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JEL Classification: E32, E52, E58

Keywords: Monetary policy

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Monetary Policy, Information and Country Risk Shocks in the Euro Area

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Abstract

This study examines high-frequency market responses to ECB policy announcements, providing instrumental variables to identify four types of monetary policy shocks – conventional policy, forward guidance, quantitative easing/tightening, and asymmetric country risk – along with information shocks. Our findings show that non-linear information effects, especially prominent during episodes of acute market stress in euro area crises, are key to resolving puzzles in macroeconomic and financial variable responses reported in studies using high-frequency European data. The IVs obtained by controlling for these effects yield, in a VAR model, dynamic responses to monetary tightenings with contractionary impacts on output and prices.

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We thank Refet Gürkaynak, Lucrezia Reichlin, Burçin Kısacıkoğlu and Sang Sang Seok Lee for providing helpful suggestions. We also thank participants to the Bilkent University economic seminars for useful comments.

1 Introduction

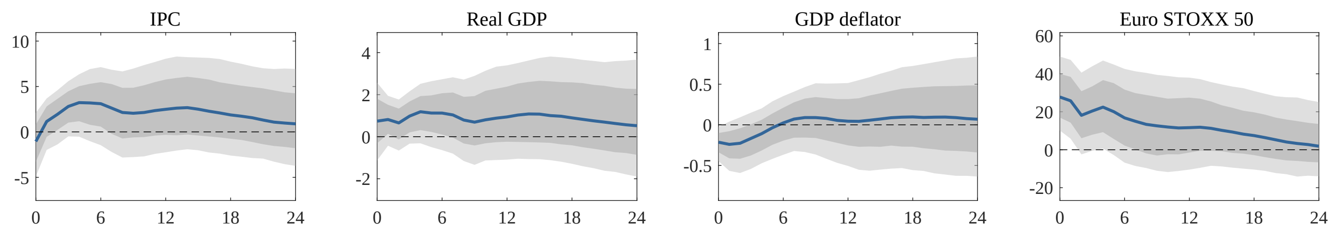
The study of high-frequency market reactions to monetary policy decisions, pioneered by Kuttner (2001) and Gürkaynak et al. (2005), has provided researchers with instrumental variables (IVs) for identifying policy shocks in reduced-form macro models without relying on assumptions about the sign or timing of macroeconomic responses, an approach initially proposed by Gertler and Karadi (2015). Initially limited to the United States, this approach has been extended to other economies, notably the euro area by Altavilla et al. (2019), who provided a comprehensive set of high-frequency responses of risk-free rates across different maturities and other assets to ECB policy announcements.

This detailed dataset is a valuable asset for studying the unique aspects of monetary policy in Europe and understanding the transmission of both the conventional and the unconventional tools in the ECB's toolkit. However, it is well known that puzzling results often emerge when monetary policy surprises for the euro area – i.e. the identified principal components of the high-frequency responses to policy decisions – are used as IVs for policy shocks.[1] For example, Figure 1 reports the impulse response functions (IRFs) to two exogenous monetary policy shocks, identified in a VAR model using the target (conventional monetary policy) and timing (next policy decision) factors of Altavilla et al. (2019). Following a policy tightening, output expands, the stock market surges, and prices show no deflationary pressure.

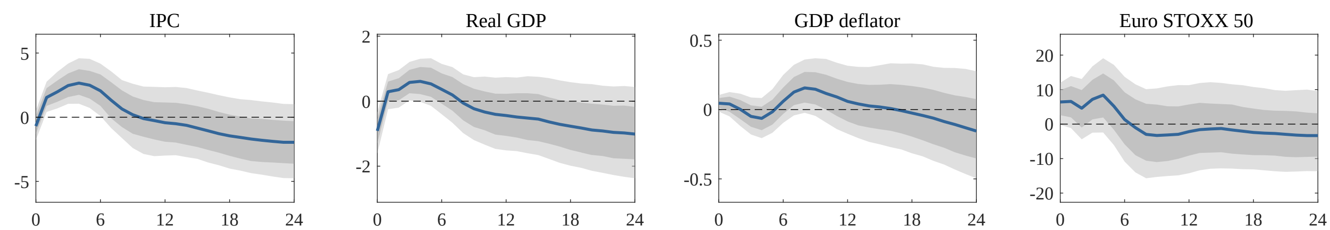
Similar puzzling responses have been reported in studies using U.S. monetary policy surprises as instruments to identify policy shocks in a VAR or local projection (LP) approach (see the excellent review by Ramey, 2016). Recent literature has pointed to the information effects of policy communication as the likely source of these puzzles in the United States (see, among others, Campbell et al., 2012, Nakamura and Steinsson, 2018, Jarociński and Karadi,

[1] From an econometric point of view, the use of monetary surprises in event studies is uncontroversial, as surprises in these studies are only intended to reflect news with respect to market participants' information sets. Conversely, VARs and LPs can identify the causal effect of monetary policy shocks only if the IV captures innovations that are (i) news to market participants, and (ii) orthogonal to the economic state. This assumption is violated when policymakers' and agents' information sets diverge, as in the presence of informational frictions (see Miranda-Agrippino and Ricco, 2021 and Gürkaynak et al., 2021 for a discussion).

Figure 1: Monetary policy shocks identified with Altavilla et al. (2019)'s IVs



(a) IRFs to a conventional MP shock – Target Factor of Altavilla et al. (2019)



(b) IRFs to a conventional MP shock – Timing Factor of Altavilla et al. (2019)

Notes: Impulse response functions to two monetary policy shocks identified using as instruments (1a) the target, and (1b) the timing factors of Altavilla et al. (2019). The target shock is normalised to induce a 100 basis points increase of the 1m-OIS rate, while the timing shock is normalised to have a 100 basis points increase of the 2y-OIS rate. The plotted variables are Industrial Production (including construction), Real GDP, GDP Deflator and Euro stock market index. The shocks are identified in a VAR(12) model with monthly variables and Minnesota priors, using the factors as an external instrument. The grey areas are 90% coverage bands. The sample considered is 2002m1-2018m8.

2020, and Miranda-Agrippino and Ricco, 2021).

Information effects in monetary policy refer broadly to the hypothesis that, not being able to perfectly observe the economic fundamentals, market participants can infer information about the economic outlook from central bank actions (and possibly communication). When a central bank takes policy decisions such as changing interest rates or implementing quantitative easing, market participants interpret these actions as signals about the central bank's view of the economy and update their own projections accordingly (see Melosi, 2017). For instance, an unexpected interest rate hike may signal that the central bank anticipates inflationary pressure exceeding market forecasts, rather than simply indicating a policy shock.

The key contribution of this work is to show that the particularly strong and non-linear information frictions that arise during periods of market stress and dislocation, which have marked the history of the euro area, explain the puzzles in the ECB's monetary policy factors. The intuition is straightforward: when financial markets are under stress and transactions are dominated by high volatility, market participants find it harder to extract clear signals about economic developments from market prices and news. In contrast, the central bank has a more direct gauge of the economy due to its access to primary data sources and its ability to directly survey financial and economic institutions. During these events, market participants rely more heavily on information conveyed by policy decisions and communication, thus amplifying the central bank's information effects.

In Section 2, we formalise this intuition within a model of dispersed information, where agents are rational but have imperfect information (see, Coibion and Gorodnichenko, 2012, 2015). They receive private, noisy signals about the state of the economy. The noise in these signals can alternate between low-variance and high-variance states. The central bank, however, receives a signal with constant noise and sets interest rates based on it. Agents observe these interest rates and, given their forecast errors, use a Kalman filter to update their beliefs about the economy, interpreting the central bank's decision as a public signal.[2] A key prediction of the model is that, when the economy enters a high-noise state – interpreted as a phase of market stress – the private sector's forecasts become less precise, and agents rely more heavily on the central bank's signal, leading to a sharp increase in information effects distorting market price surprises.

Before presenting our empirical strategy to test for information effects, let us briefly discuss some salient characteristics of monetary policy in the euro area (a comprehensive reference is Rostagno et al., 2021). The euro area is characterised by a single central bank responsible for monetary policy and, currently, 20 national governments responsible for fiscal policy, each issuing debt with varying maturities and facing its own default risk. This makes the ECB

[2]The model serves as a stylised representation of an economy where agents with information constraints independently sample noisy signals from a pool of public information about the economy. It is important to note that the model's predictions do not depend on the central bank possessing a superior information set, as is sometimes suggested. The precision of the central bank's signal only influences the strength of information effects.

policy problem in setting its stance particularly complex since the monetary tools which affect the common risk-free yield curve (typically proxied by the OIS curve), can also affect differentially the risk premia associated with country-specific yield curves. Furthermore, this incomplete federal architecture of the euro area makes it intrinsically exposed to episodes of high market stress.

Indeed, during periods of macroeconomic and financial stress, the lack of a federal fiscal authority and the existence of large fiscal imbalances in the euro area periphery, coupled with the absence of a central bank able to act as a lender of last resort, can create scope for flight to safety – i.e., investors shifting capital from peripheral countries such as Italy or Greece to German bunds and other core country treasuries –, market fragmentation along geographical lines, and potentially break-up risks. This, in turn, produces large asymmetric movements in country yields in response to perceived country risks, with the potential for self-fulfilling debt crises, as was evident during the European sovereign debt crisis (see, for example, Corsetti and Dedola, 2016, Bocola and Dovis, 2019, Lorenzoni and Werning, 2019, and the empirical work of Leombroni et al., 2021).

To test and implement the predictions of our imperfect information model, we proceed with the following empirical strategy. In Section 3, we extract common factors from Altavilla et al. (2019)'s high-frequency reactions of asset prices to monetary policy announcements, adopting a strategy similar to their original work but with some important modifications.[3] Specifically, we consider the total effect of policy announcements by summing the market responses to the ECB's press release on the decision and the details provided in the ECB President's press conference. Alongside the risk-free yield curve price revisions, we also consider changes in (i) the stock market, (ii) exchange rates, and (iii) spreads between Germany and Italy. Our empirical results confirm the existence of four significant principal components, i.e., four independent dimensions of monetary policy in the euro area, one more than in the United States (as also reported by Motto and Özen, 2022).

[3]The Euro Area Monetary Policy Database (EA-MPD) is maintained and updated on the ECB's website.

Following Gürkaynak et al. (2005), in Section 3, we use restrictions on the responses of various assets to map these four principal components into factors representing different dimensions of the ECB's policy decisions: (i) a target factor associated with conventional monetary policy; (ii) a forward guidance factor capturing communication about medium-term policy developments; (iii) a QE/QT factor representing unconventional monetary policy in the form of quantitative easing/tightening and potential changes to risk premia triggered by policy communication (as in Swanson, 2021); and (iv) an asymmetric country risk factor capturing opposite risk premia dynamics between sovereign bonds in core and peripheral euro area countries. While the first three factors are similar to those identified by Altavilla et al. (2019), the last one is akin to the market stabilisation factor of Motto and Özen (2022), though obtained under different assumptions that do not restrict the spreads' response. Empirically, the target factor lifts the short-end of the yield curve, with diminishing effects on longer maturities and almost no effect at the 10-year horizon. It strengthens the euro and negatively affects the stock market. The forward guidance factor has its largest impact on the medium-segment of the risk-free yield curve and a positive impact on the stock market – this possibly indicating a dominant information component, as argued by Jarociński and Karadi (2020). The QE/QT factor lifts the long end of the yield curve, with a strong positive exchange rate effect and a negative impact on the stock market. The last factor, capturing asymmetric country risk, leaves the risk-free yield curve almost unchanged while producing a significant increase in the ITA-GER spreads.

In Section 4, we test for the non-linear information effects predicted by the model. We do this by projecting the market price revisions triggered by policy announcements onto (i) a set of ECB and professional forecasts, and (ii) their interaction with a market stress index that equals one when market volatility (the Euro Stoxx Volatility index) is one standard deviation above its average, using a threshold regression model. Following Miranda-Agrippino and Ricco (2021), we employ the residuals from these non-linear information regressions to construct instrumental variables to identify four exogenous monetary policy shocks: conventional monetary policy, forward guidance, quantitative easing/tightening, and asymmetric country risk shocks. An additional IV for information in monetary surprises is obtained as the common factor of the fitted component in the non-linear information regressions.

The empirical results from the information regressions align with the model's predictions. Monetary policy surprises in the euro area are predictable by the pre-decision forecasts of the ECB (and private forecasts). In a linear information regression specification, predictability mainly arises from short-term forecasts, diminishing over longer maturities, with an R^2 of around 7% for shorter maturities. This result parallels findings from the U.S. (see Miranda-Agrippino and Ricco, 2021) and validates the existence of an information channel of monetary policy in the euro area. Moreover, the model's key prediction – that information effects of central bank announcements strengthen during periods of heightened volatility, as market participants place greater weight on the central bank's information – is supported by the data. Non-linear information effects are particularly strong yet concentrated in a limited number of high-volatility events, explaining up to around 40% of the price revisions at short maturities. This is a novel and key result for understanding both policy communication transmission and the role of imperfect information in the economy.

Finally, in Section 5, we examine the transmission of monetary policy shocks and information 'shocks' using a medium-scale Bayesian VAR model with standard macroeconomic priors and a rich set of macroeconomic variables. The shocks are identified using the four information-robust IVs and the proxy for the information component as external instruments.[4] A few results are worth noting. First, the transmission of monetary policy shocks, identified with IVs that control for non-linear information effects, shows that exogenous tightenings from both conventional and unconventional monetary policy have contractionary effects on production, prices, and the stock market. Almost no puzzling response appears, with the exception of the response of inflation to a forward guidance shock. Asymmetric country risk

[4]This methodology was introduced by Stock and Watson (2012) and Mertens and Ravn (2013). See Stock and Watson (2018) and Miranda-Agrippino and Ricco (2023) for a discussion on the conditions under which IV methods enable successful identification in VARs and LPs.

shocks, meanwhile, widen the spreads and affect prices and production differently in the euro area core and periphery. Second, a detailed analysis of the impact of the various empirical choices indicates that non-linear information effects are crucial for addressing the puzzles reported in the literature; linear information corrections are insufficient to eliminate these puzzles and provide only marginal improvements. These findings further supports our model's predictions. Third, IRFs for the information component of monetary surprises suggest that the set of shocks to which the bank responds are akin to the aggregate effects of demand shocks, increasing prices and production. Finally, results obtained with these IVs are robust across subsamples.

A number of robustness exercises and additional results are presented in Section 6 and the Online Appendix, while Section 7 concludes the paper. The remainder of this introduction provides a non-exhaustive review of related works.

Related Literature. A comprehensive survey of the literature on monetary policy shocks far exceeds the scope of this paper. Here, we mention only a few studies closely related to our work. In constructing monetary policy surprises from high-frequency shocks, our study follows the pioneering work of Kuttner (2001) and Gürkaynak et al. (2005). Specifically, Gürkaynak et al. (2005) were the first to observe the existence of multiple common components in the responses of forward contracts on the U.S. yield curve to policy surprises – labelled by them as a target and a path factor. Swanson (2020) extended this approach to capture unconventional monetary policy in the U.S., including forward guidance and LSAP (i.e. QE) factors. This method has been applied to the euro area by Altavilla et al. (2019), who employed risk-free OIS rates. Wright (2019) and Leombroni et al. (2021) were among the first to highlight the potentially important role of sovereign spread surprises in the euro area.[5] Different approaches to understanding the role of spreads in the transmission of shocks identified with high-frequency surprises have been proposed in Reichlin et al. (2022) and Motto and Özen (2022). The latter was the first to isolate an additional factor in policy surprises related to

[5]In the context of emerging markets, Pirozhkova et al. (2024) has shown the role of monetary policy in modulating country risk, using a high-frequency identification of monetary policy.

diverging dynamics in core and periphery country spreads, which they labelled the 'market stabilisation factor'. To the best of our knowledge, our work is among the first to propose a comprehensive study of all the different policy dimensions and information shocks, in the euro area.

The use of high-frequency surprises as instrumental variables to identify policy shocks was pioneered by Gertler and Karadi (2015) and has quickly become the standard approach in the literature on monetary policy shocks. Two approaches have been proposed to control for information effects in these surprises: one 'survey-based' and the other 'market-based.' The first approach involves regressing high-frequency market surprises on the central bank's internal forecasts, which serve as a direct measure of the policymaker's information set, as in Miranda-Agrippino and Ricco (2021).[6] The market-based approach, as in Jarociński and Karadi (2020), Cieslak and Schrimpf (2019), and Cieslak and Pang (2020), uses the stock market response to separate a component of surprises that moves interest rates and asset prices in the same direction (macroeconomic news) from a component that raises interest rates but depresses asset prices, or vice versa (policy shocks).[7]

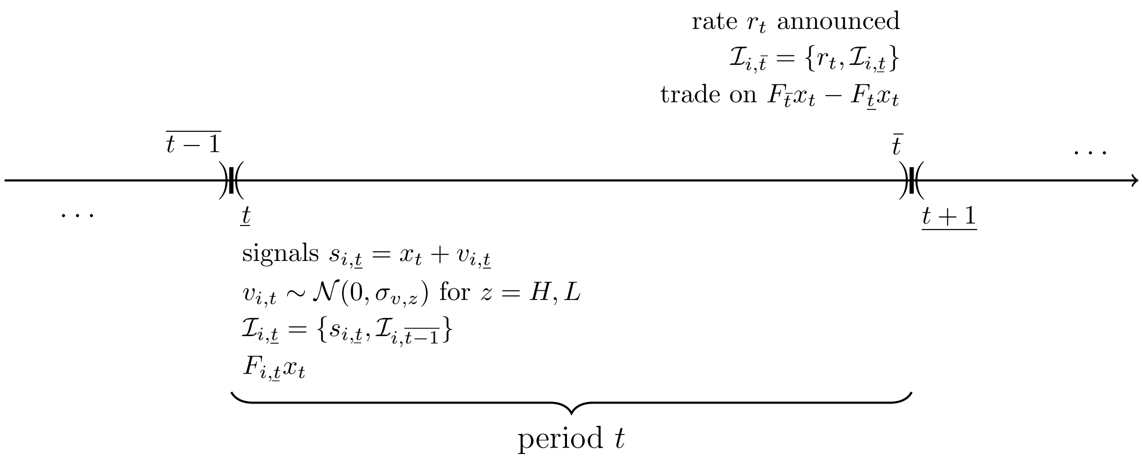
For the euro area, Jarociński and Karadi (2020) pioneered the market-based approach, demonstrating a marked attenuation of the puzzles. More recently, Kerssenfischer (2022) has provided evidence that this methodology may help reduce puzzles in monetary policy surprises derived from one-year maturity futures.[8] Badinger and Schiman (2023) combined

[6]This approach was introduced by Campbell et al. (2012), who used survey data from professional forecasters (SPF). While central banks' forecasts provide a more direct measure of policymakers' expectations, the mean SPF forecast is likely a good proxy for the bank's forecast given private signals and dispersed information.

[7]Bauer and Swanson (2023)'s alternative explanation of the empirical evidence on information effects involves two key elements: private agents using a misspecified Taylor rule to forecast the policy rate, and imperfect information, as discussed in Coibion and Gorodnichenko (2012, 2015). To address the predictability of monetary surprises, they suggest regressing these surprises on a set of past financial indicators. Their approach and the implications of their model are largely observationally equivalent to those of Miranda-Agrippino and Ricco (2021). However, their interpretation of the information effects appears ill-suited to explain the non-linear information reported in this work. Finally, it is worth noting that information frictions of the type they discuss naturally lead to autocorrelation in forecast revisions and to information effects from policy actions, as discussed in this paper.

[8]In Section K, of the Online Appendix we provide some comparison of the empirical results of these two approaches.

Figure 2: THE INFORMATION FLOW



Note: Each period t has a beginning $\underline{t}$ and an end $\bar{t}$. At $\underline{t}$ agents (both private and central bank) receive noisy signals $s_{i,\underline{t}}$ about the economy x_t, and update their forecasts $F_{i,\underline{t}}x_t$ based on their information set $\mathcal{I}_{i,\underline{t}}$. At $\bar{t}$ the central bank announces the policy rate i_t based on its forecast $F_{cb,\underline{t}}x_t$. Agents observe i_t, infer $F_{cb,\underline{t}}x_t$, and form $F_{i,\bar{t}}x_t$. Trade is a function of the aggregate expectation revision between $\underline{t}$ and $\bar{t}$.

high-frequency surprises with a narrative approach, using sign restrictions on structural residuals to address information effects. To our knowledge, this paper is the first to apply the survey-based methodology to the euro area and the very first to demonstrate the significance of non-linear information effects in the dynamics of attention to policy signals.[9] This contribution has potential implications beyond the policy space we focus on.

