I use the Citi macroeconomic surprise indices for Switzerland, the euro area and the U.S., which aggregate news surprises using weights that are based on to their historical, high-frequency impacts on exchange rates. The results reported in panel (b) are qualitatively and quantitatively almost unchanged from the baseline specification.

Response of foreign variables to the CHF exchange rate. In the baseline specification, it is assumed that foreign interest rates and stock prices do not respond to the Swiss franc exchange rate. This assumption is motivated by the fact that Switzerland is a small open economy, while the euro area and the U.S. are large economies. Here, I relax this assumption, as follows:

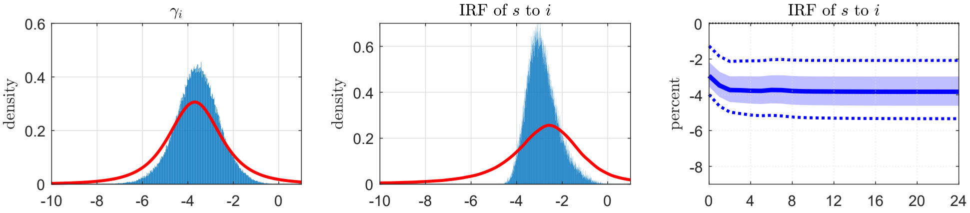
$$\mathbf{A} = \begin{pmatrix} 1 & -\alpha_p^* & 0 & 0 & -\alpha_s^* \\ -\beta_i^* & 1 & 0 & 0 & -\beta_s^* \\ -\alpha_{i^*} & 0 & 1 & -\alpha_p & -\alpha_s \\ 0 & -\beta_{p^*} & -\beta_i & 1 & -\beta_s \\ -\gamma_{i^*} & -\gamma_{p^*} & -\gamma_i & -\gamma_p & 1 \end{pmatrix}$$

where α_s^* and β_s^* capture the effects of an exchange rate change on foreign interest rates and stock prices, respectively. I set a tight prior (scale parameter 0.1) for α_s^* and β_s^*, with a prior mode of zero. The posterior distributions for both parameters turn out to be more sharply peaked around zero than the priors, indicating no influence of CHF on foreign variables, as assumed in the baseline specification. The results concerning the effects of a change in the CHF 3-month Libor, shown in panel (c), are only slightly changed relative to the baseline.

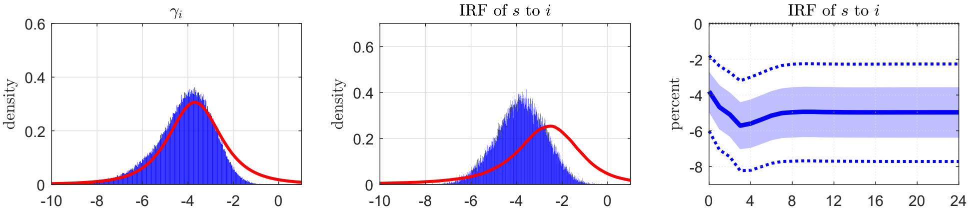
Cross-market international comovement. The main specification assumes that foreign stock prices do not *directly* affect Swiss interest rates and, similarly, that foreign interest rates

Figure 6: Robustness checks: EURCHF model

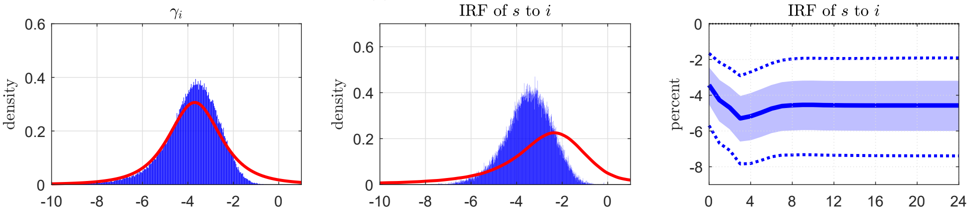
(a) Pre-crisis sample: 2000/1 to 2007/7



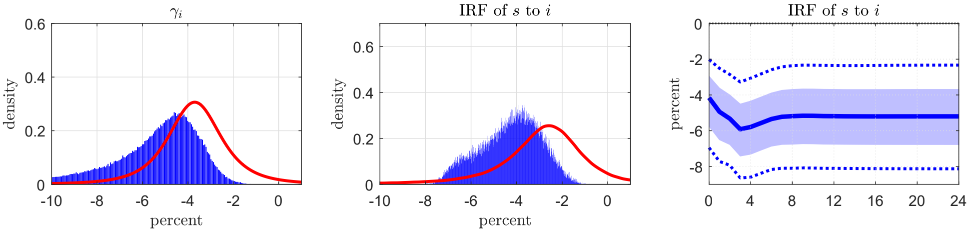
(b) Controlling for macro news



(c) Allowing i^*, p^* to respond to s



(d) Allowing for cross-market international spillovers



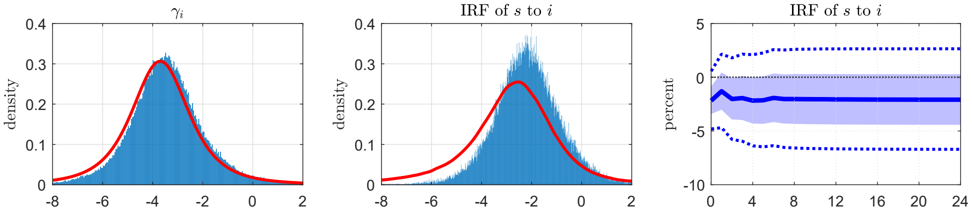
Notes: The left and middle columns report the priors (red lines) and posteriors (blue bars) for γ_i and the impact IRF of EURCHF to a 1 pp CHF interest rate shock. The right column reports the median, 68% and 95% credibility sets for the cumulated IRF of EURCHF to a 1 pp CHF interest rate shock.

do not *directly* influence Swiss stock prices. This is intuitive. Ehrmann et al. (2011) make the same assumption in the context of a VAR estimated for the euro area and the United States. In a robustness check, I nevertheless allow these effects to be nonzero, with the matrix $\mathbf{A}$ becoming as follows:

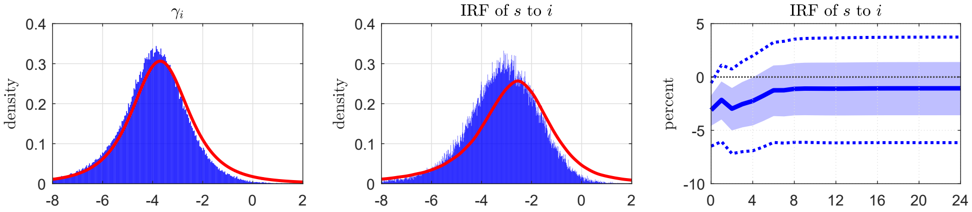
$$\mathbf{A} = \begin{pmatrix} 1 & -\alpha_p^* & 0 & 0 & 0 \\ -\beta_i^* & 1 & 0 & 0 & 0 \\ -\alpha_{i^*} & -\alpha_{p^*} & 1 & -\alpha_p & -\alpha_s \\ -\beta_{i^*} & -\beta_{p^*} & -\beta_i & 1 & -\beta_s \\ -\gamma_{i^*} & -\gamma_{p^*} & -\gamma_i & -\gamma_p & 1 \end{pmatrix}$$