2 Information effects under market stress

To provide a framework for our empirical analysis, let us consider a model in which private agents and the central bank have imperfect information about the state of the economy, forming expectations conditional on private signals clouded by state-dependent observational noise. In doing so, we extend the model in Miranda-Agrippino and Ricco (2021) to the case where the variance of the noise is not constant.

[9]In adding other assets, and particularly the stock market, when extracting policy surprises, we build on the work and insights of Jarociński and Karadi (2020).

Agents in the model live in discrete time, with each period t being divided in an opening and a closing stage, i.e. $t \in \{\underline{t}, \overline{t}\}$. The inflation process evolves over time with an AR(1) process:

$$\pi_t = \rho \pi_{t-1} + u_t^{\pi}, \qquad u_t^{\pi} \sim \mathcal{N}(0, \sigma_{\pi}^2) \ , \tag{1}$$

with normally distributed innovations, u_t^{π}, and $|\rho| < 1$.

At the beginning of time t, i.e. $\underline{t}$, each agent i receives a private signal about inflation contaminated by observational noise

$$s_{i,t} = \pi_t + v_{i,t}, \qquad v_{i,t} \sim \mathcal{N}(0, \sigma_{v,z}^2), \tag{2}$$

with a state-dependent variance, σ_s^v, which is equal across agents and is characterised by the existence of two states, $z \in \{L, H\}$, respectively with high and low noise, i.e. $\sigma_{H,z}^v > \sigma_{L,z}^v$. Agents form and update their expectations about current and future inflation, conditional on the signals observed using a Kalman filter

$$F_{i,\underline{t}}\pi_t = K_{1,\underline{t}} s_{i,\underline{t}} + (1 - K_{1,\underline{t}}) F_{i,\overline{t-1}} \pi_t, \tag{3}$$

$$F_{i,\underline{t}}\pi_{t+h} = \rho F_{i,\underline{t}} \pi_t, \tag{4}$$

where $K_{1,\underline{t}}$ is the Kalman gain. Conditional on their expectations for inflation, agents forecast (and trade) the policy rate, that is set by the central bank following a Taylor rule,

$$i_t^{(0)} = r_t = \delta \pi_t + u_t^{mp}, \tag{5}$$

along with interest rates at longer horizons, $i_{\underline{t}}^{(h)}$ for $h \geq 0$

$$i_{\underline{t}}^{(h)} = \alpha_h F_{\underline{t}} \pi_{t+h} + \xi_t^{(h)}, \tag{6}$$

where $\xi_t^{(h)}$ captures risk premia, $\alpha_0 = \delta$, and $F_{\underline{t}}$ indicates the average expectations over the market.

Let us define $V_{t|\overline{t-1}} \equiv \text{Var}\left(\pi_t - F_{i,\overline{t-1}}\pi_t\right)$, i.e. the variance of the forecast errors for inflation at time t, made at time $\overline{t-1}$. The Kalman gain $K_{1,\underline{t}}$ is given by:

$$K_{1,\underline{t}} = \frac{V_{t|\overline{t-1}}}{V_{t|\overline{t-1}} + \sigma^2_{v,z}}. \tag{7}$$

From the expression for $K_{1,\underline{t}}$, it is clear that, for a given $V_{t,\overline{t-1}}$, the agents will update more their forecasts in states of low noise, as compared to the states of high noise. The variance of the forecast of π_t made at $\underline{t}$ will depend on $V_{t|\overline{t-1}}$ as[10]

$$V_{t|\underline{t}} = V_{t|\overline{t-1}} - \frac{(V_{t|\overline{t-1}})^2}{V_{t|\overline{t-1}} + \sigma^2_{v,z}}, \tag{8}$$

$$V_{t|\overline{t-1}} = \rho^2 V_{t-1|\overline{t-1}} + \sigma^2_{\pi}. \tag{9}$$

During period t, the central bank also receives a private signal about the state of the economy, contaminated by noise with constant volatility, and updates its forecast:

$$s_{cb,t} = \pi_t + v_{cb,t} \qquad v_{cb,t} \sim \mathcal{N}(0, \sigma^2_{v,cb}), \tag{10}$$

$$F_{cb,t}\pi_t = K_{cb,t}s_{cb,t} + (1 - K_{cb,t})F_{cb,t-1}\pi_t. \tag{11}$$

The assumption of constant volatility captures in a stylised manner the fact that the central bank, differently from market operators which have to sample information from prices and data releases, can have a more direct access to data offices and survey directly financial and economic institutions to take the pulse of the economy. Given the constant noise in the central bank's signal, we consider the asymptotic value of the Kalman gain, denoted K_{cb}, with the time index dropped. Given its forecast for π_t, the central bank sets and announces

[10] Agents in the model know all of the model parameters, including the variance of the signal (either low or high).

the interest rate for the period:

$$r_t = \delta F_{cb,t}\pi_t + u_t^{mp}. \tag{12}$$

where u_t^{mp} is a monetary policy shock drawn from a normal distribution centred at zero and with variance σ_{mp}^2.

At time $\bar{t}$, agents observe the interest rate, which conditional on the past interest rate, is a public signal on the state of the economy of the form:

$$\tilde{s}_{\bar{t}} = \pi_t + \tilde{v}_{cb,\underline{t}} \equiv \pi_t + v_{cb,t} + (\delta K_{cb})^{-1}[u_t^{mp} - (1-K_{cb})\rho u_{t-1}^{mp}]. \tag{13}$$

Agents update their expectations with a Kalman filter, using the public signal delivered by the policy rate[11]

$$F_{i,\bar{t}}\pi_t = K_{2,\bar{t}}\tilde{s}_{cb,\bar{t}} + (1-K_{2,\bar{t}})F_{i,\underline{t}}\pi_t,$$

where the gain $K_{2,\bar{t}}$ is:

$$K_{2,\bar{t}} = \frac{V_{t|\underline{t}}}{V_{t|\underline{t}} + \sigma_{\tilde{v}}^2}, \tag{14}$$

and the forecast error variance is such that:

$$V_{t|\bar{t}} = V_{t|\underline{t}} - \frac{(V_{t|\underline{t}})^2}{V_{t|\underline{t}} + \sigma_{\tilde{v}}^2}. \tag{15}$$

Given their updated forecasts, agents revise the price for the rates at longer horizons and trade. The following proposition links revisions to interest rates to current and past structural shocks, and to past forecast revisions and generalise results in Miranda-Agrippino and Ricco (2021) to the case in which the observational noise in public signal can vary.

[11] For the sake of simplicity, we assume that agents update with a standard Kalman filter without taking into account the structure in the noise of this public signal due to the moving average component in the monetary policy shock.

Proposition 1. *The price revisions in interest rates at different maturities triggered by the policy announcement are*

$$\Delta i_{\underline{t}}^{(h)} = \alpha_h \rho^h \left(F_{\bar{t}} \pi_t - F_{\underline{t}} \pi_t \right) + \Delta \xi_t^{(h)}, \tag{16}$$

where

$$\begin{aligned} F_{\bar{t}}\pi_t - F_{\underline{t}}\pi_t = {} & (1 - K_{1,\underline{t}}) K_{2,\bar{t}} K_{2,\overline{t-1}}^{-1} (1 - K_{2,\overline{t-1}}) [F_{\overline{t-1}}\pi_t - F_{\underline{t-1}}\pi_t] + (K_{2,\bar{t}})(1 - K_{1,\underline{t}}) u_t^{\pi} \\ & + K_{2,\bar{t}} [\nu_{cb,\underline{t}} - (1 - K_{1,\underline{t}}) \rho \nu_{cb,\underline{t-1}}] + K_{2,\bar{t}} (K_{cb}\delta)^{-1} [u_t^{mp} - \rho(2 - K_{cb} - K_{1,\underline{t}}) u_{t-1}^{mp} \\ & + (1 - K_{1,\underline{t}})(1 - K_{cb}) \rho^2 u_{t-2}], \end{aligned} \tag{17}$$

are the average revision in expectations across agents in the market, and $\Delta \xi_t^{(h)}$ *are revisions to risk premia.*

Proof. See Section A of the Online Appendix. □

The expression in Eq. (17) shows that, after observing the policy decision, all agents update their expectations towards the view of the bank, thereby inducing a market-wide information effect. The first term in the expression above represents the autocorrelation between revisions of expectations, which is due to the sluggish adjustment of expectations in models of imperfect information. The second term, $(K_{2,\bar{t}})(1 - K_{1,\underline{t}}) u_t^{\pi}$, captures the information channel of monetary policy, that is the fact the the policy announcement delivers information about the shocks hitting the economy. The remaining terms include both monetary policy shocks and central bank noise (another source of policy shock), along with their lags.

In this setting, the coefficients of the different terms, particularly the information effects, are time-varying. Therefore, to control for information effects, it is insufficient to project the monetary policy surprises onto a set of central bank forecasts with a fixed-coefficient regression, and then retain the residuals as a measure of monetary policy.[12]

[12] In this framework, the coefficient in front of the monetary policy shocks would also be time-varying.

Our aim here is to understand how the economy being in a state of low or high variance changes the strength of information effects. To this end, let us consider how the asymptotic variance of the forecast errors depends on the variance of the observational noise. The idea is to compare information effects in states of low and high noise by assuming that the economy has remained in that state for an extended period.

Proposition 2. *The asymptotic variances of the forecast errors of the Kalman filter are increasing in the noise in the private signals received by the agents, i.e.*

$$\frac{dV}{d\sigma^2_{v,z}} > 0, \qquad \frac{dW}{d\sigma^2_{v,z}} > 0, \qquad \frac{dU}{d\sigma^2_{v,z}} > 0, \tag{18}$$

and hence

$$V^H > V^L, \qquad W^H > W^L, \qquad U^H > U^L. \tag{19}$$

Proof. See Section A of the Online Appendix. □

Proposition 2 supports the intuition that, when the private agents find it harder to assess the state of the economy due to market disruptions, their assessment of the economy becomes less precise. In fact, it indicates that, all else being equal, when the economy shifts to a state of higher noise, the variances of forecast errors begin to increase towards the asymptotic values of the high-variance state. Conversely, they decrease in a transition to lower noise. The increase in the variance of forecast errors makes the public signals obtained by the central bank relatively more valuable. This intuition is developed further in the next proposition.

Proposition 3. *The information channel of monetary policy strengthens with the increase in the noise in the economy, i.e.*

$$\frac{d}{d\sigma^2_{v,z}}(K_{2,\bar{t}}(1 - K_{1,\underline{t}})) > 0, \tag{20}$$

Hence, even if one manages to cleanse the policy surprises of their endogenous component, they may still represent a measure of the policy shock scaled by a time-varying coefficient. We abstract from this aspect in this analysis.

and hence

$$K_2^H(1 - K_1^H) > K_2^L(1 - K_1^L), \tag{21}$$

where $K_1^H)$, K_1^L *and* $K_2^H)$, K_2^L *are the asymptotic values of the Kalman gains in the states of high and low variance, respectively.*

Proof. See Section A of the Online Appendix. □

This proposition is central to the empirical analysis in the remainder of this work. It predicts that, during periods of market stress and dislocation – which we interpret as periods of higher volatility in private signals – the information effects of central bank announcements become stronger, as market participants place more weight on the information contained in the central bank's signal relative to their own assessment of the economy. In the following section, we empirically test the prediction of Proposition 3, adopting a non-linear regression model based on Eq. (17).

3 Monetary policy surprises in the euro area

In this section we first provide an overview of the intraday market responses to monetary policy announcements in the euro area, as collected by Altavilla et al. (2019). We then present our methodology to construct the monetary surprises, and discuss some of the key choices in our specification. In doing so, we abstract from the correction for information effects, and postpone this discussion to the next section.

3.1 The Euro Area Monetary Policy Event-Study Database

Monetary policy decisions by the ECB are communicated to the markets in two stages, with the policy decision and a statement motivating the decision being delivered at different times. The press release, containing the main policy changes (including non-standard measures since March 2016) is released at 13.45 hours, followed by a press conference that begins at 14.30

hours, where the ECB President provides the policy committee's view on the policy decision in an introductory statement and does a question-and-answer (Q&A) session.

The standard reference for the high-frequency reactions of asset prices to monetary policy announcements is the Euro Area Monetary Policy Database (EA-MPD) that the ECB maintains on its website, and which is built using the methodology proposed by Altavilla et al. (2019). It reports the intraday price changes of several assets in two time frames on the days of policy decisions: the first is the 'press release window', and the second is the 'press conference window' that contains the President's statement and the follow up Q&A session. The sum of the two windows is called the 'monetary event window'. By looking at changes of the price of several assets in tight windows around the communications of the ECB's monetary policy decision, the EA-MPD captures the reaction of financial markets to these two connected events.

The assets covered by the dataset are the Overnight Index Swap (OIS) rates with 1, 3, 6 month and 1 to 10, 15, and 20 year maturities, German bund yields with 3 and 6 month and 1 to 10, 15, 20, and 30 year maturities, French, Italian, and Spanish sovereign yields with 2, 5, and 10 year maturities, the stock market price index and the stock price index comprising only banks, and the exchange rate of the euro.

The construction of monetary policy surprises, following Gürkaynak et al. (2005), involves two steps. First, we extract principal components from the selected intraday price changes, and then we rotate them to allow for interpretability.

3.2 Common components in intraday price changes

To extract the meaningful common components in the price changes, we consider the total effect of the announcements over several assets by summing the price changes in the press release and press conference windows. In doing this, we deviate from Altavilla et al. (2019).[13]

[13] In Section 5, we assess the empirical impact of this choice by comparing the transmission of policy shocks identified using as an IV the original factors of Altavilla et al. (2019), and the factors obtained with this approach.

Table 1: TEST OF NUMBER OF FACTORS

Press release and conference window			
Full sample (2002-2019)			
$H_0 : k = 0$	$H_0 : k = 1$	$H_0 : k = 2$	$H_0 : k = 3$
114.2679 (0.000)	98.4844 (0.000)	83.6753 (0.000)	69.8322 (0.000)

Notes: The table reports the Wald statistics and associated p-values in parentheses of Cragg and Donald (1997) testing of the null hypothesis of $k = k_0$ factors against the alternative that $k > k_0$. The full sample spans from January 2002 to December 2019. We find four statistically significant factors at 5 percent as p-values are lower than 0.05.

The rationale for the summation of the surprise is to incorporate the revisions of expectations triggered by the press conference across the yield curve, and potentially reduce noise.

In particular, in our analysis, we extract principal components from 14 times series of price changes for every ECB governing council meeting from 2002 to 2019 ($T = 197$), obtained from the EA-MPD:

- OIS risk-free rates at 1-month, 3-month, 6-month, 1-year, 2-year, 5-year and 10-year maturities;
- spreads between Italian and German treasuries at 2-year, 5-year and 10-year maturity;
- euro exchange rates against dollar, pound and yen;
- stock market (STOXX50).

In extracting the surprises, we do not remove any observation in the time period of interest.

We assess the number statistically significant factors which capture commonalities in the dataset using Cragg and Donald (1997)'s test. Results point towards the presence of four factors after summing surprises (see Table 1). The test developed by Alessi et al. (2010) also confirms the existence of four factors.[14]

[14] See Section D of the Online Appendix.

Table 2: Variance decomposition of the principal components

	1-m OIS	3-m OIS	6-m OIS	1-y OIS	2-y OIS	5-y OIS	10-y OIS
PC1	26.5031	64.2123	79.3931	83.2877	83.1267	77.4396	57.0428
PC2	0.2861	0.0013	0.0020	0.0056	0.0009	0.0350	0.0294
PC3	36.4215	25.2405	15.2288	7.3892	2.2853	0.3869	5.8950
PC4	21.8784	4.5679	0.0112	3.6473	9.3373	15.1299	19.3456
Res	14.9109	5.9780	5.3650	5.6701	5.2499	7.0086	17.6873
	2-y Spread	5-y Spread	10-y Spread	EURGBP	EURJPY	EURUSD	STOXX50
PC1	9.3464	7.0030	2.2828	51.7118	52.9622	48.8984	6.1288
PC2	69.6579	79.8489	83.0093	5.7785	0.9141	4.4933	55.4352
PC3	0.0170	2.3301	2.1786	22.9618	30.2340	31.0056	0.1039
PC4	3.2012	2.5028	2.1204	7.2968	1.8036	8.6446	13.1422
Res	17.7775	8.3152	10.4088	12.2510	14.0861	6.9582	25.1899

Notes: The table reports the Anova decomposition of the principal components of the prices revisions triggered by policy announcements. Values are in percentage.

The factor model considered is therefore of the form

$$Y = F\Lambda + \epsilon, \tag{22}$$

where Y is a $T \times 14$ matrix of surprises. F represents the matrix of principal components (or factors) which, in our case, is $T \times 4$, Λ is the loading matrix (4×14), while ϵ is a vector of idiosyncratic components ($T \times 14$). The four principal components extracted explain a large share of the variance of the assets considered (see Table 2), with some residual variance at the short and long end of the yield curve, in the stock market and the spreads. It is also worth noticing that no factor appear to be idiosyncratic or variable-specific, since they all affect most of the variable considered, albeit the second principal component mainly moves the spreads and the stock market.

3.3 Monetary policy surprises

The factors in the model in Eq. (22) are unique up to a rotation matrix U, which is our case is a 4×4 orthonormal matrix. To pin down a unique representation of the model and give interpretation to the factors, we need to specify 6 restrictions on a generic orthonormal matrix U.[15] To identify the factors we impose the following restrictions:[16]

- The first factor is the only factor that loads on short-term, i.e. all the other factors have zero effect on 1-month OIS.
- The variance of the third and fourth factor are minimal before the financial crisis (i.e. August 2008).[17]
- The fourth factor has zero impact on 10-year OIS.

The first assumption is the standard assumption of Gürkaynak et al. (2005) that allows to identify a target factor (F1) that relates to conventional monetary policy being the only factor moving the short end of the yield curve. The second assumption is in line with the approach proposed by Swanson (2021) to identify a QE/QT factor that relates to unconventional monetary policy in the form of quantitative easing/tightening and possibly changes to risk premia triggered by the policy communication. In our approach this assumption separates two factors (F3, F4) from the others.

The last assumption disentangle the QE/QT factor affecting the long end of the risk free yield curve, from a factor, which we call asymmetric country risk factor (F4). It appears in the euro area after the financial crisis but does not move the long end of the OIS curve, hence it is different from QE for macroeconomic stability. We consider this factor as related to asymmetric increases in the risk premia between core and periphery countries in the euro area. In doing so, we take an approach similar in spirit to Reichlin et al. (2022) and Motto and Özen (2022), which we discuss in detail later. However, it is important to note that we

[15]The condition of orthonormality, $U'U = UU' = I$, imposes n(n+1)/2 restrictions, which corresponds to 10 restrictions for $n = 4$. Hence, the space of orthonormal matrices of dimension n has $n(n-1)/2$ free parameters.

[16]Additional details about the identification of the factors are reported in Appendix C.

[17]Since the 2007 financial crisis, the ECB began adopting various unconventional monetary policy measures. The first of these were long-term refinancing operations (LTROs), aimed at providing emergency liquidity to the financial system. These were followed in September 2014 by targeted longer-term refinancing operations (TLTROs), designed to stimulate bank lending to the real economy. The ECB's first explicitly defined quantitative easing program with a focus on price stability, the asset purchase programme (APP), was launched in March 2015. Further details are provided in Section M of the Online Appendix.

impose no restrictions on government spread surprises. Hence, the fact that one of the factors capture spread dynamics is a feature of the data, and of the policy problem of the euro area.