Figure 7: Robustness checks: USDCHF model

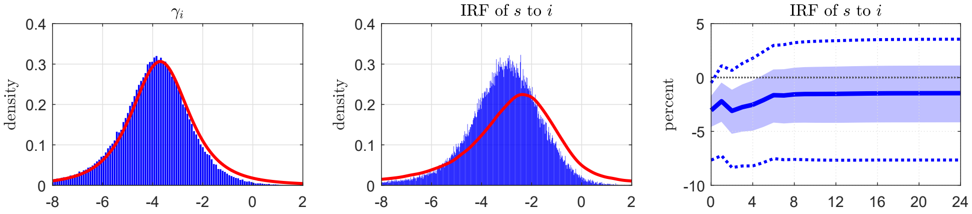
(a) Pre-crisis sample: 2000/1 to 2007/7



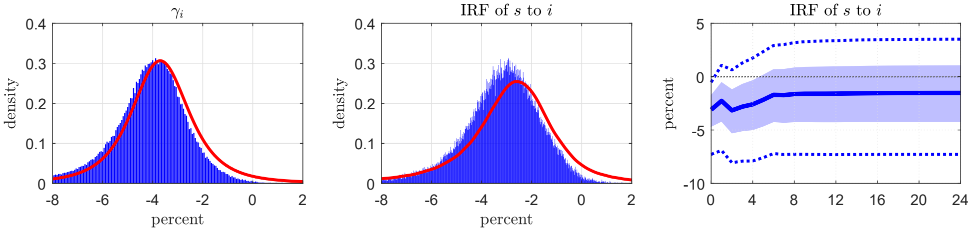
(b) Controlling for macro news



(c) Allowing i^*, p^* to respond to s



(d) Allowing for cross-market international spillovers



Notes: The left and middle columns report the priors (red lines) and posteriors (blue bars) for γ_i and the impact IRF of USDCHF to a 1 pp CHF interest rate shock. The right column reports the median, 68% and 95% credibility sets for the cumulated IRF of USDCHF to a 1 pp CHF interest rate shock.

Here, α_{p^*} is the direct effect of foreign stock prices on CHF interest rates, while β_{i^*} is the direct effect of foreign interest rates on Swiss stock prices. I again set tight priors (scale parameter 0.1) for α_{p^*} and β_{i^*}, with a prior mode of zero. The posteriors are sharply peaked at approximately zero, again confirming that the assumptions in the baseline specification are supported by the data. The results concerning the effects of a change in the CHF 3-month Libor, shown in panel (d), are only slightly changed relative to the baseline results, with a slightly stronger EURCHF response to a 1 pp CHF interest rate increase (-5.5% in the long-run).

8 Conclusion

Motivated by the key role the exchange rate plays for the Swiss economy and as a transmission channel for Swiss monetary policy, this paper studies the response of the Swiss franc to interest rate changes. Consistent with standard economic theory and existing empirical evidence, I find that the Swiss franc appreciates immediately and permanently following increases in Swiss interest rates. This result is obtained in a structural VAR estimated with weekly data over the period from 2000 to 2011.

In addition to putting forward new results for the response of the Swiss franc to interest rate shocks, this paper extends the previous structural VAR literature on the effects of monetary policy shocks on the exchange rate in two ways. First, the identification rests on plausible sign restrictions on the contemporaneous comovement of interest rates and stock prices. Second, the priors are based on existing empirical evidence and are implemented via the Bayesian methods proposed by Baumeister and Hamilton (2015).

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Appendix

A Data sources

- 3-month Libor: Measures the interest rate at which banks are able to borrow funds in the interbank market just prior to 11 am London time, based on quotes supplied by contributing banks.
- Exchange rates: WM/Reuters closing spot rates (mid rates) measured at or approximately 4 pm London time.
- MSCI equity price indices: In local currency, calculated based on closing prices of local stock exchanges.
- Citigroup economic surprise indices: These indices aggregate news surprises of macroeconomic data announcements, defined as the difference between the released numbers and the market survey expectation prior to the release. The weights used reflect estimates of the historical high-frequency impact of data announcements on exchange rates. The index values reflect news surprises over the past 3 months, with decaying weights for older surprises.

Table 3: Data sources

Variable	Source	Time stamp	Datastream ticker
CHF 3-month Libor	BBA	11.00 London	BBCHF3M
EUR 3-month Libor	BBA	11.00 London	BBEUR3M
USD 3-month Libor	BBA	11.00 London	BBUSD3M
EURCHF	WM/Reuters	16.00 London	SWEURSP
USDCHF	WM/Reuters	16.00 London	SWISSF$
MSCI Switzerland (local currency)	MSCI Inc.	17.30 Zurich	MSSWITL
MSCI euro area (local currency)	MSCI Inc.	17.35 Frankfurt	MSEMUIL
MSCI United States (local currency)	MSCI Inc.	16.00 New York	MSUSAML
Citigroup Economic surprise index Switzerland	Citigroup	n/a	SWCESIR
Citigroup Economic surprise index euro area	Citigroup	n/a	EKCESIR
Citigroup Economic surprise index US	Citigroup	n/a	USCESIR

Notes: Datastream codes for daily data.