To understand the rationale for this factor, one has to observe that monetary policy in all jurisdictions is about steering the yield curve via a variety of tools. In the euro area, the ECB faces an extra dimension to monetary policy since the policies which affect the common risk-free yield curve (typically proxied by the OIS curve) may differentially affect the risk premia associated with country-specific yield curves (countries face their own default risks), adding a second dimension to the policy problem (see discussion in Reichlin et al., 2022). In fact, a feature of the euro area is that, in bad times, there can be a flight to safety dynamics with investors moving to German bonds and away from the periphery countries' government bond markets (see, among others, Beber et al., 2008 and Costantini and Sousa, 2022)

Finally, the assumptions identify, by orthogonality to the others, a factor that by constructions moves the mid segment of the yield curve and hence relates to information about the path of monetary policy, i.e. a forward guidance factor (F2), potentially both conditional on the expected macro development and unconditionally to them (i.e. Delphic and Odyssean forward guidance as labelled by Campbell et al., 2012). The variance of the asset considered that is explained by the identified factors is reported in Table 3.

Figure 3 plots the time series of the identified factors, with vertical lines marking important events in the euro area. [18] In Figure 4, instead, we report the loadings of of the factors (i.e. Λ in Equation 22) on different assets' price revisions. On the x-axis we plot the different market surprises, and on the y-axis we report the magnitude of the loadings by normalising the peak impact of the four factors on the 1-month, 2-year, 10-year, and 10-year spread, respectively, to one.

The target factor (blue) is by construction the only factor with loading different from zero on the 1-month rate, with a slowly decaying pattern of loading over increasing maturities. The flattening of the yield curve induced by this factor is typical of conventional monetary

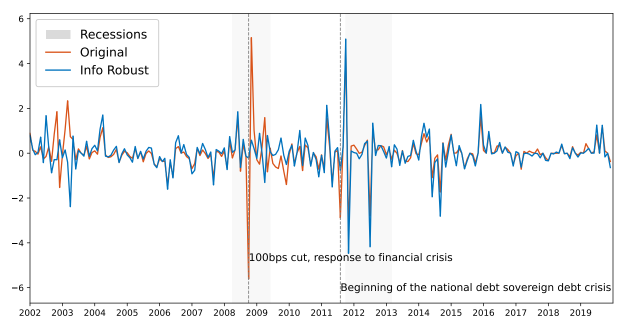
[18] Details on the largest surprises are provided in Section L of the Online Appendix.

Table 3: Variance decomposition of the factors

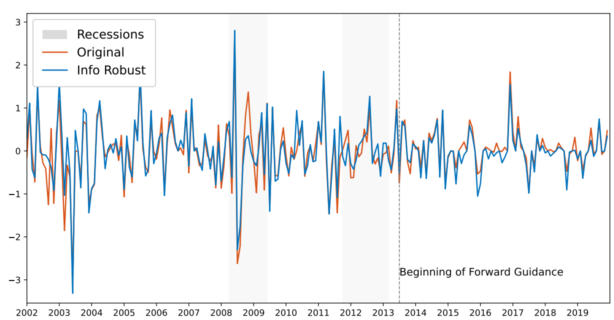
	1-m OIS	3-m OIS	6-m OIS	1-y OIS	2-y OIS	5-y OIS	10-y OIS
F1	85.0891	78.2336	57.4888	34.7983	20.4873	6.4657	0.1651
F2	0.0000	10.6786	26.1526	43.7926	52.8031	52.7025	44.0776
F3	0.0000	4.8871	10.8581	15.6165	21.3997	33.8224	38.0701
F4	0.0000	0.2226	0.1356	0.1225	0.0600	0.0009	0.0000
Res	14.9109	5.9780	5.3650	5.6701	5.2499	7.0086	17.6873
	2-y Spread	**5-y Spread**	**10-y Spread**	**EURGBP**	**EURJPY**	**EURUSD**	**STOXX50**
F1	4.1785	0.5811	0.0077	5.6998	1.4414	3.5097	11.8386
F2	0.2405	0.0244	0.0624	0.0666	0.7157	0.5335	6.1445
F3	2.6377	5.0434	1.9661	80.0959	83.7552	87.9149	10.3712
F4	75.1659	86.0359	87.5550	1.8867	0.0016	1.0838	46.4558
Res	17.7775	8.3152	10.4088	12.2510	14.0861	6.9582	25.1899

Notes: The table reports the Anova decomposition of the identified factors. Values are in percentage.

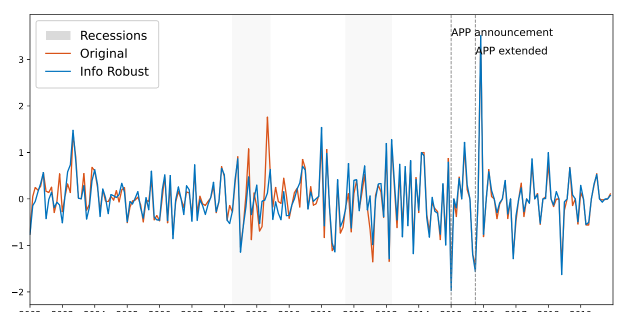
Figure 3: Identified and informationally corrected factors.



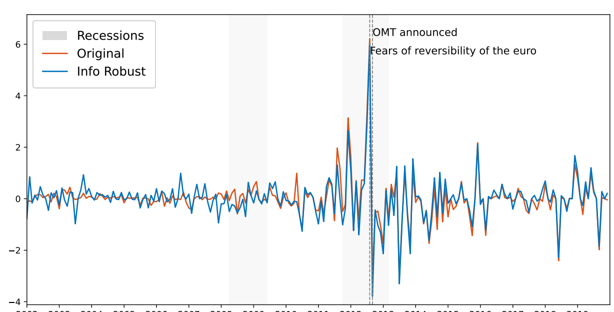
(a) Target



(b) Forward guidance



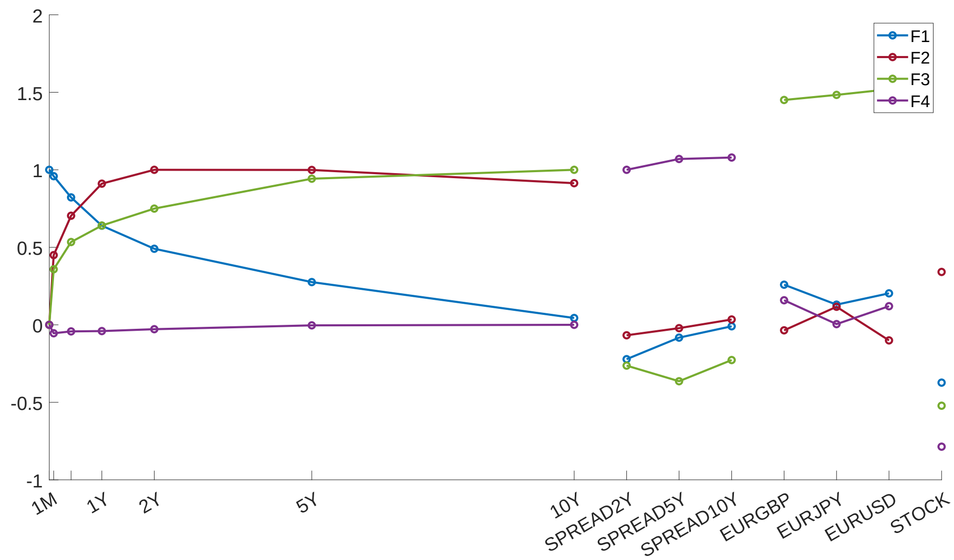
(c) QE



(d) Asymmetric country risk

Notes: The figure plots the identified factor extracted without any correction for information effects, and the identified factor after the orthogonalisation of price surprises, obtained using the regression specification for non-linear information effects. Details on the largest surprises are provided in Section L of the Online Appendix.

Figure 4: LOADINGS FOR THE IDENTIFIED FACTORS



Notes: The figure reports the loading of the identified factors on the market surprises. F1 (in blue) loads primarily on short-term surprises. F2 (in red) loads on medium-term surprises. F3 (in green) has its largest effect on OIS-10y and F4 (in purple) loads on the markets surprise describing the variation in spread between Italian and German government bonds. In this figure, the market surprises are not corrected for information effects.

policy. The forward guidance factor (in red) loads mostly on medium-term maturities (2-year to 5-year OIS with a sizeable effect on longer maturities). These two factors have also a limited effects on governments spreads (mostly negative) and exchange rates (mostly positive). While the target factor has a negative impact on the stock market, the forward guidance factor has a positive effect. This is potential indication of a dominant information component in the forward guidance factor, following the intuition proposed by Jarociński and Karadi (2020). We shall discuss this point in the next section.

The QE factor (green) has the largest positive effect on 10-year OIS and exchange rates while it displays negative coefficients on government spreads and the stock market. Even if some of the government yields variation is captured by the asymmetric country risk factor, QE has still a sizeable effect on those surprises by moving spread and risk-free rates in opposite direction.

The asymmetric country risk factor (purple) has almost zero effect on the yield curve and highest coefficients on government spread and stock market surprises. Consistently with our

Table 4: Assumptions to identify factors

	Sample	Ex. Dates	Assets	Std	Info	# Factors	Assumptions
Altavilla et al. (2019)	Jan2002 to Aug2018	8-Oct-2008 4-Nov-2008	1, 3, 6-month OIS 1, 2, 5, 10-year OIS	No	No	1 press release	$\Lambda_{F2,OIS-1m} \equiv 0$ $\Lambda_{F3,OIS-1m} \equiv 0$ $F2$, $F3$ dropped
						3 press conf.	$\Lambda_{F2,OIS-1m} \equiv 0$ $\Lambda_{F3,OIS-1m} \equiv 0$ $min_{t<Aug2008} var(F3)$
Motto and Özen (2022)	Jan2002 to Jun2020	8-Oct-2008 4-Nov-2008	1, 3, 6-month OIS 1, 2, 5, 10-year OIS 2, 5, 10-year ESP 2, 5, 10-year FRA 2, 5, 10-year ITA	No	No	4 press conf.	$\Lambda_{F2,OIS-1m} \equiv 0$ $\Lambda_{F3,OIS-1m} \equiv 0$ $\Lambda_{F4,OIS-1m} \equiv 0$ $min_{t<Aug2008} var(F3)$ $min_{t<Apr2010} var(F4)$ $min_{t\in[Jan2013,Dec2019]} var(F4)$ $\Lambda_{F4,ITA-5y} \times \Lambda_{F4,OIS-5y} \leq 0$
This work	Jan2002 to Dec2019	none	1, 3, 6-month OIS 1, 2, 5, 10-year OIS 2, 5, 10-year ITA-DEU FX rate EUR-USD FX rate EUR-GBP FX rate EUR-JPY stock mkt STOXX50	Yes	Yes	4 press release + press conf.	$\Lambda_{F2,OIS-1m} \equiv 0$ $\Lambda_{F3,OIS-1m} \equiv 0$ $\Lambda_{F4,OIS-1m} \equiv 0$ $min_{t<Aug2008} var(F3)$ $min_{t<Aug2008} var(F4)$ $\Lambda_{F4,OIS-10y} \equiv 0$

Notes: The table compare the main empirical choices in estimating the monetary policy surprises proposed in this work with the ones of Altavilla et al. (2019) and Motto and Özen (2022). In one of the many robustness exercises proposed about the identification assumptions, Motto and Özen (2022) impose that F4 has zero impact on both the 5y and 10y OIS rates, similarly to what done in this work.

interpretation, we find a dimension orthogonal to conventional and unconventional monetary policy that has almost zero effect on risk-free rates and influences positively the spread between Italian and German bond yield and negatively the stock market.

Before discussing the presence of information effects in the market surprises in the next section, in the reminder of this section we detail the differences between our approach and other approaches in the literature and the potential empirical implications.

3.4 Comparison with other approaches

The approach we detailed in this section diverges from Altavilla et al. (2019) in several aspects, which are potentially of importance (see Table 4 for a summary). Let us highlight the four main ones.

The assets considered. In addition to considering market surprises in risk-free rates across various maturities, ranging from 1 month to 10 years as in Altavilla et al. (2019), we also incorporate in our analysis surprises to the spreads between Italian and German treasury bonds, exchange rates, and the stock market index. By considering surprises to spreads, we want to capture the potentially divergent dynamics between core and periphery countries, which is a defining characteristic of the policy problem in the euro area that was particularly in evidence during the European sovereign debt crisis. In doing so, we follow the same intuition proposed by Reichlin et al. (2022) and Motto and Özen (2022).

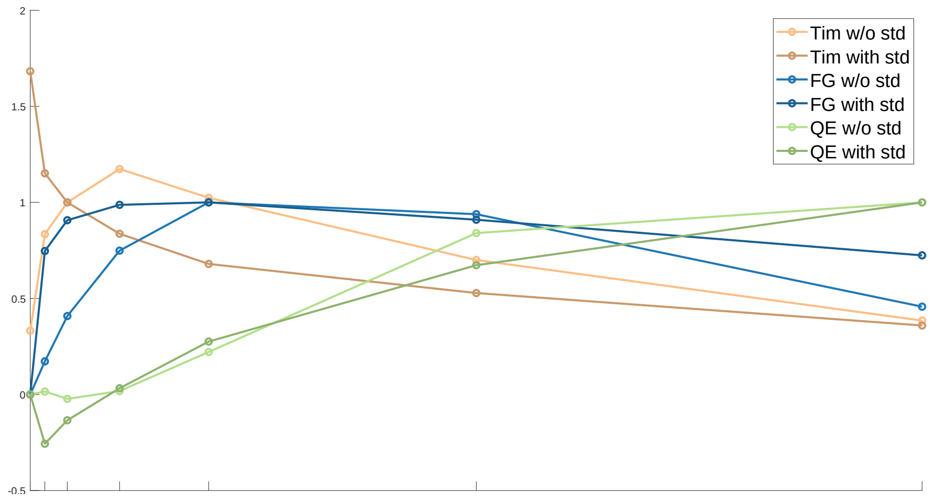
The introduction of the stock market is potentially relevant to 'sign' the response of the markets to each of the factor extracted, which is key in the approach proposed by Jarociński and Karadi (2020) to disentangle information effects from policy shocks. It is interesting to observe that all factors bar F2 have a negative correlation between the response of the stock market and the factors.[19]

The exchange rates do not play a decisive role, with their reactions to the announcements being well captured by a rather standard number of monetary surprises. In fact, their presence in the analysis does not show the presence of an additional dimension of the policy communication. This in line with the declared objective of the ECB, which does not target the exchange rates. However, it is interesting to observe that conventional monetary policy affects exchange rates less than changes to long-term yields.

The windows. Differently from Altavilla et al. (2019) and Motto and Özen (2022), that consider separately the press release and the press conference windows, we sum the surprises in the two windows. Altavilla et al. (2019) extract a target factor that captures surprises on the setting of the policy rates during the press release window, and a timing factor that incorporate revisions of expected policy changes from the current meeting to the next or the following one using the press conference window. These two factors are obtained by requiring

[19]As showed in the rest of the paper, F2 has a strong information content, in line with the intuition proposed by Jarociński and Karadi (2020).

Figure 5: The role of standardisation



Notes: The figure reports the loadings for the factors obtained with the procedure of Altavilla et al. (2019), where the price revisions are only demeaned and compares them with the loading obtained when the dataset is standardised before the PCs are obtained.

that they are the only factors moving the short end of the yield curve.[20]

Our approach to summing the two policy windows is potentially helpful in reducing the noise in the market reaction to the press release and capture the corrections that are triggered by market participants revising and updating their views during the press conference window. This is particularly important in the presence of information effects, which would also affect the first factor (target). It is interesting to observe that the test on the number of factors present in the sum of the two window only signal four factors, with one capturing movements at the short end of the yield curve.

The standardisation of the price revisions. There is an additional specification in our approach which has bearing for the short term factors: the standardisation of the price revisions. In the original work of Altavilla et al. (2019) the price revisions were only demeaned and not standardised before extracting the principal components.

Figure 5 plots the loadings of the factors identified from the Overnight Index Swap (OIS) surprises in the press conference window with price revisions on maturities spanning from 1

[20]The other factors, which are not significant for the press release window, in the analysis of Altavilla et al. (2019) are discarded.

month to 10 year, as in Altavilla et al. (2019). Let us focus on the timing factor (orange and brown lines), which is obtained as the only factor that loads on the 1-month OIS rate.

The timing factor in orange is obtained by only demeaning the price revisions as in Altavilla et al. (2019). This factor peaks on the 1-year OIS rate (normalised to one), with a normalised value below 0.5 for 1-month OIS. This pattern of responses across maturities allows for an interpretation of it as capturing revisions of expectations about the next policy rounds.

The factor in brown, is the corresponding factor but obtained under the same assumptions, and from the same assets, from PCs extracted from the standardised price revisions.[21] It displays a pattern of loadings comparable to the target factor extracted from the press release window.[22] This evidence suggests that, beyond being important for monetary policy surprises regarding the future path of monetary policy, the press conference window also contain information about the short-term policy expectations, which support our choice to consider the total effects of the two policy events.

The asymmetric country risk factor. This factor is additional to the ones discussed in Altavilla et al. (2019). As mentioned, it follows the intuition proposed by Reichlin et al. (2022), and is close to the market stabilisation QE factor of Motto and Özen (2022). Differently from Motto and Özen (2022), we do not directly impose restrictions on the European sovereign debt crisis, nor on the sovereign yield curves but only on the OIS rates. The effects of our F4 on the spreads is hence a result and not an assumption.[23]

[21]PCA criterion is based on the variance of the matrix which is not a scale-invariant measure. That is why it is generally recommended to standardise the data before extracting PCs (see for instance Hastie et al., 2009).

[22]Figure E.5 in Appendix E provides a similar exercise comparing the target factor obtained in the press release window standardising the data with the one obtained from demeaned data.

[23]In one of the many robustness exercises proposed about the identification assumptions, Motto and Özen (2022) impose that F4 has zero impact on both the 5y and 10y OIS rates, similarly to what done in this work.

4 Information effects in the euro area

The literature on monetary policy in the United States has pointed to the presence of information effects in monetary surprises as the source of puzzles in the dynamic responses of macro variables obtained when using those as instrumental variables for the identification of policy shocks (see, for example, Jarociński and Karadi, 2020; Miranda-Agrippino and Ricco, 2021). To control for this effects and isolate the effects of policy, the most common approaches are to use the differences in the co-movements of the yield curve with the stock market conditional on policy and demand shocks, as proposed by Jarociński and Karadi (2020), or to use the central bank's or others' forecasts about the economic conditions and pre-dating the policy decision, as discussed in Miranda-Agrippino and Ricco (2021).[24]

In this work, and in line with the predictions of the model presented in Section 2, we follow an approach similar to the one proposed by Miranda-Agrippino and Ricco (2021) to control for information effects, but with some important differences.

4.1 Linear and non-linear information effects

Instead of employing only the central bank's pre-meeting forecast as Miranda-Agrippino and Ricco (2021), we consider both the ECB's and professional forecasts. The forecasts produced by the ECB considered are quarterly projections for GDP and inflation.[25] We supplement these forecasts, that can be stale with respect to the information set of the policymakers at the moment of the policy decision, with the pre-meeting monthly polls from Reuters, on inflation, GDP and the MRO policy rate (main refinancing operations rate) and which consist of quarterly and annual growth rates forecasts. While the use of the private sector forecasts

[24]Bauer and Swanson (2023) propose a related approach, consisting of regressing monetary policy surprises onto past financial variables. While they suggest an interpretation of the information effects as due to market participants' forecast model being based on a misspecified Taylor rule, from the point of view of the correction of the surprises their approach and predictions are equivalent to those of Miranda-Agrippino and Ricco (2021).

[25]The forecasts are produced before but published after the monetary policy meetings of the Governing Council (in March, June, September and December), and disseminated in the form of a projections article on the ECB's website. We retrieve them from the Macroeconomic Projection Database (MPD) of the ECB.

may seem surprising in dealing with information effects in central bank communication, it is in fact fully in line with the predictions of Proposition 1, and in particular of Eq. (17). They show that private forecast revisions are correlated with past private forecasts, as well as with any variable, be it forecasts or financial variables, capturing both lagged and current structural shocks. This observation provides justification for our approach, given the limitations of the ECB's forecasts. Let us finally observe that the use of the Fed's Greenbook forecasts is convenient since they provide a simple and direct measure of the central banks' expectations, and provides a clear test of the information effects since the forecasts are not published for five years. However, in the framework dispersed information presented in Section 2, it is not strictly speaking necessary and other variables can be adopted.

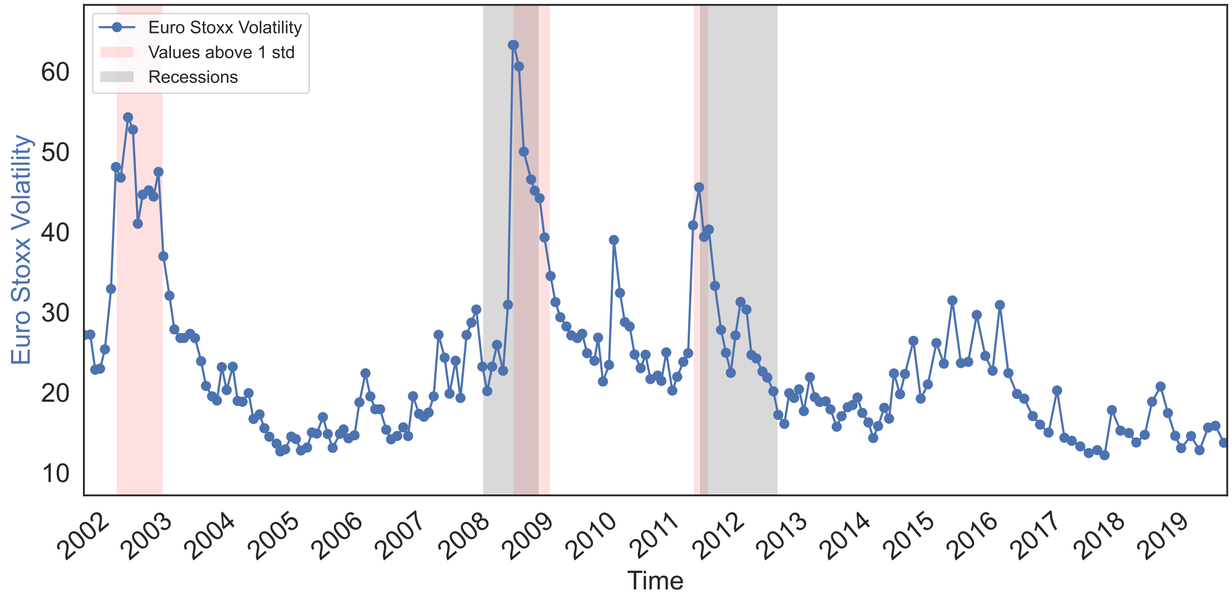
In dealing with information effects on the whole yield curve and other assets and not only one maturity, we operate in two steps. First, we project the price revisions of each single asset we consider – the risk-free yield curve, the government spreads, the exchange rates and the stock market – on the ECB's and Reuters' forecast and forecast revisions to obtain residuals that are orthogonal to economic shocks other than policy. Then, we extract the monetary policy factors using the restrictions detailed in the previous section from the residuals of these 'information' regressions.

In controlling for information effects, we consider two OLS regression specifications, both at ECB governing council meeting's frequency. The first is a linear regression, of the form

$$ms_t^i = \beta_0 + \sum_{j=0}^{J} \theta_j^i F_t x_{q+J} + \sum_{j=0}^{J-1} \eta_j \Delta F_t x_{q+j} + \widetilde{ms}_t^i \tag{23}$$

where ms_t^i (i.e. the monetary surprises) are the price revisions of the assets i in the monetary window related to the governing council meeting at t. $F_t x_{q+j}$ denotes the forecast for variable x at horizon $q+j$, while and $\Delta F_t x_{q+j} = F_t x_{q+j} - F_{t-1} x_{q+j}$ denotes revisions to forecasts between consecutive ECB meetings. The index j represents the period j to which the forecast refers i.e. one period ahead, two periods ahead, and so on. $\widetilde{ms}_t^i$ is the residual of the regression

Figure 6: VSTOXX index and dates selected



Notes: Dates for which the value of the Euro Stoxx Volatility index (blue) is one standard deviation above its average are marked by the vertical light red bars. The vertical grey bars are the recessions dates for the euro area, as defined by the CEPR-EABCN Euro Area Business Cycle Dating Committee.

and represents the informationally robust monetary policy surprises. As mentioned, we run a separate regression for every asset we consider: risk-free rates, government spreads, exchange rates, and the stock market.

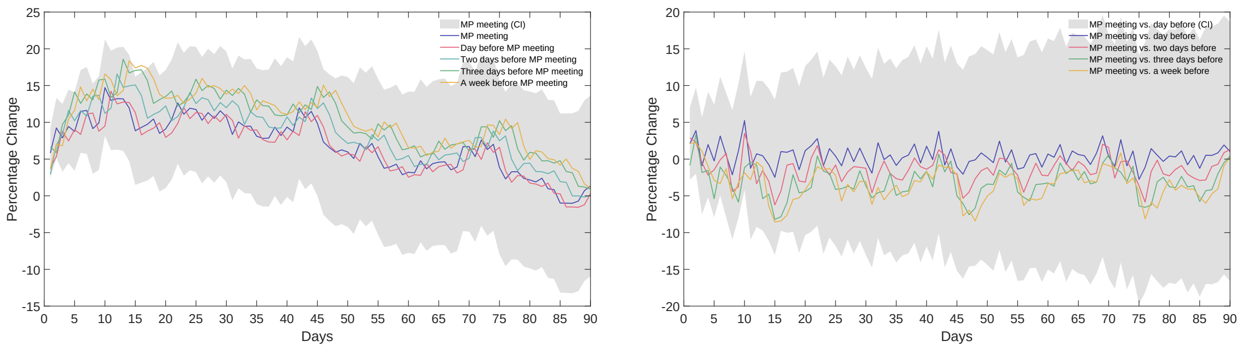
The second specification is a non-linear threshold regression of the form

$$\begin{aligned} ms_t^i =& \beta_0 + \sum_{j=0}^{J} \theta_j F_t x_{q+J} + \sum_{j=0}^{J-1} \eta_j \Delta F_t x_{q+j} \\ &+ I(S_t > \bar{s}) \left[\sum_{j=0}^{J} \kappa_j F_t x_{q+J} + \sum_{j=0}^{J-1} \psi_j \Delta F_t x_{q+j} \right] + \widetilde{\widetilde{ms}}_t^i \end{aligned} \tag{24}$$

where $I(S_t > \bar{s})$ is a Heaviside step function that takes value one when an indicator of market stress, S_t, is above the threshold, $\bar{s}$. We interpret the residuals of these second regression, i.e. $\widetilde{\widetilde{ms}}_t^i$, as a measure of monetary policy shocks corrected for non-linear information effects.

This second regression specification tests the predictions of Proposition 3 obtained from of the model presented in Section 2. When there is a state of high stress and dislocation

Figure 7: The impact of monetary policy announcement on VSTOXX



(a) Local projections of VSTOXX

(b) Differences between LPs

Notes: Panel (a) presents local projection IRFs of the daily VSTOXX index during periods of high volatility for (i) a dummy variable set to one on the days of monetary policy announcements and (ii) placebo dummies set to one on the day before, two days before, three days before, and one week before the policy announcement. Panel (b) shows the differences between the IRFs for the placebo dates and for the actual monetary policy announcement date.

on the financial markets, which can be thought of as an increase in the noise in the private signals obtained by market participants, the model predicts information effects to be stronger. In fact, in such a state private agents update more their expectations towards the public signal delivered by the central bank with its monetary policy decision. This is possible a salient characteristic of the euro area, that was in evidence during the period spanned by the financial crisis and the subsequent sovereign debt crisis, and later during the COVID crisis.

To capture these conditions, we consider an index of stock market volatility in the euro area (VSTOXX) as indicator of market stress, and we set the threshold level as one standard deviation above this index's mean (Figure 6).[26] The chart reports the time series of the VSTOXX index from 2002 to 2019, with the recession bands for the euro area, and in light blue the periods selected by our indicator. From Figure 6, it is clear that the indicator does not simply coincide with the recession indicator, but instead it captures moments of turbulence on the markets not necessarily associated to the two large recessions in the sample.

A potential concern is the endogeneity between observed high stock market volatility and

[26] Varying this threshold within large limits does not lead to different results in terms of both information effects and the transmission of monetary policy shocks. This is due to the clear non-linear nature of this index with very localised spikes above its average level.

monetary policy decisions – some of which may have disappointed or even caused panic in the market during crisis periods. Figure 7 addresses this concern by showing that during high-volatility periods, ECB's monetary policy decisions were not the primary cause of market volatility. Figure 7a reports local projections of the daily VSTOXX index during high-volatility periods for (i) a dummy variable set to one on the days of monetary policy announcements, and (ii) placebo dummies set to one on the day before, two days before, three days before, and one week before the policy announcement. While stock market volatility tends to increase following a monetary policy announcement, this is not due to the decision itself, as the response to placebo dummies preceding policy decisions follows a similar pattern. Indeed, the differences between the IRFs for the announcement dummy and the placebo dummies are not statistically different from zero, as shown in Figure 7b.

4.2 Information robust monetary surprises

Table 5 reports the results of the nonlinear regression specification in Eq. (24) for the OIS curve. It reports the adjusted R^2 of the regressions, as a measure of predictability of the surprises and, as a reference, the adjusted R^2 of the related linear specification. Results for the spreads, the exchange rates and stock market surprises are reported in Section G of the Online Appendix, along with the results of the linear regression specification in Eq. (23). Let us here summarise some noteworthy findings.

Overall, the results confirm the predictions of the model: both the linear and the threshold regression models indicate predictability in the monetary policy surprises, in line with the presence of imperfect information. While many of the regressors are correlated, making the interpretation of their coefficients not straightforward, many of them are significant. Similarly, to what reported by Miranda-Agrippino and Ricco (2021) for the U.S., the linear information regression explains around seven per cent of the surprises on the yield curve, and mainly at short horizon and as related to forecast and forecast revisions in the current quarter. This confirms a key prediction of the model, and indicates that the information at short term is

Table 5: PROJECTION OF YIELD CURVE SURPRISES ON FORECASTS - NON-LINEAR SPECIFICATION

	(1) 1m-OIS b/(se)	(2) 3m-OIS b/(se)	(3) 6m-OIS b/(se)	(4) 1y-OIS b/(se)	(5) 2y-OIS b/(se)	(6) 5y-OIS b/(se)	(7) 10y-OIS b/(se)
$MRO_{q=0}$	-0.041	0.041	0.039	0.039	-0.009	0.288	0.234
	(0.128)	(0.245)	(0.328)	(0.438)	(0.458)	(0.492)	(0.280)
$\Delta MRO_{q=0}$	1.300	0.827	0.260	0.558	0.727	2.536	2.817*
	(1.468)	(1.698)	(1.827)	(2.508)	(2.888)	(2.727)	(1.550)
$HICP_{q=1}$	-0.227	0.430	0.210	0.039	-0.610	-1.131	0.257
	(0.500)	(0.920)	(1.196)	(1.558)	(1.705)	(1.702)	(1.304)
$GDP_{q=0}$	-1.769**	-1.582	-2.106	-2.312	-1.020	1.330	1.116
	(0.691)	(1.362)	(1.767)	(2.377)	(2.580)	(2.374)	(1.770)
$GDP_{q=2}$	0.543	0.539	1.420	1.923	1.001	-1.027	-1.752
	(1.259)	(1.724)	(2.410)	(3.642)	(4.079)	(3.893)	(2.832)
$GDP_{y=0}$	0.402***	0.406*	0.388	0.338	0.205	0.047	-0.071
	(0.119)	(0.212)	(0.255)	(0.334)	(0.404)	(0.383)	(0.313)
$HICP_{y=0}$	0.195	-0.161	-0.389	-0.736	-0.997	-0.318	-0.555
	(0.445)	(0.699)	(0.853)	(1.154)	(1.351)	(1.407)	(1.094)
$HICP_{y=1}$	-1.105	-1.976	-1.098	-0.857	-0.047	-1.045	-1.953
	(1.134)	(1.588)	(1.965)	(2.458)	(2.688)	(2.517)	(1.969)
$\Delta HICP_{y=0}$	-0.251	-0.435	0.047	0.200	0.062	-0.206	0.927
	(0.401)	(0.644)	(0.883)	(1.315)	(1.501)	(1.516)	(1.200)
$HICP^{ECB}_{q=0}$	0.765	0.185	0.776	1.648	2.963	3.116	1.693
	(0.719)	(1.159)	(1.569)	(2.213)	(2.482)	(2.484)	(1.872)
$\Delta HICP^{ECB}_{q=0}$	-0.236	-0.179	-0.808	-0.803	-0.819	0.094	0.609
	(0.496)	(0.725)	(0.958)	(1.223)	(1.417)	(1.540)	(1.341)
$GDP^{ECB}_{y=0}$	-0.017	-0.036	0.024	0.116	-0.099	-0.291	-0.097
	(0.167)	(0.231)	(0.302)	(0.408)	(0.510)	(0.466)	(0.375)
$HICP^{ECB}_{y=0}$	-0.704	0.149	-0.205	-0.738	-1.803	-2.007	-1.005
	(0.733)	(1.308)	(1.785)	(2.486)	(2.737)	(2.678)	(1.938)
$I(index) * MRO_{q=0}$	-1.464	-1.358	-1.890	-2.199	-2.441	-1.337	0.026
	(3.397)	(2.381)	(2.419)	(2.846)	(2.833)	(1.904)	(1.038)
$I(index) * \Delta MRO_{q=0}$	-19.280***	-13.417***	-11.415***	-8.849**	-4.933	-2.898	-0.139
	(4.241)	(3.237)	(3.291)	(3.963)	(4.269)	(3.859)	(2.325)
$I(index) * HICP_{q=1}$	-17.588	-21.621***	-26.495***	-30.821**	-28.333**	-12.170	-0.498
	(10.985)	(8.011)	(9.442)	(12.346)	(13.093)	(9.228)	(4.513)
$I(index) * GDP_{q=0}$	0.715	-0.853	0.856	0.916	-1.669	-6.155	-5.705
	(3.313)	(5.107)	(6.621)	(8.393)	(8.742)	(7.007)	(3.794)
$I(index) * GDP_{q=2}$	19.357	20.797**	17.006	19.408	22.567	29.849**	17.497**
	(12.599)	(10.108)	(12.113)	(15.378)	(15.522)	(12.957)	(7.658)
$I(index) * GDP_{y=0}$	3.438	3.190**	4.453**	4.814*	3.772	-1.417	-2.776**
	(2.431)	(1.613)	(1.941)	(2.533)	(2.673)	(2.060)	(1.121)
$I(index) * HICP_{y=0}$	6.536	12.759**	15.931**	20.259***	22.396***	17.404***	8.086***
	(8.059)	(6.305)	(6.385)	(7.363)	(7.647)	(5.330)	(2.712)
$I(index) * HICP_{y=1}$	4.950	1.925	4.242	3.195	-0.948	-11.591*	-10.495***
	(5.454)	(4.683)	(6.148)	(8.067)	(8.344)	(6.917)	(3.721)
$I(index) * \Delta HICP_{y=0}$	8.604***	5.543***	4.428**	2.682	-0.295	-2.122	-3.004*
	(2.176)	(1.752)	(1.994)	(2.527)	(2.684)	(2.486)	(1.694)
$I(index) * HICP^{ECB}_{q=0}$	15.764***	16.926***	11.410**	9.568	4.719	7.224	5.003
	(4.083)	(3.625)	(4.817)	(6.525)	(7.617)	(5.926)	(3.131)
$I(index) * \Delta HICP^{ECB}_{q=0}$	-19.273***	-12.577***	-6.273*	-2.476	3.777	1.964	0.996
	(5.492)	(3.987)	(3.673)	(4.002)	(4.806)	(4.179)	(2.650)
$I(index) * GDP^{ECB}_{y=0}$	9.646**	7.039**	2.127	0.013	-3.609	-0.716	1.265
	(4.150)	(2.942)	(2.828)	(3.202)	(3.732)	(2.929)	(1.653)
$I(index) * HICP^{ECB}_{y=0}$	-19.804***	-20.679***	-13.322**	-11.058	-4.931	-8.505	-6.505*
	(5.470)	(4.132)	(5.150)	(6.955)	(8.284)	(6.737)	(3.645)
Constant	1.777	2.443	1.406	1.597	1.627	2.948	3.284
	(1.484)	(1.986)	(2.518)	(3.123)	(3.345)	(3.255)	(2.445)
$\mathcal{R}^2_{adj}$	0.468	0.306	0.199	0.104	0.066	0.024	0.015
N	197	197	197	197	197	197	197
Linear Info – $\mathcal{R}^2_{adj}$	0.074	0.057	0.060	0.023	0.017	0.008	0.015

Notes: The table reports regression results for a test of non-linear information effects along the yield curve surprises. We also report, for references, the adjusted R^2 for the linear specification.

more salient in forecasting the policy surprises. The explanatory power of the regressors for the other assets is limited, possibly indicating a larger role for changes in risk premia.

The R^2 of the nonlinear specification, explains a much larger share at short maturities but a similar share at longer ones (Table 5). This confirms the prediction of the model in terms of stronger information effects in phases of market stress. The coefficients on the forecast of GDP are generally positive, as well as the coefficients on the inflation forecast, with some exceptions. Overall this is in line with the model predictions – despite having many collinear regressors. Interestingly, past revisions to forecasts of the MRO appear with a negative signs, as is the coefficient of past monetary policy shocks in Eq. (17) of Proposition 1.[27]

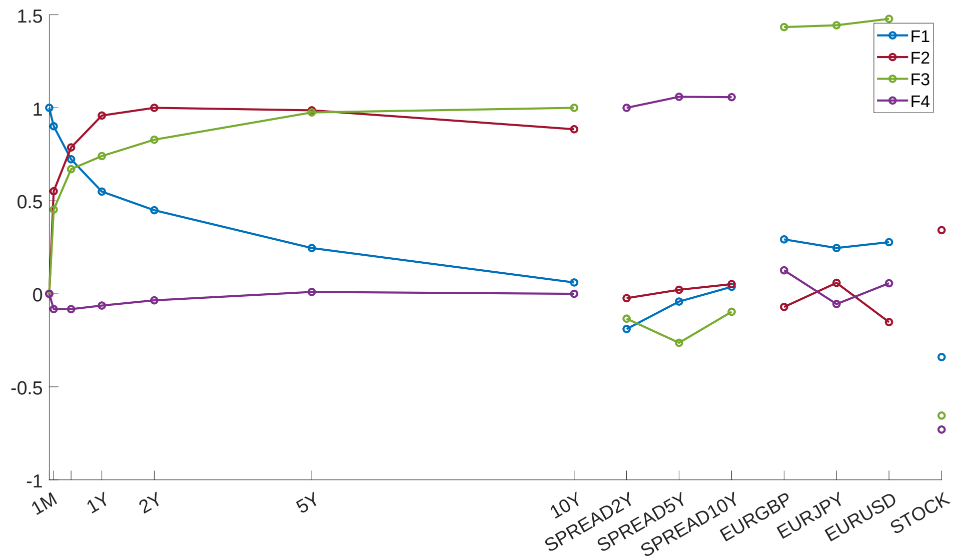
4.3 Informationally robust IVs for monetary policy

The informationally robust policy factors we adopt in our benchmark specifications are obtained from the residuals of the regressions employing the restrictions described in the previous section. Figure 3 reports the times series of these factors along with the factors obtained before the information correction, while Figure 8 plots their loadings. The interpretation for each factor is the same as the one that we have when we extract factors without information effects, and their magnitude remains very similar. This shows that the convolution of structural shocks to which the ECB responds, and that determines the information effects, appears as an unspanned 'information factor' in the data.

In particular, the target factor (i.e. conventional monetary policy) loads more strongly on the short-term rates with declining weights over the yield curve, with a positive impact on the exchange rates and a negative impact on the stock market. The forward guidance factor has the largest weight on the medium maturities, while a tightening in the QE factor lifts the end of the yield curve, has a large positive impact on the exchange rates and a large negative

[27]Results are robust both in terms of the properties of the residuals of the non-linear regressions, and of the macroeconomic effects obtained from the IV thus obtained. In Section G of the Online Appendix, we report results obtained with a larger set of regressors and a LASSO or RIDGE regression specification. The information effects for longer maturities of the yield curve are stronger, as compared to the baseline results (the adjusted R^2 for the 10y-OIS exceeds 11%). However, the impact of these on the IRFs obtained in an identified VARs using the IVs obtained from residuals of the regressions is marginal.