B Priors and estimation

The prior assumptions, including the setting of the hyperparameters (except those reported in Table 2), follow the recommendations in Baumeister and Hamilton (2015). They are reproduced here to keep the analysis self-contained. Begin by writing equation (9) as follows:

$$\mathbf{A}\mathbf{y}_t = \mathbf{B}\mathbf{x}_{t-1} + \mathbf{u}_t$$

where

$$\begin{aligned} \mathbf{x}_{t-1} &\equiv \begin{pmatrix} \mathbf{y}'_{t-1} & \mathbf{y}'_{t-2} & \cdots & \mathbf{y}'_{t-m} & 1 \end{pmatrix}' \\ \mathbf{B} &\equiv \begin{pmatrix} \mathbf{B}_1 & \mathbf{B}_2 & \cdots & \mathbf{B}_m & \mathbf{b}_0 \end{pmatrix} \end{aligned}$$

The prior distribution of the matrices of parameters $\mathbf{A}, \mathbf{B}, \mathbf{D}$ can be written as follows:

$$p(\mathbf{A}, \mathbf{B}, \mathbf{D}) = p(\mathbf{A})p(\mathbf{D}|\mathbf{A})p(\mathbf{B}|\mathbf{A}, \mathbf{D})$$

The prior distributions are chosen to have particular functional forms that ensure that the posterior distributions have closed-form expressions, thus reducing computational demands.

Priors for A. Let A_j, $j = 1, ..., n_A$ denote the free parameters in $\mathbf{A}$. Assuming that the A_j are independent across elements in $\mathbf{A}$, we can write the following:

$$p(\mathbf{A}) = \Pi_{j=1}^{n_A} p(A_j)$$

where $p(A_j)$ are truncated t-distributions with 3 degrees of freedom, as detailed in Table 2.

Priors for D|A. Let d_{jj} denote the jth diagonal element in $\mathbf{D}$, i.e., the variance of the jth structural shock. We assume that conditional on $\mathbf{A}$, the d_{jj} are independent across VAR equations, so that we can write the following

$$p(\mathbf{D}|\mathbf{A}) = \Pi_{j=1}^{n} p(d_{jj}|\mathbf{A})$$

We assume that $d_{jj}^{-1}|\mathbf{A} \sim \Gamma(\kappa, \tau_j(\mathbf{A}))$, where κ is a parameter and

$$\tau_j(\mathbf{A}) = \kappa \mathbf{a}'_j \hat{\mathbf{S}} \mathbf{a}_j$$

Here, $\mathbf{a}'_j$ denotes the jth row of $\mathbf{A}$ and $\hat{\mathbf{S}}$ is the variance-covariance matrix of residuals from estimating univariate $AR(m)$ models for the endogenous variables. These prior assumptions ensure that the structural shock variances $\mathbf{D}$ reflect the scale of the data. These assumptions imply a prior mean of κ/τ_j and a prior variance of κ/τ_j^2 for d_{jj}^{-1}, so that larger values for both κ and τ_j correspond to a tighter prior. I set $\kappa = 2$, following Baumeister and Hamilton (2015), which implies that the prior carries as much weight as $2\kappa = 4$ observations.

Priors for B|A, D. Let $\mathbf{b}'_j$ denote a $1 \times (1 + nm)$ vector containing the jth row of $\mathbf{B}$ (the coefficients on the constant and lagged terms in the jth VAR equation). Assuming that conditional on $\mathbf{A}$ and $\mathbf{D}$, the $\mathbf{b}_j'$ are independent across VAR equations, we can write the following:

$$p(\mathbf{B}|\mathbf{A}, \mathbf{D}) = \Pi_{j=1}^{n} p(\mathbf{b}_j'|\mathbf{A}, \mathbf{D})$$