Figure 8: LOADINGS WITH NON-LINEAR INFORMATION EFFECTS



Notes: The figure reports the loading of the identified factors on the market surprises. F1 (in blue) loads primarily on short-term surprises. F2 (in red) loads on medium-term surprises. F3 (in green) has the largest effect on OIS-10y, and F4 (in purple) loads on the changes of the spread between Italian and German government bonds triggered by the announcements. In this figure, the market surprises are obtained after controlling for non-linear information effects.

impact on the stock market. The asymmetric risk factor has no effect on the OIS curve but strongly affects country spreads.

5 Policy shocks and information

This section discusses the macroeconomic propagation of the four monetary shocks that are identified by the information robust IVs we proposed: conventional monetary policy, forward guidance, quantitative easing/tightening and country risk shocks. We identify these structural shocks in a rich VAR model with the external IV approach of Stock and Watson (2012) and Mertens and Ravn (2013), which is valid under mild conditions of relevance and exogeneity, and the invertibility of the shocks of interest for the model adopted (see Miranda-Agrippino and Ricco, 2023).

For each shock, we estimate a monthly Bayesian VAR with 12 lags and standard Minnesota priors, on the sample 2001 to 2019. The informativeness of the priors is set following Giannone et al. (2015). Our baseline specification includes a rich set of real, nominal and financial variables. We choose industrial production including construction (IPC) and a measure of real GDP as proxies for economic activity in the euro area. We use non-seasonally adjusted series for core inflation (CoreEA) and headline inflation (HICPEA), together with GDP deflator as indicators of the price dynamics in the euro area.[28] The VAR also include the Euro STOXX50 as a measure of the stock market, different maturities of risk-free rates (OIS) going from 1 month to 10 years, and the euro to dollar (€/$) exchange rate. All variables, with the exception of rates, are in log-levels.

For the four shocks, we compare the impulse response functions (IRFs) obtained using as IVs the factors that are extracted from market surprise (in amber), and those obtained from those by correcting for non-linear informationally effects (in blue). We consider IRF over a horizon of 24 months. As we discuss later, while using as IVs the factors obtained from the market price changes deliver responses with several puzzles, notably for prices, output and the stock market, the information-robust IVs offers dynamic response in line with the expected effects of monetary policy.

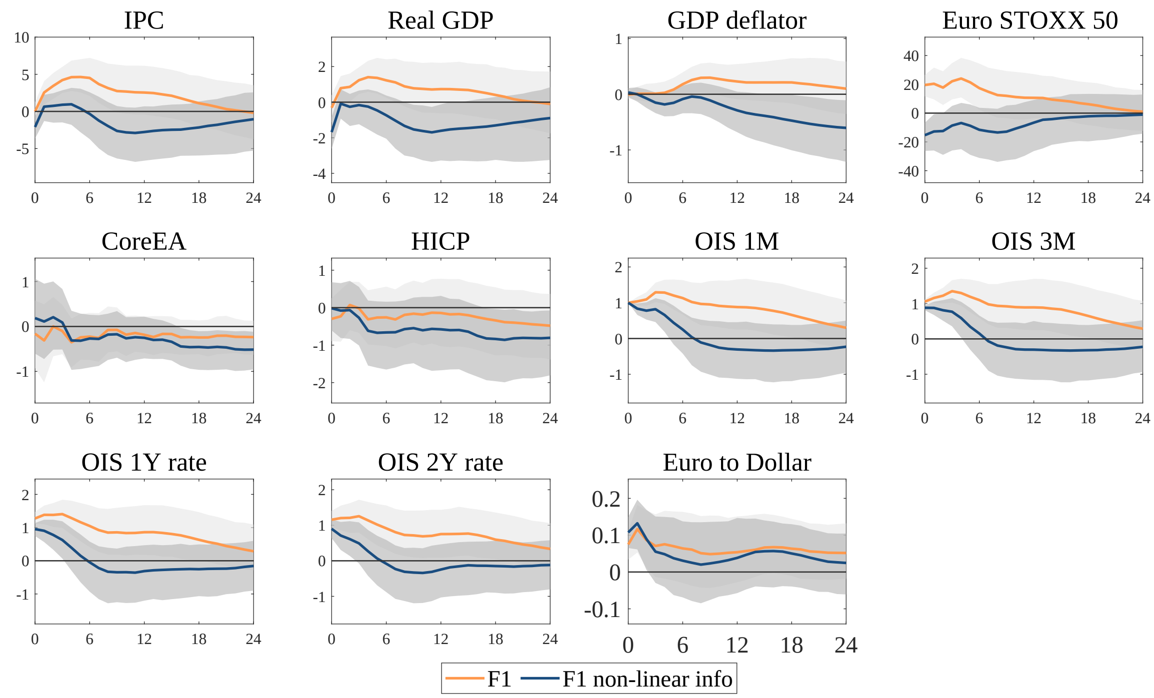
Finally, we show the propagation of the information component of the monetary policy announcements. This cannot strictly speaking be thought of as a structural shock, but rather as a bundle of structural shocks (and potentially their lags) to which monetary policy responds. The IRFs are obtained from the VAR using as an instrument the principal components of the fitted values of Eq. (24).

5.1 Conventional monetary policy shocks

Let us start by commenting the effects of a conventional monetary policy shock, normalised to induce a 100 bps tightening of the 1-month OIS (Figure 9). The informationally robust IV, obtained correcting in the nonlinear regression setting, delivers impulse response functions

[28] Real GDP and its deflator are obtained by interpolating quarterly measures to obtain monthly frequency as in Stock and Watson (2010); Jarociński and Karadi (2020). Results for IP excluding construction are almost indistinguishable from those for IPC (see Section B of the Online Appendix).

Figure 9: Conventional monetary policy shock



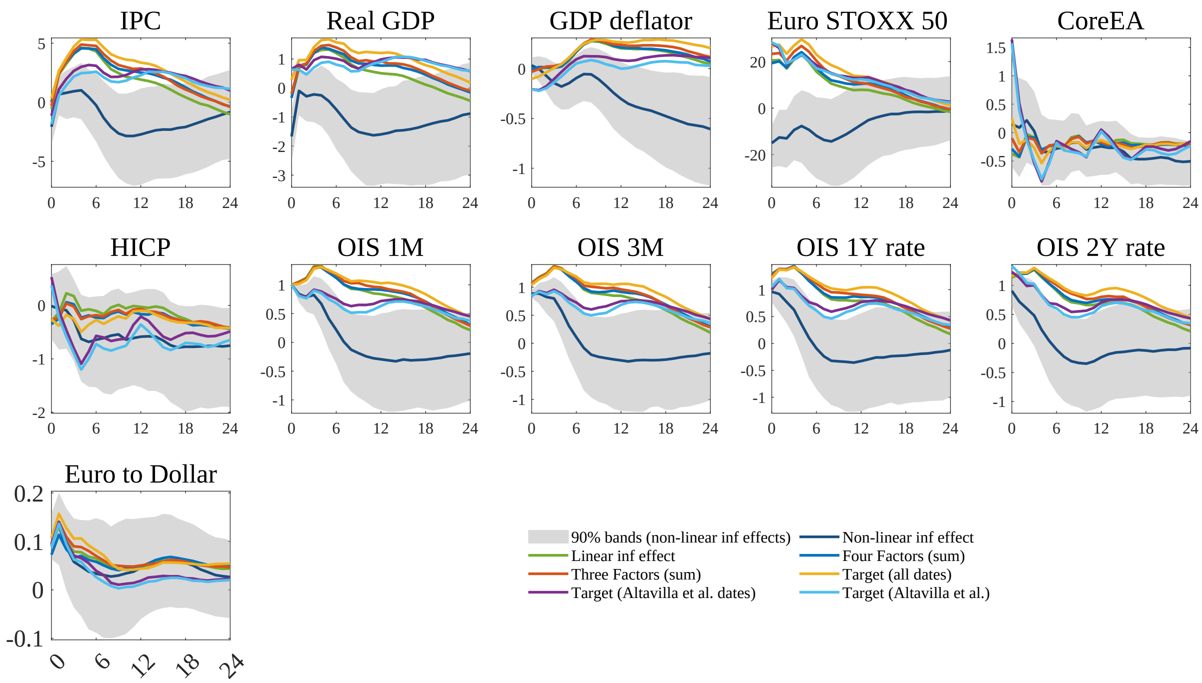
Notes: The figure reports the IRFs to a conventional monetary policy shock, normalised to induce a 100 basis points increase in the 1m-OIS rate. In amber, it reports the responses obtained with the original F1 factor, without any correction for information effects. In blue, it reports the IRFs by using the informationally robust F1 factor. The grey areas are 90% coverage bands. The sample considered is 2002-2019.

to a monetary tightening with significant contractionary effects (blue IRFs). IPC and real GDP contract, with output reaching a trough of about 2% after 12 months, while industrial production contracts of 3% over the same horizon. The different measure of prices indicates deflationary pressure, with HICP contracting of 1% over 24 months. The stock market contracts of 15%, while the euro appreciates agains the dollar, and the short medium segment of the OIS yield curve is lifted for about 6 months.[29]

This picture contrasts with the one obtained when the with the same factor extracted without taking into account information effects (amber IRFs), which shows strong output and prices puzzles, as well as a strong positive response of the stock market – a clear image of the strength of the information effects in the original monetary policy surprises.

[29]The variables present significant responses for the 68% coverage bands (not shown), with several also significant for the 90% coverage bands, shown in Figure 9.

Figure 10: Conventional monetary policy shock – comparison across methods



Notes: The chart reports the IRFs to a conventional monetary policy shock, normalised to induce a 100 basis points increase in the 1m-OIS rate. The baseline median responses (in blue) and the associated grey shaded area that report the 90% bands are the IRFs to a shock identified with the target factor (F1) corrected for non-linear information effects. The green IRFs are the responses to a shock identified with target factor (F1) with a linear information correction. The orange IRFs are the median responses to a shock identified with a target factor obtained by only considering the market surprises on the OIS curve, and not employing other assets. The yellow IRFs are the median responses to a shock identified with a target factor identified only on the OIS market surprises of press release window, without excluding any date. The purple IRFs are the median responses to a shock identified with a target factor obtained from the OIS market surprises of press release window but excluding the surprises associated to the ECB meetings of 8 October 2008 and 6 November 2008 (as in Altavilla et al., 2019). In light blue, we report the responses of the target factor identified by Altavilla et al. (2019), obtained on from the press release window, by excluding the surprises associated to the ECB meetings of 8 October 2008 and 6 November 2008, demeaning, but not standardising, the market surprises. The sample considered is 2002-2019.

To gauge the importance of the non-linear information effects, against other choices in the treatment of the data, we report a detailed comparison of different approaches in Figure 10. In particular we compare IRFs for the following IVs:

– the target factor corrected for non-linear information effects (blue), which is our baseline specification;

– the target factor corrected for linear information effects (green);

- the target factor obtained by only considering the market surprises on the OIS curve, and not employing other assets (orange);
- the target factor identified only on the OIS market surprises of press release window, without excluding any date (yellow);
- the target factor obtained from the OIS market surprises of press release window but excluding the surprises associated to the ECB meetings of 8 October 2008 and 6 November 2008 (purple);
- the target factor identified by Altavilla et al. (2019), obtained on from the press release window, by excluding the surprises associated to the ECB meetings of 8 October 2008 and 6 November 2008, and only demeaning but not standardising the market surprises (light blue).

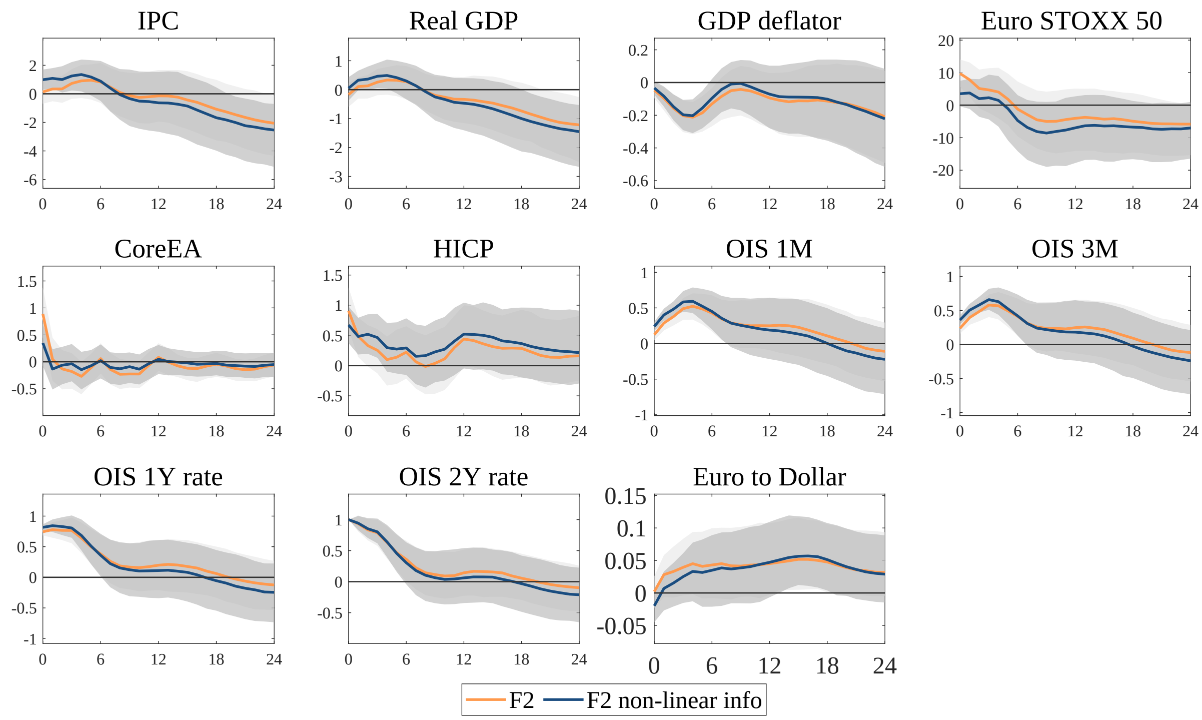
The results show that while different assumptions – as for example excluding some dates – marginally reduce the extent of the puzzles, they do not change the overall picture, differently from the IVs corrected for nonlinear information effects. It is worth observing that the charts provide a visual validation to the predictions of the model presented in Section 2.

5.2 Forward guidance

The informationally robust forward guidance factor offers result that are overall in line with the economic theory and the effects reported for conventional monetary policy (Figure 11). The non-linear information correction, reduce most of the puzzles in the F2 factors, with the notable exception of HICP inflation and a few impact response with a positive sign.

A positive forward guidance shock lifts for about 12 months the short-medium segment of the yield curve, with its short-end (one month OIS) peaking at the 4-months horizon. Industrial production and real GDP decline over a 2 year horizon, and so does the stock market, the euro appreciate against the dollar. While the GDP deflator indicates deflationary pressure, HICP displays a puzzling response.

Figure 11: FORWARD GUIDANCE



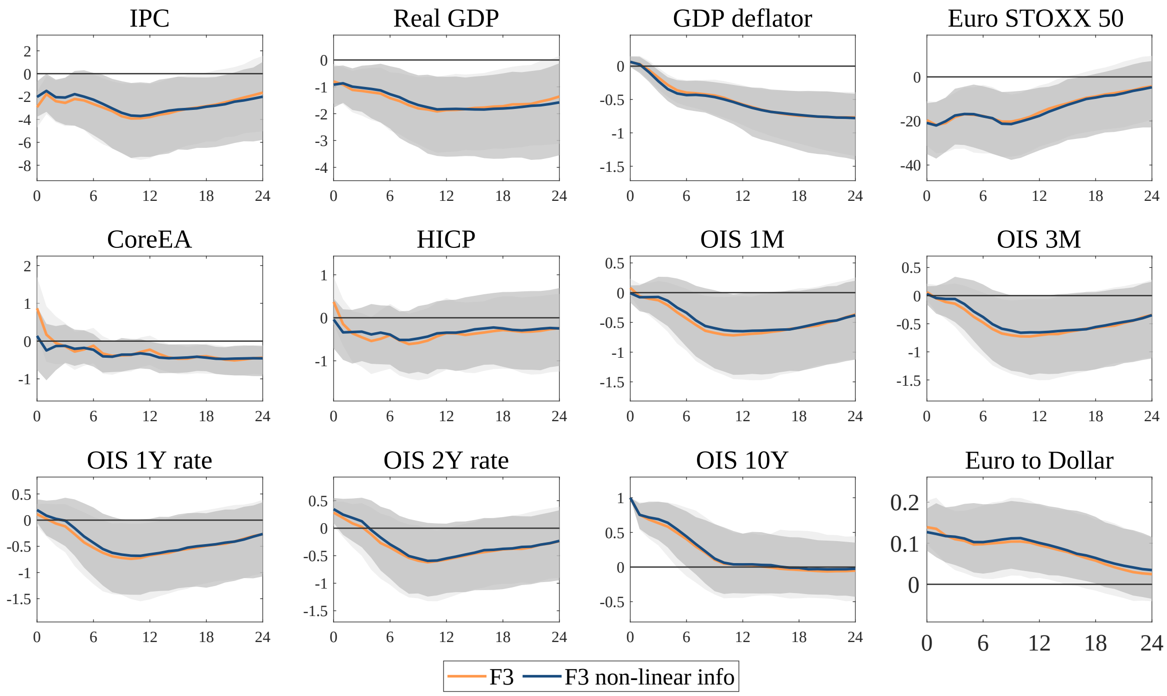
Notes: The figure reports the IRFs to a forward guidance shock, normalised to induce a 100 basis points tightening in the 2y-OIS rate. In amber, we report the responses to a shock identified with the forward guidance factor (F2), without any correction for information effects. In blue, we report the responses to a shock identified with the informationally robust F2 factor, obtained correcting for non-linear information effects. The grey areas are 90% coverage bands. The sample considered is 2002-2019.

While overall, the responses are of the expected signs, the puzzling response of inflation may due to either measurement issues in HICP or in residual information effects for which the limited coverage of the available forecasts cannot correct. We explore some possible measurement issues in the euro area measures of inflation in Section B of the Online Appendix.

5.3 Quantitative easing/tightening

A quantitative tightening has powerful contractionary effects, with results significant at 90% confidence bands (Figure 12). The shock lifts the long end of the OIS curve (normalised to a 100 basis points increases at the 10-year maturity), while depressing over the medium run the short end of the curve and hence inducing a steepening of the yield curve. The easing in the short-term OIS is likely to reflect the weakening of the economy, following the monetary

Figure 12: Quantitative easing/tightening



Notes: The figure reports the IRFs to a quantitative tightening shock, normalised to induce a 100 basis points tightening in the 10y-OIS rate. In amber, we report the responses to a shock identified with the QE/QT factor (F3), without any correction for information effects. In blue, we report the responses to a shock identified with the informationally robust QE/QT factor, obtained correcting for non-linear information effects. The grey areas are 90% coverage bands. The sample considered is 2002-2019.