I assume that $\mathbf{b}_j|\mathbf{A}, \mathbf{D} \sim N(\mathbf{m}_j, d_{jj}\mathbf{M}_j)$. I implement a standard Minnesota prior. Since the data are in first differences and thus exhibit very low persistence, I expect all variables to have zero persistence and set an uninformative prior for the constant term. In particular, letting $\mathbf{a}_j'$ denote the jth row of $\mathbf{A}$, I set the prior mean of $\mathbf{b}_j$ to the following:

$$\mathbf{m}_j' = \mathbf{a}_j' \begin{pmatrix} \mathbf{0}_{n\times 1} & \mathbf{0}_{n\times nm} \end{pmatrix}$$

For the prior variance $\mathbf{M}_j$, define

$$\begin{aligned} \mathbf{v}_1 &= \begin{pmatrix} 1^{-2\lambda_1} & 2^{-2\lambda_1} & \cdots & m^{-2\lambda_1} \end{pmatrix}' \\ \mathbf{v}_2 &= \begin{pmatrix} s_{11}^{-1} & s_{22}^{-1} & \cdots & s_{nn}^{-1} \end{pmatrix}' \\ \mathbf{v}_3 &= \lambda_0^2 \begin{pmatrix} \mathbf{v}_1 \otimes \mathbf{v}_2 \\ \lambda_3^2 \end{pmatrix} \end{aligned}$$

The covariance matrix $\mathbf{M}_j$ is taken as a diagonal matrix whose rth diagonal element is the rth element of $\mathbf{v}_3$. For the hyperparameters, I use the values recommended in Baumeister and Hamilton (2018), as follows: $\lambda_0 = 0.1$ (summarizing the overall confidence in the prior), $\lambda_1 = 1$ (governing lag decay) and $\lambda_3 = 100$ (implying an essentially uninformative prior over the constant term).

Estimation. Baumeister and Hamilton (2015) derive a closed-form expression for the joint distribution of $\mathbf{A}$, $\mathbf{B}$, $\mathbf{D}$, conditional on the data. A random walk Metropolis-Hastings algorithm is used to make draws of $\mathbf{A}$, $\mathbf{B}$, $\mathbf{D}$ from the posterior distribution, with the tuning parameter set to ensure an acceptance ratio of 0.3. The Hessian and local optimum of the target function, which are found using the `fminunc` function in MATLAB, are used to make the draws from the posterior more efficient.[11] The results are based on 1'000'000 draws, after discarding 1'000'000 burn-in draws. The reported prior distributions for the impact impulse response functions are generated directly by drawing the free parameters in $\mathbf{A}$ from independent truncated t-distributions, as specified in Table 2, and calculating $\mathbf{A}^{-1}$ for each draw.

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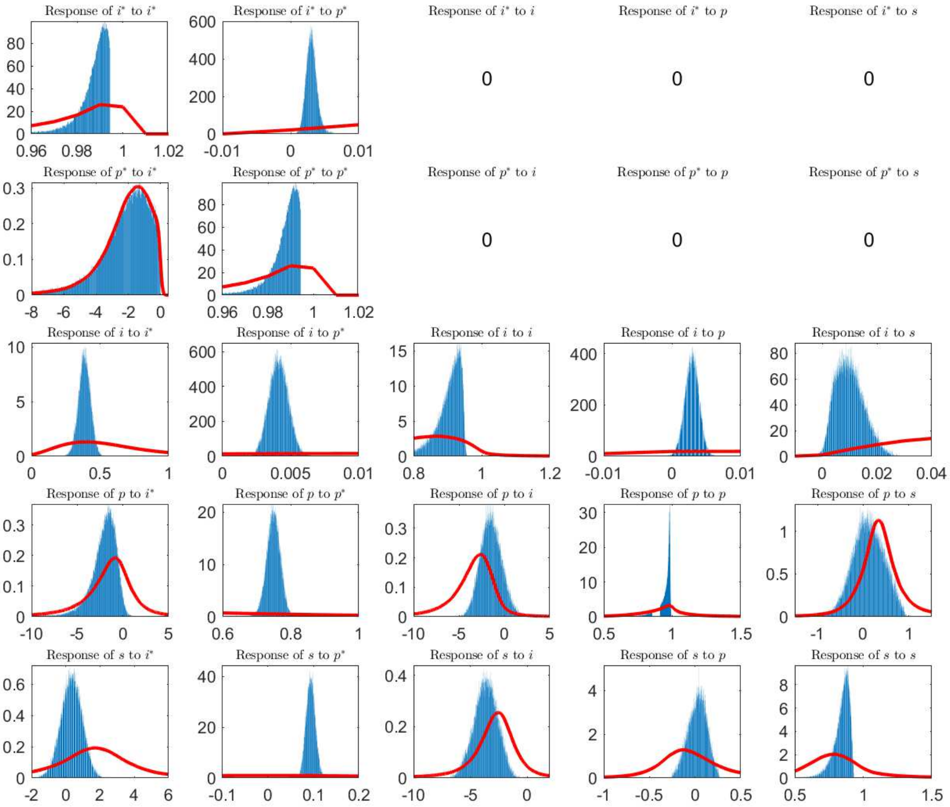
[11] One reason for estimating the VAR in first differences rather than in levels is that the `fminunc` optimization for the VAR in levels yields a Hessian with negative eigenvalues, which cannot be used to inform the Metropolis-Hastings algorithm. As a result, the algorithm is much less efficient.

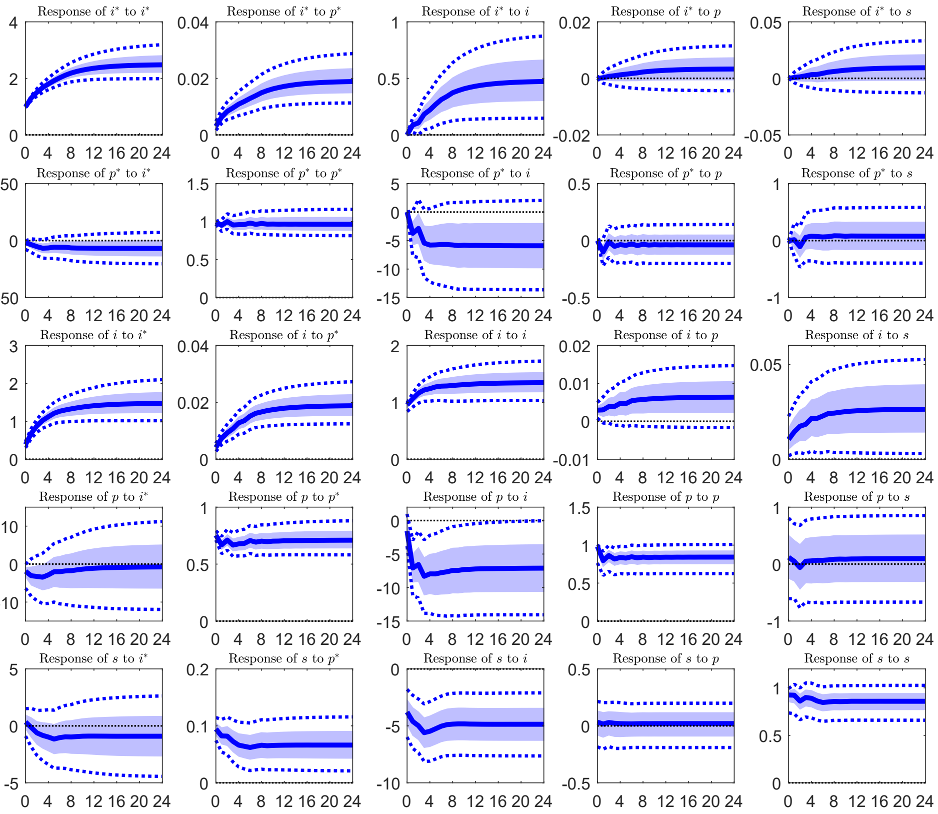
C Additional figures

Figure 8: Impact impulse response functions, EURCHF model



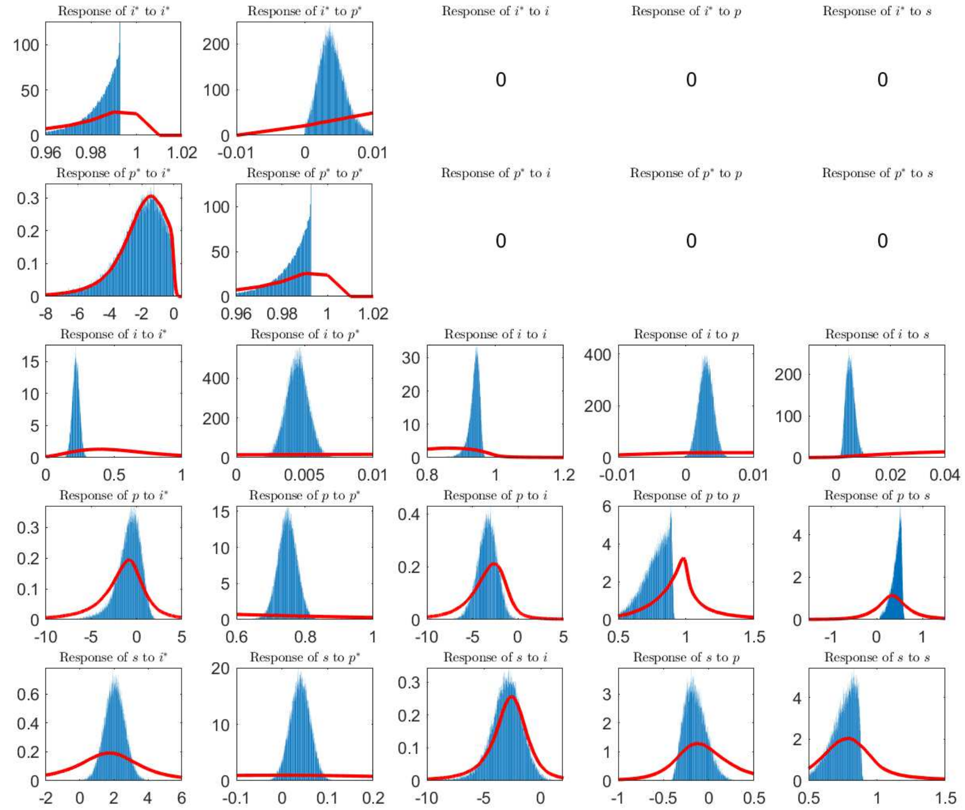
Notes: Posterior distributions (blue histograms) and prior distributions (red lines) for the impact IRFs, for the VAR estimated using CHF and EUR 3-month Libor, Swiss and euro area stock prices, and EURCHF. IRFs are shown for unit shocks (1 pp