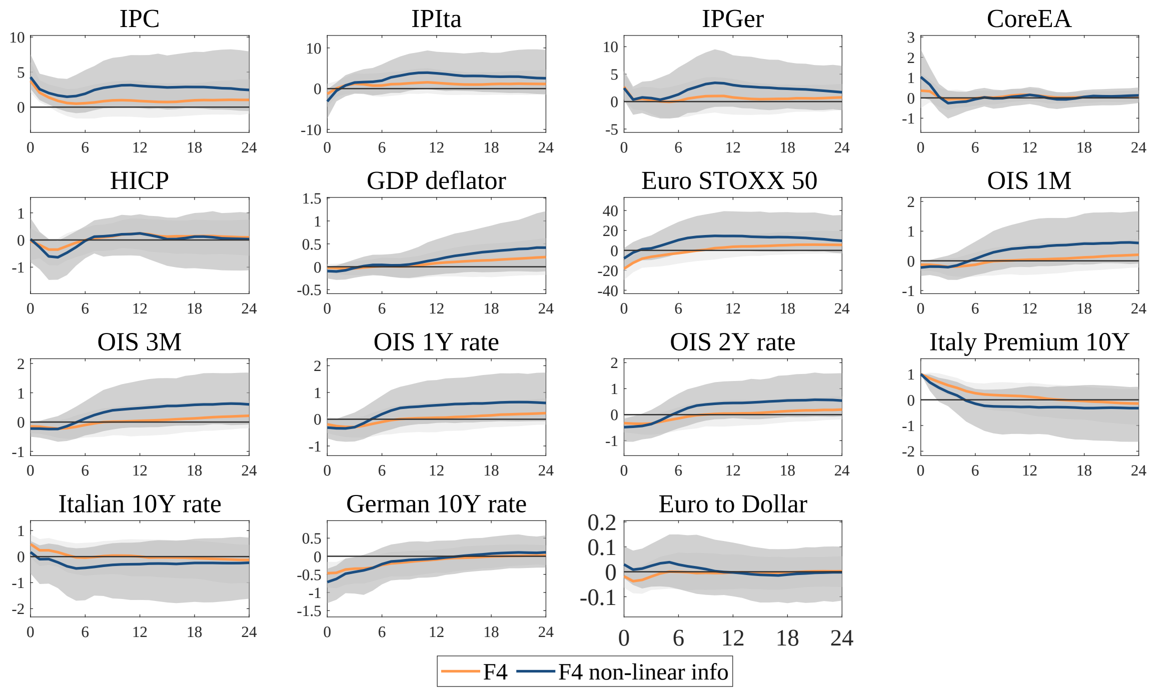
tightening.

Output and prices contracts, as well as the stock market, while the euro appreciate against the dollar. GDP contracts sharply with a peak of -2% after about a year, while industrial production contracts of -3% at the trough. The response of the stock market is significantly negative for the whole period and the largest decrease is about -15% after a year from the shock. There is little difference between the IRFs obtained from the informationally robust and the original instrument.

5.4 Asymmetric country risk shock

An asymmetric country risk shock (Figure 13), delivered by the ECB communication, brings about an increase in the spread between 10-year Italian and 10-year German bonds (Italy

Figure 13: Asymmetric country risk shock

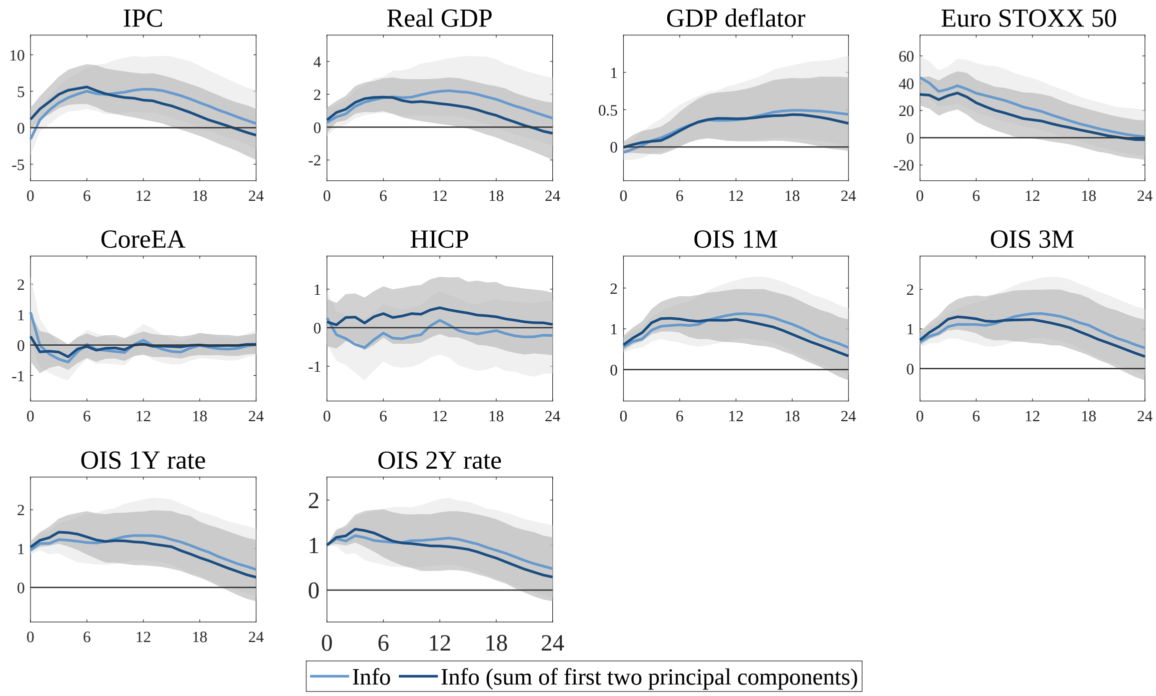


Notes: The figure reports the IRFs to an asymmetric country risk shock, normalised to induce a 100 basis points increase in the spread between the 10Y Italian government bond yield and the 10Y German government bond yield (Italy Premium 10Y in the figure). In amber, we report the responses to a shock identified with the asymmetric country risk factor (F4), without any correction for information effects. In blue, we report the responses to a shock identified with the informationally robust asymmetric country risk factor, obtained correcting for non-linear information effects. The grey areas are 90% coverage bands. The sample considered is 2002-2019.

Premium 10Y), which we interpret as an increase in sovereign risk for southern-European countries with the associated flight to safety towards the core countries of the union. The OIS curve remains relatively flat.

Following the shock, industrial production contracts for Italy, while it expands for Germany and for the aggregated euro area economy. The stock market contracts on impact, with a -10% reduction to its value, to recover rapidly. Headline and core inflation contract, with a significant effect at the impact of around -0.5% for headline inflation. The differences between the IRFs obtained from the informationally robust and the original instrument are minor.

Figure 14: Information in monetary policy



Notes: The figure reports the IRFs to an 'information shock', normalised to induce a 100 basis points increase in the 2y-OIS rate. In amber, we report the responses to a shock identified with an information factor defined as the first principal component of the fitted values of the non-linear information effects regressions. In blue, we report the responses to a shock identified with an information factor defined as the sum of the first two principal components of the fitted values of the non-linear information effects regressions. The grey areas are 90% coverage bands. The sample considered is 2002-2019.

5.5 Information propagation

We conclude the presentation of the macroeconomic transmission of the shocks extracted from the ECB communication, by looking at the information component (Figure 14). It is important to stress, once again, that this component cannot be interpreted as a structural shock or an information shock delivered by the central bank. The correct interpretation of this component, in line with the model in Section 2, is as a bundle of different structural shocks to which the ECB responds via its systematic reaction function. The presence of imperfect information delivers contamination of the market surprises by these shocks. While the policy decision and communication inform the market participants on the view of the central bank, they cannot be seen as 'delivering' the shocks but only as being part of their transmission through the economy. Hence, the IRFs in Figure 14 should be seen as informative of the reaction function of the ECB and not as structural response functions to a given shock. This observation is also important when looking at the variance decomposition for this component for which a correct identification of a given shock it is not possible.

The IRFs to the information component are normalised to induce a 100 basis points increase in the 2y-OIS. They are obtained using either (i) the first, or (ii) the sum of the first and the second principal components of the fitted values of the non-linear information effects regressions. The pattern of responses indicates that the ECB mainly reacts to a bundle of business cycle shocks with aggregate effects similar to those of demand shocks. Industrial production and real GDP expands, as well as prices. The stock market value increases, while the short-medium maturities of the OIS curve all respond positively with a hump-shaped response.

5.6 How powerful are monetary shocks?

An important question is how powerful the effects of monetary policy shocks are at business cycle frequency. Several interesting findings emerge from the variance decomposition analysis reported in Table 6.[30] First, conventional monetary policy shocks explain around 4.5% of the variance in real activity and prices at business cycle frequencies, consistently with results reported for the U.S. on a similar sample (see, for example, Forni et al., 2022). Second, forward guidance and QE shocks account for approximately 10% and 13% of the variance in GDP, and 6% and 4% of the variance in headline inflation, respectively. Third, QE shocks have a large impact on the stock market, explaining around 14% of its variance, while forward guidance explains an additional 6%.

Notably, 'information' shocks explain a significant portion of the variance across the variables considered. It is important to stress that the information component should not be interpreted as a structural shock, as it capture a combination of contemporaneous (and

[30] Section J, in the Online Appendix reports the contributions of the different identified shocks to the variances of the variables of interests, at shorter and longer periods.

Table 6: VARIANCE DECOMPOSITION AT A BUSINESS CYCLE FREQUENCY

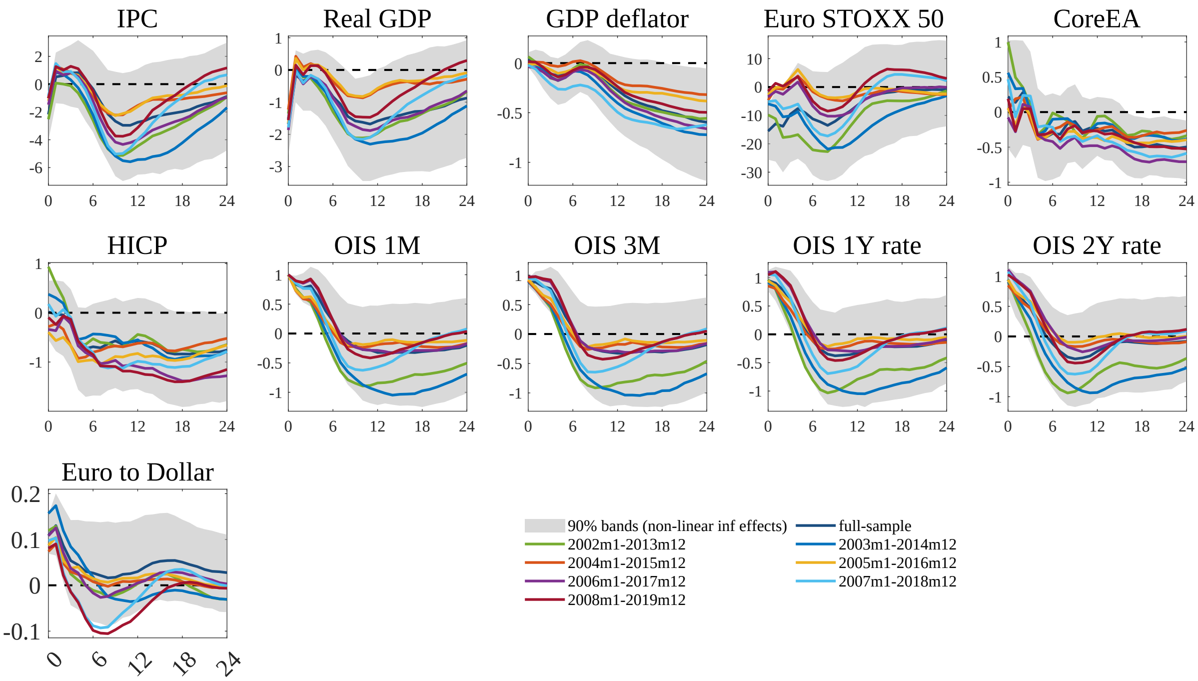
Variables	*Target*	*Forward Guidance*	*QE*	*Asymmetric Country Risk*	*Information*
IP	2.97	7.37	9.03	5.95	25.66
	(0.74, 6.91)	(3.43, 13.77)	(3.53, 16.73)	(1.94, 11.98)	(16.40, 36.69)
Real GDP	4.40	9.82	13.35	–	16.50
	(1.20, 9.51)	(3.99, 17.13)	(6.12, 21.53)	–	(8.93, 25.02)
Stock Market	3.17	6.18	14.07	7.10	31.92
	(0.90, 7.18)	(1.72, 12.33)	(6.72, 23.11)	(2.43, 13.33)	(19.79, 43.76)
HICP	4.43	5.94	3.85	1.97	5.83
	(0.95, 10.00)	(2.01, 12.32)	(0.99, 8.69)	(0.59, 4.99)	(1.52, 14.41)
1m-OIS	4.23	8.59	7.49	5.45	43.68
	(1.66, 7.91)	(4.92, 13.60)	(1.83, 15.09)	(1.32, 10.98)	(31.77, 55.42)
1y-OIS	3.07	11.18	6.54	6.02	42.10
	(1.10, 6.34)	(6.50, 16.77)	(1.87, 13.89)	(1.68, 11.62)	(29.93, 53.99)
2y-OIS	2.51	12.60	5.43	6.11	40.49
	(0.93, 5.47)	(7.08, 18.03)	(1.54, 11.94)	(1.95, 11.37)	(28.74, 52.02)
10y-OIS	–	–	9.66	–	–
	–	–	(5.06, 15.48)	–	–
Spread 10Y	–	–	–	3.44	–
	–	–	–	(1.20, 7.09)	–
IP Italy	–	–	–	5.40	–
	–	–	–	(1.73, 11.23)	–
IP Germany	–	–	–	3.49	–
	–	–	–	(0.83, 8.52)	–

Notes: The table reports the percentage share of the variance for each variable considered as due to each monetary policy shock, in the range of business cycle frequencies (i.e. 24 and 96 months), following the approach of Forni et al. (2022). 68% confidence bands are reported in parenthesis.

potentially lagged) macro shocks to which central banks respond. Thus, interpreting the variance decomposition results is less straightforward. However, the findings indicate that the ECB responds to the primary sources of business cycle fluctuations, consistent with its mandate for macroeconomic stabilisation. Furthermore, the pervasiveness of information component explains the observed extent of the puzzles in the IRFs derived from policy factors, despite the limited R^2 of some of the information regression reported in Section 4.[31]

[31] As shown by Miranda-Agrippino and Ricco (2023), the bias due to contamination of the instrument depends both on the extent to which the share of variance of the IV due to non-policy shocks, and on the variance of the variables of interest that these shocks explain.

Figure 15: Conventional monetary policy – rolling samples



Notes: The figure reports the IRFs to a conventional monetary policy shock on the baseline sample and on a set of rolling subsamples. The shock is identified with the informationally robust target factor, corrected for nonlinear information effects, and normalised to induce a 100 basis points increase of the 1m-OIS rate. The grey areas are 90% coverage bands of the baseline specification.

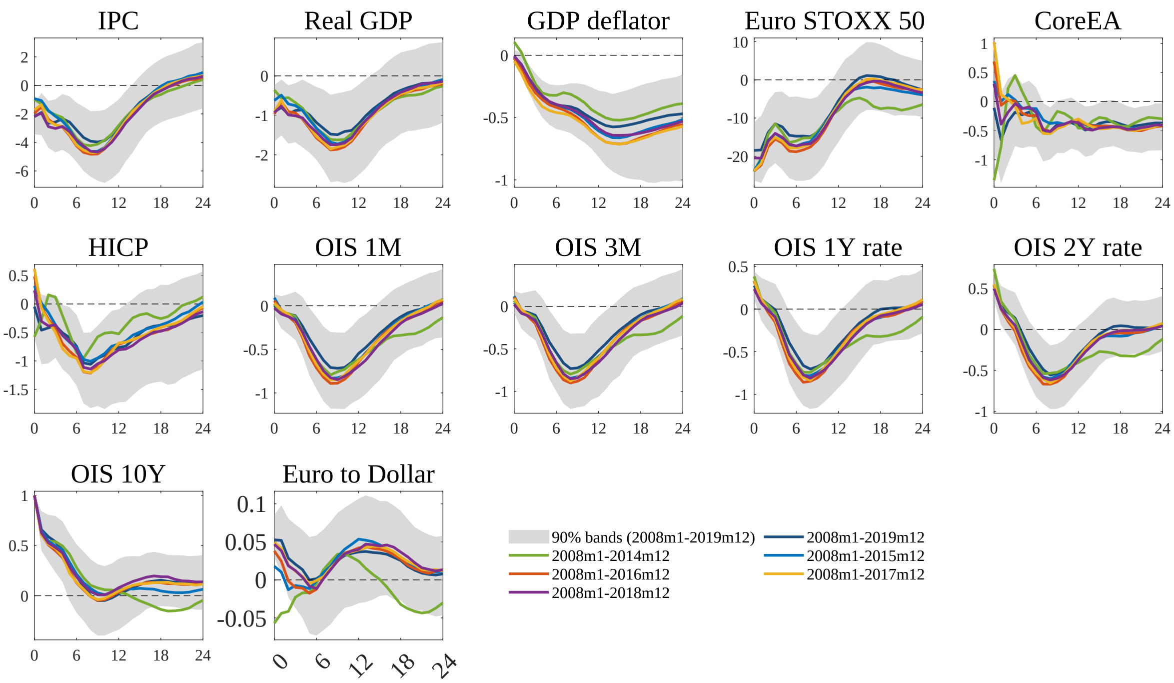
6 Robustness of the results

We conclude our empirical analysis by providing some robustness exercises, by considering a subsample analysis, and the sensitivity of our results to the methodology used in the information regressions. In this section, we focus on conventional monetary policy shocks, while Section H in the Online Appendix provides additional charts and results relating to the other shocks identified in this paper.

6.1 Subsample analysis

Figure 15 plots the median and confidence bands of the IRF for the benchmark sample (2002-2019, blue) together with the median responses for a set of rolling subsamples starting

Figure 16: QUANTITATIVE EASING/TIGHTENING – EXPANDING SAMPLES

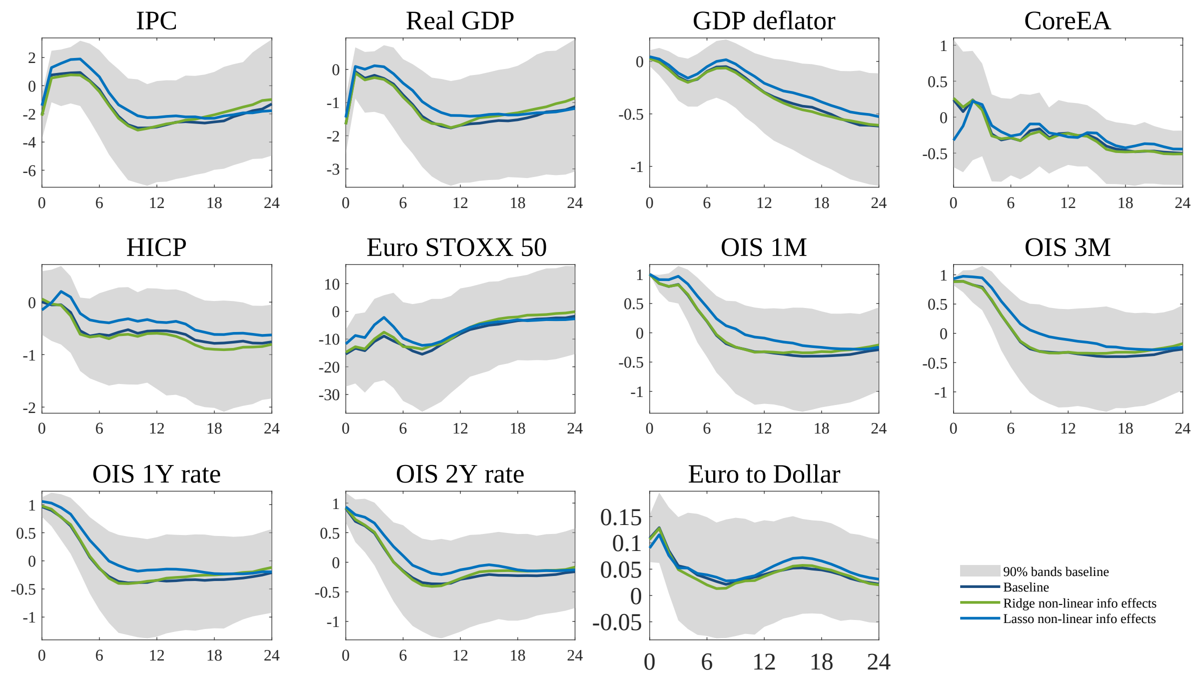


Notes: The figure reports the IRFs to a quantitative tightening shock, normalised to induce a 100 basis points tightening in the 10y-OIS, for a a set of samples starting from 2008. The shock is identified with the informationally robust QE/QT factor, corrected for nonlinear information effects, and normalised to induce a 100 basis points increase in the 10y-OIS rate.

in a different year of the sample, and each spanning ten years of data. The chart shows the high degree of robustness of the benchmark results, and almost all the IRFs for each subsample inside the coverage bands of the baseline model. The contractionary textbook effects of monetary policy in the euro area are confirmed in each subsample.[32]

Figure 16 presents a similar exercise for the information-robust QE/QT factor, showing the effects of the shock estimated on a series of expanding samples starting from 2008, when the ECB began deploying several unconventional monetary policy instruments. The results reported in the baseline specification are confirmed across the different samples.