interest rate shocks, 1% exchange rate and stock price shocks).

Figure 9: Impulse response functions, EURCHF model



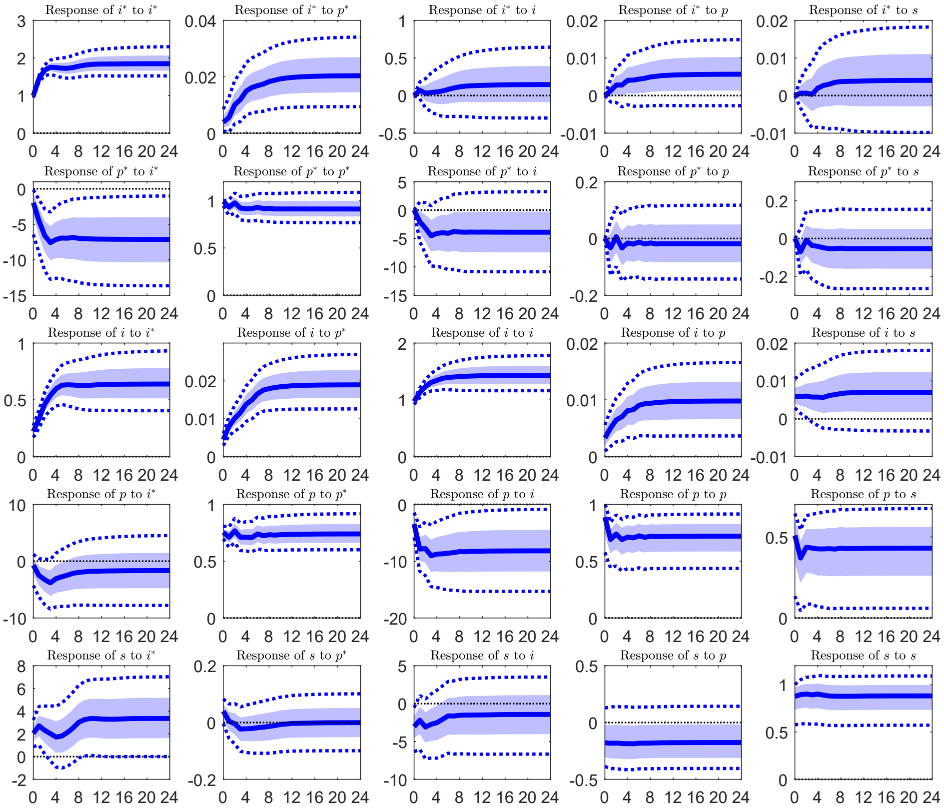
Notes: Cumulated impulse response functions for the VAR estimated using CHF and EUR 3-month Libor, Swiss and euro area stock prices, and EURCHF. IRFs are shown for unit shocks (1 pp interest rate shocks, 1% exchange rate and stock price shocks).