Figure 17: Conventional monetary policy – info corrections



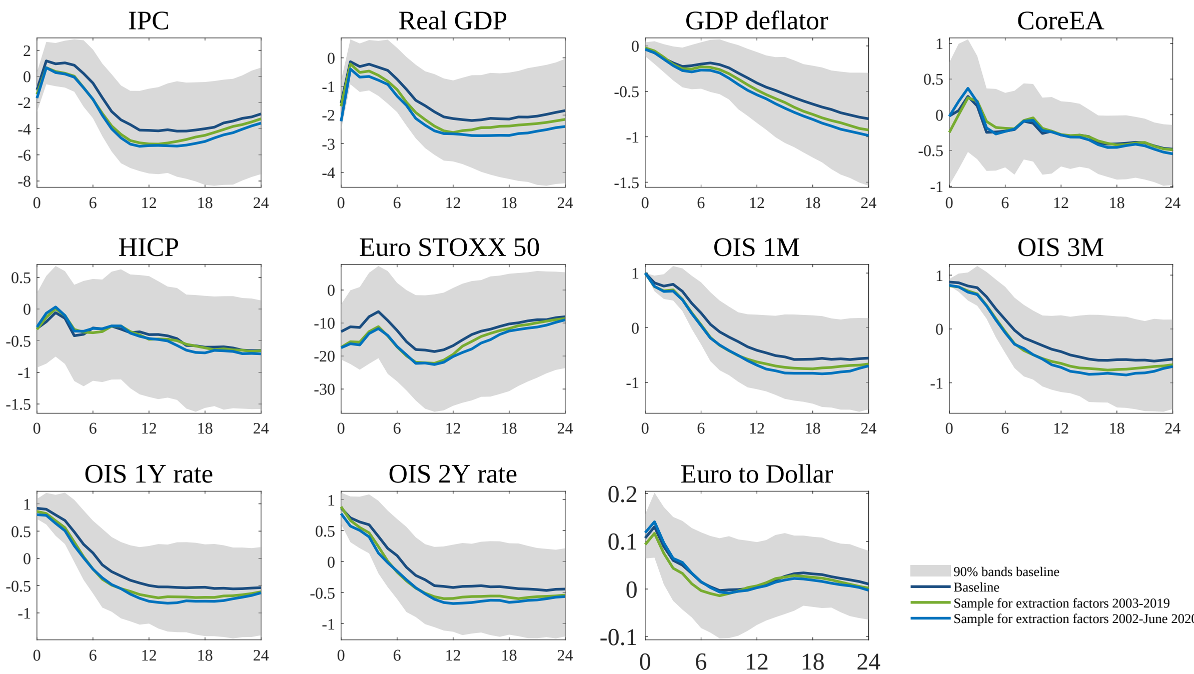
Notes: The figure reports the IRFs to a conventional monetary policy shock, normalised to induce a 100 basis points increase of the 1m-OIS rate. The shock is identified with three informationally robust target factors, corrected for nonlinear information effects adopting different regression models and the same set of regressors: baseline OLS specification (blue), Ridge regression (green), Lasso (light blue). The grey areas are 90% coverage bands of the baseline specification. The sample considered is 2002-2019.

6.2 Information regression specification

Are results sensitive to the nonlinear regression specification adopted, or the set of regressors? To a large extent no. Figure 17 reports the IRFs to a conventional monetary policy shock identified with three variation of the informationally robust target factors with the nonlinear information correction in (i) the baseline OLS specification (blue), (ii) a Ridge regression approach (green), and a (iii) a Lasso regression (light blue). The three specifications adopt and the same set of regressors. Results are relatively unchanged. Including a larger set of regressors changes, to some extent, the share of the surprises at longer maturities that is explained by information, but leaves macroeconomic results unchanged (see Section G, in the

[32] Section I in the Online Appendix reports similar results for the target and timing factors of Altavilla et al. (2019).

Figure 18: Conventional monetary policy – different samples



Notes: The figure reports the IRFs to a conventional monetary policy shock, normalised to induce a 100 basis points increase of the 1m-OIS rate. The shock is identified with three informationally robust target factors, corrected for nonlinear information effects on different samples: the baseline 2002m1-2019m12 (blue), 2003m1-2019m12 (green), 2002m1-2020m6 (light blue). The grey areas are 90% coverage bands of the baseline specification. The sample considered is 2003-2019.

Online Appendix).

6.3 Pandemic period

Our baseline analysis excludes the COVID pandemic period, which is known to distort VAR results and may require ad hoc adjustments (see Lenza and Primiceri, 2022). However, results reported in the previous analysis are generally robust to the inclusion of the pandemic recession. Figure 18 compares the effects of conventional monetary policy shocks on macroeconomic aggregates for the baseline sample (2002m1-2019m12, blue) with those for the periods 2003m1-2019m12 (green) and 2002m1-2020m6 (light blue). The first excludes 2002, a year marked by high volatility in surprises sometimes attributed to ECB communication errors, while the second includes the COVID period. The results in the are only marginally affected, and if any stronger.

7 Conclusions

Information frictions play a significant role in the transmission of policy shocks, and hence in the methods that have to be used to identify their effects. The findings reported in this paper align with the predictions of imperfect information models: during periods of elevated market stress, agents increasingly rely on central bank policy signals to track and forecast economic developments.

In the euro area, these non-linear information effects appear to contribute to the pronounced puzzles in the dynamic responses to policy shocks identified through high-frequency interest rate changes triggered by policy announcements. By accounting for these non-linear information effects, it is possible to identify the effects of both conventional and unconventional policy shocks, as well as to understand the transmission of the 'information shocks' – i.e. the bundle of shocks to which the central bank responds. Our results demonstrate that the ECB's multidimensional policy toolkit has powerful effects on the European economy, with policy tightenings producing contractionary effects on real economic activity, prices, and financial markets.

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Online Appendix to

Monetary Policy, Information and Country Risk Shocks in the Euro Area

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Abstract

This online appendix contains model derivations, details on the data used, and additional results for the paper 'Monetary Policy, Information and Country Risk Shocks in the Euro Area'.

JEL classification: E32, E52, E58

Keywords: Monetary policy, euro area, information effects, unconventional monetary policy

Contents

A A model of information effects with high and low noise

Let us consider a model in which private agents and the central bank have imperfect information about the state of the economy, and form expectations conditional on private signals clouded by state dependent observational noise. In doing so we extend the model in Miranda-Agrippino and Ricco (2021) to the case where the variance of the noise is not constant.

Agents in the model live in a discrete time, with each period t being dividend in an opening and a closing stage, i.e. $t \in \{\underline{t}, \bar{t}\}$. The inflation process evolves over time with an AR(1) process:

$$\pi_t = \rho \pi_{t-1} + u_t^{\pi} \qquad u_t^{\pi} \sim \mathcal{N}(0, \sigma_{\pi}^2) \ , \tag{1}$$

with normally distributed innovations, u_t^{π}, and $|\rho| < 1$.

At the beginning of time t, i.e. $\underline{t}$, the private agents (indexed by i) receive a private signal about inflation contaminated by observational noise

$$s_{i,t} = \pi_t + v_{i,t} \qquad v_{i,t} \sim \mathcal{N}(0, \sigma_{v,z}^2), \tag{2}$$

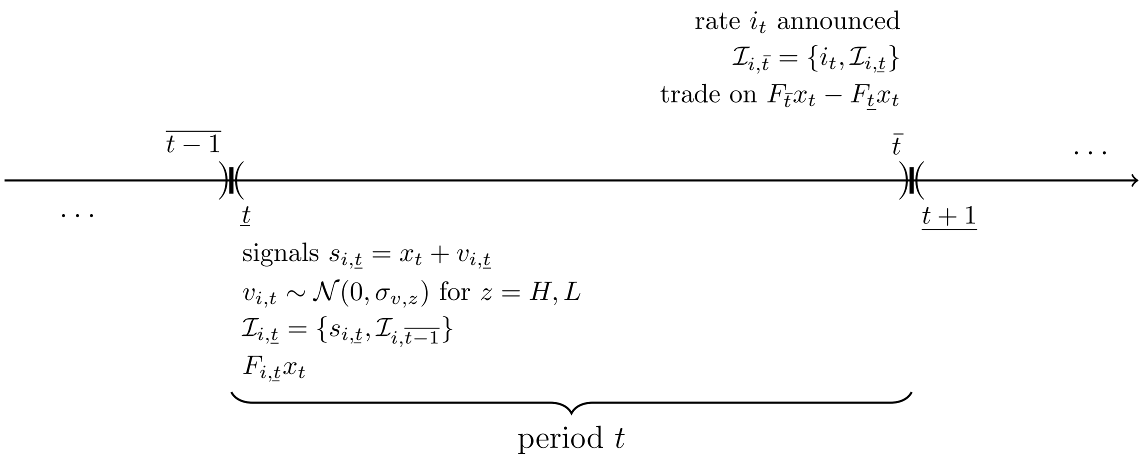
with a state-dependent variance, σ_s^v, which is equal across agents and is characterised by the existence of two states, $z \in \{L, H\}$, respectively with high and low noise, i.e. $\sigma_{H,z}^v > \sigma_{L,z}^v$. Agents form and update their expectations about current and future inflation, conditional on the signals observed using a Kalman filter

$$F_{i,\underline{t}}\pi_t = K_{1,\underline{t}} s_{i,\underline{t}} + (1 - K_{1,\underline{t}}) F_{i,\overline{t-1}}\pi_t, \tag{3}$$

$$F_{i,\underline{t}}\pi_{t+h} = \rho F_{i,\underline{t}}\pi_t, \tag{4}$$

where $K_{1,\underline{t}}$ is the Kalman gain. Conditional on their forecasts, agents form expectation and

Figure A.1: The Information Flow



Note: Each period t has a beginning $\underline{t}$ and an end $\bar{t}$. At $\underline{t}$ agents (both private and central bank) receive noisy signals $s_{i,\underline{t}}$ about the economy x_t, and update their forecasts $F_{i,\underline{t}}x_t$ based on their information set $\mathcal{I}_{i,\underline{t}}$. At $\bar{t}$ the central bank announces the policy rate i_t based on its forecast $F_{cb,\underline{t}}x_t$. Agents observe i_t, infer $F_{cb,\underline{t}}x_t$, and form $F_{i,\bar{t}}x_t$. Trade is a function of the aggregate expectation revision between $\underline{t}$ and $\bar{t}$.

trade the policy rate that will be set by the central bank following a Taylor rule

$$i_t^{(0)} = r_t = \delta\pi_t + u_t^{mp}, \tag{5}$$

and interest rates at longer horizons, i.e. $i_t^{(h)}$ for $h \geq 0$

$$i_{\underline{t}}^{(h)} = \alpha_h F_{\underline{t}}\pi_{t+h} + \xi_t^{(h)}, \tag{6}$$

where $\xi_t^{(h)}$ captures risk premia, $\alpha_0 = \delta$, and $F_{\underline{t}}$ indicate the average expectations over the market.

Let us define $V_{t|\overline{t-1}} \equiv \text{Var}\left(\pi_t - F_{i,\overline{t-1}}\pi_t\right)$, i.e. the variance of the forecast errors for inflation at time t, made at time $\overline{t-1}$. The Kalman gain $K_{1,\underline{t}}$ is given by:

$$K_{1,\underline{t}} = \frac{V_{t|\overline{t-1}}}{V_{t|\overline{t-1}} + \sigma_{v,z}^2}. \tag{7}$$

From the expression for $K_{1,\underline{t}}$, it is clear that, for a given $V_{t,\overline{t-1}}$, the agents will update more their forecasts in states of low noise, as compared to the states of high noise.

The variance of the forecast of π_t made at $\underline{t}$ will depend on $V_{t|\overline{t-1}}$ as[1]

$$V_{t|\underline{t}} = V_{t|\overline{t-1}} - \frac{(V_{t|\overline{t-1}})^2}{V_{t|\overline{t-1}} + \sigma^2_{v,z}}, \tag{8}$$

$$V_{t|\overline{t-1}} = \rho^2 V_{t-1|\overline{t-1}} + \sigma^2_{\pi}. \tag{9}$$

During period t, the central bank receives a private signal about the state of the economy, contaminated by a noise of constant volatility, and updates its forecast:

$$s_{cb,t} = \pi_t + v_{cb,t} \qquad v_{cb,t} \sim \mathcal{N}(0, \sigma^2_{v,cb}), \tag{10}$$

$$F_{cb,t}\pi_t = K_{cb,t}s_{cb,t} + (1 - K_{cb,t})F_{cb,t-1}\pi_t. \tag{11}$$

The assumption of constant volatility captures in a stylised manner the fact that the central bank, differently from market operators which have to sample information from prices and data releases, can have a more direct access to data offices and even survey directly financial and economic institutions to take the pulse to the economy. Given the constant noise in the central bank's signal, we can consider the asymptotic value of the Kalman gain, K_{cb}, where we drop the index t.

Conditional on its forecast for π_t, the central bank set and announces the interest rate for the period:

$$r_t = \delta F_{cb,t}\pi_t + u_t^{mp}. \tag{12}$$

where u_t^{mp} is a monetary policy shocks drawn from a normal distribution centred at zero and with variance σ^2_{mp}.

[1]Agents in the model know all of the model parameters, including the variance of the signal (either low or high).

At time $\bar{t}$, agents observe the interest rate

$$r_t = \delta \left(K_{cb} s_{cb,t} + (1 - K_{cb}) F_{cb,t-1} \pi_t\right) + u_t^{mp} \tag{13}$$

$$= \delta K_{cb} \pi_t + \delta K_{cb} v_{cb,t} + (1 - K_{cb}) \rho F_{cb,t-1} \pi_{t-1} + u_t^{mp} \tag{14}$$

$$= \delta K_{cb} \pi_t + \delta K_{cb} v_{cb,t} + (1 - K_{cb}) \rho \left(i_{t-1} - u_{t-1}^{mp}\right) + u_t^{mp} \ , \tag{15}$$

i.e. conditional on the past interest rate, a public signal on the state of the economy:

$$\tilde{s}_{\bar{t}} = \pi_t + \tilde{v}_{cb,\underline{t}} \equiv \pi_t + v_{cb,t} + (\delta K_{cb})^{-1} [u_t^{mp} - (1 - K_{cb}) \rho u_{t-1}^{mp}]. \tag{16}$$

Given this public signal, agents update their expectations[2]

$$F_{i,\bar{t}} \pi_t = K_{2,\bar{t}} \tilde{s}_{cb,\bar{t}} + (1 - K_{2,\bar{t}}) F_{i,\underline{t}} \pi_t,$$

where the gain $K_{2,\bar{t}}$ is:

$$K_{2,\bar{t}} = \frac{V_{t|\underline{t}}}{V_{t|\underline{t}} + \sigma_{\tilde{v}}^2}, \tag{17}$$

and the forecast error variance is such that:

$$V_{t|\bar{t}} = V_{t|\underline{t}} - \frac{(V_{t|\underline{t}})^2}{V_{t|\underline{t}} + \sigma_{\tilde{v}}^2}. \tag{18}$$

Conditional on their updated forecasts, agents revise the price for the rates at longer horizons and trade.

Proposition 1. *The price revisions in interest rates at different maturities triggered by the*

[2]For sake of simplicity we assume that agents update with a standard Kalman filter without taking into account the structure in the noise of this public signal due to the moving average component in the monetary policy shock.

policy announcement are

$$\Delta i_{\underline{t}}^{(h)} = \alpha_h \rho^h \left(F_{\bar{t}} \pi_t - F_{\underline{t}} \pi_t \right) + \Delta \xi_t^{(h)}, \tag{19}$$

where

$$\begin{aligned} F_{\bar{t}} \pi_t - F_{\underline{t}} \pi_t = & (1 - K_{1,\underline{t}}) K_{2,\bar{t}} K_{2,\overline{t-1}}^{-1} (1 - K_{2,\overline{t-1}}) [F_{\overline{t-1}} \pi_t - F_{\underline{t-1}} \pi_t] + (K_{2,\bar{t}})(1 - K_{1,\underline{t}}) u_t^{\pi} \\ & + K_{2,\bar{t}} [\nu_{cb,\underline{t}} - (1 - K_{1,\underline{t}}) \rho \nu_{cb,\underline{t-1}}] + K_{2,\bar{t}} (K_{cb} \delta)^{-1} [u_t^{mp} - \rho (2 - K_{cb} - K_{1,\underline{t}}) u_{t-1}^{mp} \\ & + (1 - K_{1,\underline{t}})(1 - K_{cb}) \rho^2 u_{t-2}], \end{aligned} \tag{20}$$

are the average revision in expectations across agents in the market, and $\Delta \xi_t^{(h)}$ *are revisions to risk premia.*

Proof. Eq. (20) follows readily from the same derivations reported in the Online Appendix of Miranda-Agrippino and Ricco (2021), but for $K_{1,\underline{t}}$ and $K_{2,\overline{t-1}}$ time-varying. Eq. (19) is obtained from Eq. (5) and Eq. (6). □

The expression in Eq. (20) shows that after observing the policy decision private agents update their expectations towards the view of the bank, hence inducing a market wide information effect. The term $(K_{2,\bar{t}})(1 - K_{1,\underline{t}}) u_t^{\pi}$ captures the information channel of the monetary policy, while the first term in the expression above the autocorrelation between revision of expectations that is due to the sluggish adjustment of expectations in models of imperfect information.

We are here interested in understanding how states of low and high variance change the strength of information effects. Let us first prove that the asymptotic variance of the forecast errors, where one assumes that only one state is realised, is increasing with the variance of the noise, while the Kalman gain is decreasing.

Using the formulae of the Kalman recursion and first substituting Eq. (9), and then Eq.