Figure 10: Impact impulse response functions, USDCHF model



Notes: Posterior distributions (blue histograms) and prior distributions (red lines) for the impact IRFs, for the VAR estimated using CHF and USD 3-month Libor, Swiss and U.S. stock prices, and USDCHF. IRFs are shown for unit shocks (1 pp interest rate shocks, 1% exchange rate and stock price shocks).

Figure 11: Impulse response functions, USDCHF model



Response of i^* to i^*
Response of i^* to p^*
Response of i^* to i
Response of i^* to p
Response of i^* to s
Response of p^* to i^*
Response of p^* to p^*
Response of p^* to i
Response of p^* to p
Response of p^* to s
Response of i to i^*
Response of i to p^*
Response of i to i
Response of i to p
Response of i to s
Response of p to i^*
Response of p to p^*
Response of p to i
Response of p to p
Response of p to s
Response of s to i^*
Response of s to p^*
Response of s to i
Response of s to p
Response of s to s

Notes: Cumulated impulse response functions for the VAR estimated using CHF and USD 3-month Libor, Swiss and U.S. stock prices, and USDCHF. IRFs are shown for unit shocks (1 pp interest rate shocks, 1% exchange rate and stock price shocks).

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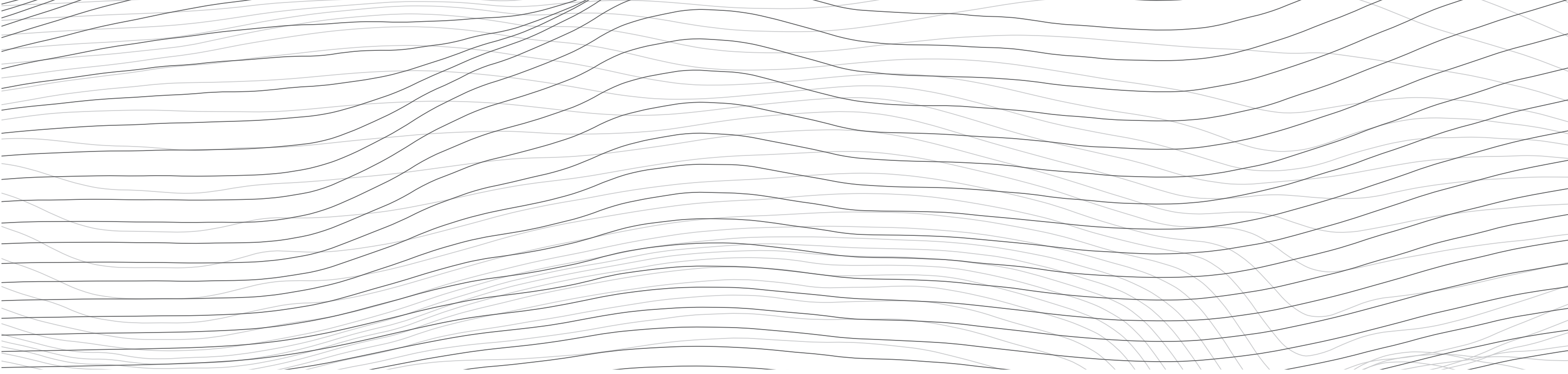

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