(18), into Eq. (8)

$$
\begin{aligned}
V_{t|\underline{t}} &= V_{t|\overline{t-1}} - \frac{(V_{t|\overline{t-1}})^2}{V_{t|\overline{t-1}} + \sigma^2_{v,z}} \ = \rho^2 V_{t-1|\overline{t-1}} + \sigma^2_{\pi} - \frac{(\rho^2 V_{t-1|\overline{t-1}} + \sigma^2_{\pi})^2}{\rho^2 V_{t-1|\overline{t-1}} + \sigma^2_{\pi} + \sigma^2_{v,z}} \\
&= \frac{(\rho^2 V_{t-1|\overline{t-1}} + \sigma^2_{\pi})\sigma^2_{v,z}}{\rho^2 V_{t-1|\overline{t-1}} + \sigma^2_{\pi} + \sigma^2_{v,z}} = \frac{(\rho^2 \frac{V_{t-1|\underline{t-1}}\sigma^2_{\tilde{v}}}{V_{t-1|\underline{t-1}}+\sigma^2_{\tilde{v}}} + \sigma^2_{\pi})\sigma^2_{v,z}}{\rho^2 \frac{V_{t-1|\underline{t-1}}\sigma^2_{\tilde{v}}}{V_{t-1|\underline{t-1}}+\sigma^2_{\tilde{v}}} + \sigma^2_{\pi} + \sigma^2_{v,z}} \\
&= \frac{(\rho^2 (V_{t-1|\underline{t-1}}\sigma^2_{\tilde{v}}) + \sigma^2_{\pi}(V_{t-1|\underline{t-1}} + \sigma^2_{\tilde{v}}))\sigma^2_{v,z}}{\rho^2 (V_{t-1|\underline{t-1}}\sigma^2_{\tilde{v}}) + (\sigma^2_{\pi} + \sigma^2_{v,z})(V_{t-1|\underline{t-1}} + \sigma^2_{\tilde{v}})},
\end{aligned}
\tag{21}
$$

and hence the asymptotic variance, V, of the forecast error, $V_{t|\underline{t}}$, solves the quadratic equation

$$
V = \frac{(\rho^2 V \sigma^2_{\tilde{v}} + \sigma^2_{\pi}(V + \sigma^2_{\tilde{v}}))\sigma^2_{v,z}}{\rho^2 V \sigma^2_{\tilde{v}} + (\sigma^2_{\pi} + \sigma^2_{v,z})(V + \sigma^2_{\tilde{v}})},
\tag{22}
$$

which admits only one positive solution:

$$
\begin{aligned}
V =& \frac{-\sigma^2_{\pi}\sigma^2_{\tilde{v}} + \sigma^2_{\pi}\sigma^2_{v,z} - (1-\rho^2)\sigma^2_{\tilde{v}}\sigma^2_{v,z}}{2\left(\sigma^2_{\pi} + \sigma^2_{\tilde{v}}\rho^2 + \sigma^2_{v,z}\right)} \\
&+ \frac{\sqrt{\left(\sigma^2_{\pi}\sigma^2_{\tilde{v}} - \sigma^2_{\pi}\sigma^2_{v,z} + (1-\rho^2)\sigma^2_{\tilde{v}}\sigma^2_{v,z}\right)^2 + 4\sigma^2_{\pi}\sigma^2_{\tilde{v}}\sigma^2_{v,z}\left(\sigma^2_{\pi} + \sigma^2_{\tilde{v}}\rho^2 + \sigma^2_{v,z}\right)}}{2\left(\sigma^2_{\pi} + \sigma^2_{\tilde{v}}\rho^2 + \sigma^2_{v,z}\right)}.
\end{aligned}
\tag{23}
$$

To understand how V depends on the variance of the noise we can look at the equations defining the asymptotic values of the forecast error variances at different points in time

$$
V = \frac{W\sigma^2_{v,z}}{W + \sigma^2_{v,z}},
\tag{24}
$$

$$
W = \rho^2 U + \sigma^2_{\pi},
\tag{25}
$$

$$
U = \frac{V\sigma^2_{\tilde{v}}}{V + \sigma^2_{\tilde{v}}},
\tag{26}
$$

where V, W and U are the asymptotic values of $V_{t|\underline{t}}$, $V_{t|\overline{t-1}}$ and $V_{t-1|\overline{t-1}}$, respectively. In particular we consider the case where only one value of the observational noise variance is realised and how the asymptotic values of the forecast error variances depends on it. We now prove the following proposition.

Proposition 2. *The asymptotic variances of the forecast errors of the Kalman filter are increasing in the noise in the private signals received by the agents, i.e.*

$$\frac{dV}{d\sigma^2_{v,z}} > 0, \qquad \frac{dW}{d\sigma^2_{v,z}} > 0, \qquad \frac{dU}{d\sigma^2_{v,z}} > 0, \tag{27}$$

and hence

$$V^H > V^L, \qquad W^H > W^L, \qquad U^H > U^L. \tag{28}$$

Proof. Taking derivative in $\sigma^2_{v,z}$ one finds

$$\begin{aligned}
\frac{dV}{d\sigma^2_{v,z}} &= \frac{1}{(W+\sigma^2_{v,z})^2}\left(\left(\frac{dW}{d\sigma^2_{v,z}}\sigma^2_{v,z} + W\right)(W+\sigma^2_{v,z}) - W\sigma^2_{v,z}\left(\frac{dW}{d\sigma^2_{v,z}}+1\right)\right) \\
&= \frac{1}{(W+\sigma^2_{v,z})^2}\left(W^2 + \sigma^4_{v,z}\frac{dW}{d\sigma^2_{v,z}}\right), & (29)\\
\frac{dW}{d\sigma^2_{v,z}} &= \rho^2\frac{dU}{d\sigma^2_{v,z}}, & (30)\\
\frac{dU}{d\sigma^2_{v,z}} &= \frac{1}{(V+\sigma^2_{\tilde{v}})^2}\left(\frac{dV}{d\sigma^2_{v,z}}\sigma^2_{\tilde{v}}(V+\sigma^2_{\tilde{v}}) - V\sigma^2_{\tilde{v}}\frac{dV}{d\sigma^2_{v,z}}\right) = \frac{\sigma^4_{\tilde{v}}}{(V+\sigma^2_{\tilde{v}})^2}\frac{dV}{d\sigma^2_{v,z}}. & (31)
\end{aligned}$$

Substituting Eq. (31) and Eq. (30) in Eq. (29), one gets

$$\frac{dV}{d\sigma^2_{v,z}} = \left(1 - \frac{\rho^2\sigma^4_{v,z}}{(W+\sigma^2_{v,z})^2}\frac{\sigma^4_{\tilde{v}}}{(V+\sigma^2_{\tilde{v}})^2}\right)^{-1}\frac{W^2}{(W+\sigma^2_{v,z})^2}. \tag{32}$$

The proposition is obtained by observing that the term in parentheses is greater than zero, and that the signs $dV/d\sigma^2_{v,z}$ determines the sign of $dW/d\sigma^2_{v,z}$ and $dU/d\sigma^2_{v,z}$ due to Eq. (30) and (31). □

This result indicates that when the economy moves from a regime with low noise to a regime of high noise, all the errors at different steps increase, and vice versa. This result will be important in proving how information effects depend on the variance of the noise in the private signals of the agents. Before doing so, we can also prove the following propositions.

Proposition 3. *The steady state variances of the forecast errors of the Kalman filter are all increasing in the noise in the public signal delivered by the central bank via the interest rate decisions, which depends on the variance of monetary policy shocks and of the noise in the private signal received by the central bank, i.e.*

$$\frac{dV}{d\sigma^2_{\tilde{v}}} > 0, \qquad \frac{dW}{d\sigma^2_{\tilde{v}}} > 0, \qquad \frac{dU}{d\sigma^2_{\tilde{v}}} > 0. \tag{33}$$

Proof. Following the same steps used in proving Proposition 2, one finds that

$$\frac{dU}{d\sigma^2_{\tilde{v}}} = \left(1 - \frac{\rho^2\sigma^4_{v,z}}{(W+\sigma^2_{v,z})^2}\frac{\sigma^4_{\tilde{v}}}{(V+\sigma^2_{\tilde{v}})^2}\right)^{-1}\frac{V^2}{(V+\sigma^2_{\tilde{v}})^2}, \tag{34}$$

from which follows the statement of the proposition. □

Proposition 4. *The steady state variances of the forecast errors of the Kalman filter are all increasing in the variance of the shock to the inflation process.*

Proof. We can observe that

$$\frac{dW}{d\sigma^2_{\pi}} = \left(1 - \frac{\rho^2\sigma^4_{v,z}}{(W+\sigma^2_{v,z})^2}\frac{\sigma^4_{\tilde{v}}}{(V+\sigma^2_{\tilde{v}})^2}\right)^{-1}. \tag{35}$$

which delivers the result. □

We can now prove the following result.

Proposition 5. *The information channel of monetary policy strengthens with the increase in the noise in the economy, i.e.*

$$\frac{d}{d\sigma^2_{v,z}}(K_{2,\bar{t}}(1-K_{1,\underline{t}})) > 0, \tag{36}$$

and hence

$$K_2^H(1-K_1^H) > K_2^L(1-K_1^L), \tag{37}$$

where $K_1^H)$, K_1^L and $K_2^H)$, K_2^L are the asymptotic values of the Kalman gains in the states of high and low variance, respectively.

Proof. Let us first prove that the Kalman gain $K_{1,\underline{t}}$ is decreasing with the variance of the noise. Let us consider the derivative of $K_{1,\underline{t}}$ in $\sigma^2_{v,z}$

$$\frac{dK_{1,\underline{t}}}{d\sigma^2_{v,z}} = \frac{1}{(V_{t|\overline{t-1}} + \sigma^2_{v,z})^2}\left(\sigma^2_{v,z}\frac{dV_{t|\overline{t-1}}}{d\sigma^2_{v,z}} - V_{t|\overline{t-1}}\right), \tag{38}$$

which shows that asymtotically the sign of $dK_{1,\underline{t}}/d\sigma^2_{v,z}$ depends on the sign of

$$\frac{\sigma^2_{v,z}}{W}\frac{dW}{d\sigma^2_{v,z}} - 1. \tag{39}$$

Let us first express the term of interest as

$$\frac{\sigma^2_{v,z}}{W}\frac{dW}{d\sigma^2_{v,z}} = \frac{\sigma^2_{v,z}}{\rho^2\frac{V\sigma^2_{\tilde{v}}}{V+\sigma^2_{\tilde{v}}} + \sigma^2_\pi}\frac{dW}{d\sigma^2_{v,z}} \tag{40}$$

$$= \frac{\sigma^2_{v,z}}{\rho^2\frac{V\sigma^2_{\tilde{v}}}{V+\sigma^2_{\tilde{v}}} + \sigma^2_\pi}\rho^2\frac{dU}{d\sigma^2_{v,z}} \tag{41}$$

$$= \frac{\sigma^2_{v,z}}{\rho^2\frac{V\sigma^2_{\tilde{v}}}{V+\sigma^2_{\tilde{v}}} + \sigma^2_\pi}\rho^2\frac{\sigma^4_{\tilde{v}}}{(V+\sigma^2_{\tilde{v}})^2}\frac{dV}{d\sigma^2_{v,z}}, \tag{42}$$

where we first used Eq.s (25-26), and then Eq.s (30-31). We can now observe that for the first factor in the above expression it is true that

$$\frac{\rho^2\sigma^2_{v,z}\sigma^4_{\tilde{v}}}{\left(\rho^2\frac{V\sigma^2_{\tilde{v}}}{V+\sigma^2_{\tilde{v}}} + \sigma^2_\pi\right)(V+\sigma^2_{\tilde{v}})^2} = \frac{\rho^2\sigma^2_{v,z}\sigma^4_{\tilde{v}}}{(\rho^2 V\sigma^2_{\tilde{v}} + \sigma^2_\pi(V+\sigma^2_{\tilde{v}}))(V+\sigma^2_{\tilde{v}})} \tag{43}$$

$$< \frac{\rho^2\sigma^2_{v,z}\sigma^4_{\tilde{v}}}{\rho^2 V\sigma^2_{\tilde{v}}(V+\sigma^2_{\tilde{v}})} = \frac{\sigma^2_{v,z}\sigma^2_{\tilde{v}}}{V(V+\sigma^2_{\tilde{v}})} < \frac{\sigma^2_{v,z}}{V}. \tag{44}$$

Hence it holds that $\frac{\sigma^2_{v,z}}{V}\frac{dV}{d\sigma^2_{v,z}} < 1$ then it is also true that $\frac{\sigma^2_{v,z}}{W}\frac{dW}{d\sigma^2_{v,z}} < 1$. Let us now focus on this simplified problem:

$$
\begin{aligned}
\frac{\sigma_{v,z}^2}{V}\frac{dV}{d\sigma_{v,z}^2} &= \frac{\sigma_{v,z}^2}{V}\left(1-\frac{\rho^2\sigma_{v,z}^4}{(W+\sigma_{v,z}^2)^2}\frac{\sigma_{\tilde{v}}^4}{(V+\sigma_{\tilde{v}}^2)^2}\right)^{-1}\frac{W^2}{(W+\sigma_{v,z}^2)^2} \\
&= \frac{\sigma_{v,z}^2}{V}\left(1-\frac{\rho^2\sigma_{v,z}^4}{(W+\sigma_{v,z}^2)^2}\frac{\sigma_{\tilde{v}}^4}{(V+\sigma_{\tilde{v}}^2)^2}\right)^{-1}\frac{W^2}{(W+\sigma_{v,z}^2)^2} \\
&= \frac{\sigma_{v,z}^2}{\frac{W\sigma_{v,z}^2}{W+\sigma_{v,z}^2}}\left(1-\frac{\rho^2\sigma_{v,z}^4}{(W+\sigma_{v,z}^2)^2}\frac{\sigma_{\tilde{v}}^4}{\left(\frac{W\sigma_{v,z}^2}{W+\sigma_{v,z}^2}+\sigma_{\tilde{v}}^2\right)^2}\right)^{-1}\frac{W^2}{(W+\sigma_{v,z}^2)^2} \\
&= \frac{W}{(W+\sigma_{v,z}^2)}\left(1-\frac{\rho^2\sigma_{v,z}^4}{(W+\sigma_{v,z}^2)^2}\frac{\sigma_{\tilde{v}}^4}{\left(\frac{W\sigma_{v,z}^2}{W+\sigma_{v,z}^2}+\sigma_{\tilde{v}}^2\right)^2}\right)^{-1} \\
&= \frac{W}{(W+\sigma_{v,z}^2)}\left(\frac{(W+\sigma_{v,z}^2)^2\left(\frac{W\sigma_{v,z}^2}{W+\sigma_{v,z}^2}+\sigma_{\tilde{v}}^2\right)^2-\rho^2\sigma_{v,z}^4\sigma_{\tilde{v}}^4}{(W+\sigma_{v,z}^2)^2\left(\frac{W\sigma_{v,z}^2}{W+\sigma_{v,z}^2}+\sigma_{\tilde{v}}^2\right)^2}\right)^{-1} \\
&= W\left(\frac{(W+\sigma_{v,z}^2)\left(\frac{W\sigma_{v,z}^2}{W+\sigma_{v,z}^2}+\sigma_{\tilde{v}}^2\right)^2}{(W+\sigma_{v,z}^2)^2\left(\frac{W\sigma_{v,z}^2}{W+\sigma_{v,z}^2}+\sigma_{\tilde{v}}^2\right)^2-\rho^2\sigma_{v,z}^4\sigma_{\tilde{v}}^4}\right) \\
&= \frac{(W^2+W\sigma_{v,z}^2)\left(\frac{W\sigma_{v,z}^2}{W+\sigma_{v,z}^2}+\sigma_{\tilde{v}}^2\right)^2}{(W^2+W\sigma_{v,z}^2+W\sigma_{v,z}^2+\sigma_{v,z}^4)\left(\frac{W\sigma_{v,z}^2}{W+\sigma_{v,z}^2}+\sigma_{\tilde{v}}^2\right)^2-\rho^2\sigma_{v,z}^4\sigma_{\tilde{v}}^4}.
\end{aligned}
$$

Let us define $\Delta \equiv (W+\sigma_{v,z}^2)\left(\frac{W\sigma_{v,z}^2}{W+\sigma_{v,z}^2}+\sigma_{\tilde{v}}^2\right)^2$. Hence we can write

$$
\begin{aligned}
\frac{\sigma_{v,z}^2}{V}\frac{dV}{d\sigma_{v,z}^2} &= \frac{\Delta}{\Delta+(W\sigma_{v,z}^2+\sigma_{v,z}^4)\left(\frac{W\sigma_{v,z}^2}{W+\sigma_{v,z}^2}+\sigma_{\tilde{v}}^2\right)^2-\rho^2\sigma_{v,z}^4\sigma_{\tilde{v}}^4} \\
&= \frac{\Delta(W+\sigma_{v,z}^2)^2}{\Delta(W+\sigma_{v,z}^2)^2+(W\sigma_{v,z}^2+\sigma_{v,z}^4)\left(W\sigma_{v,z}^2+\left(W+\sigma_{v,z}^2\right)\sigma_{\tilde{v}}^2\right)^2-\rho^2\sigma_{v,z}^4\sigma_{\tilde{v}}^4(W+\sigma_{v,z}^2)^2}.
\end{aligned}
$$

We can now define $\Delta' \equiv \Delta(W+\sigma_{v,z}^2)^2$ to rewrite

$$
\frac{\sigma_{v,z}^2}{V}\frac{dV}{d\sigma_{v,z}^2} = \frac{\Delta'}{\Delta'+\chi_1+\chi_2},
$$

where χ_1 and χ_2 are defined as

$$\begin{aligned}
\chi_1 &\equiv (1-\rho^2)\sigma_{v,z}^4\sigma_{\tilde{v}}^4(W+\sigma_{v,z}^2)^2, \\
\chi_2 &\equiv (W\sigma_{v,z}^2)\left(W^2\sigma_{v,z}^4+\left(W+\sigma_{v,z}^2\right)^2\sigma_{\tilde{v}}^4+2W\sigma_{v,z}^2\left(W+\sigma_{v,z}^2\right)\sigma_{\tilde{v}}^2\right) \\
&\qquad\qquad\qquad +\sigma_{v,z}^4\left(W^2\sigma_{v,z}^4+2W\sigma_{v,z}^2\left(W+\sigma_{v,z}^2\right)\sigma_{\tilde{v}}^2\right).
\end{aligned}$$

Observing that Δ' is positive, χ_1 is positive since $|\rho|<1$, and χ_2 is the sum of positive terms, it follows that

$$\frac{\sigma_{v,z}^2}{V}\frac{dV}{d\sigma_{v,z}^2}<1, \tag{45}$$

and hence that the Kalman gain $dK_{1,\underline{t}}$ is decreasing in the private noise, i.e.

$$\frac{dK_{1,\underline{t}}}{d\sigma_{v,z}^2}<0. \tag{46}$$

We can now observe that

$$\frac{K_{2,\bar{t}}}{d\sigma_{v,z}^2}=\frac{1}{(V_{t|\underline{t}}+\sigma_{\tilde{v}}^2)^2}\sigma_{\tilde{v}}^2\frac{dV_{t|\underline{t}}}{d\sigma_{v,z}^2}>0, \tag{47}$$

which follows from Eq. (27).

The proposition is then proved observing that $K_{2,\bar{t}}$ is increasing in the variance of the noise of the private signals obtained by the agents, while $K_{1,\underline{t}}$ is decreasing in it. □

B Data

In our empirical analysis, we employ the time series described in Table B.1. All series are at a monthly frequency.

Estimates for real GDP and the GDP deflator at a monthly frequency are obtained using a Kalman filter, following the methodology of Stock and Watson (2010) and Jarociński and Karadi (2020). The list of variables used in the interpolation exercise, along with their sources, is provided in Table B.1.

Subsections B.1 and B.2 discuss the series used for core inflation and industrial production, respectively.

Table B.1: Data Sources

Variable	Series/Dataset	Seas. Adj.	Source
HICP - All-items excluding energy and food	ICP.M.U2.N.XEF000.4.INX		Eurostat
HICP - All-items	ICP.M.U2.N.000000.4.INX		Eurostat
Industrial Production for the Euro Area[1] including construction (2015 = 100)	https://doi.org/10.2908/STS_COPR_M	•	Eurostat
Industrial production for Italy and Germany	STS_INPR_M	•	Eurostat
1 month OIS rate[2]			Datastream
3 month OIS rate[2]			Datastream
1 year OIS rate[2]			Bloomberg
2 years OIS rate[2]			Bloomberg
10 year OIS rate[2]			Datastream
10 year German government bond yield	GTDEM10Y		Bloomberg
10 year Italian government bond yield	GTITL10Y		Bloomberg
10 year ITA-DEU yield spread[3]			Eikon
EUR to USD Exchange Rate[4]	https://doi.org/10.2908/ERT_BIL_EUR_M		Eurostat
Recession dates for the euro area[5]	Euro Area business cycle chronology		EABCD Committee[6]
Quarterly forecasts for HICP inflation	440.MPD.Q.U2.HIC.A.XXX.XXXX[7]		ECB MPD
Annual forecasts for HICP inflation	440.MPD.A.U2.HIC.A.XXX.XXXX[7]		ECB MPD
Quarterly forecasts for real GDP growth	440.MPD.Q.U2.YER.P.XXX.XXXX[7]		ECB MPD
Annual forecasts for real GDP growth	440.MPD.A.U2.YER.P.XXX.XXXX[7]		ECB MPD
Quarterly forecasts for HICP inflation	Economic Indicator Polls		Reuters
Annual forecasts for HICP inflation	Economic Indicator Polls		Reuters
Quarterly forecasts for real GDP growth	Economic Indicator Polls		Reuters
Annual forecasts for real GDP growth	Economic Indicator Polls		Reuters
Quarterly forecasts for MRO rate	Central Bank Polls		Reuters
Real GDP			Authors' calculations
GDP deflator			Authors' calculations

[1] The series includes mining and quarrying, manufacturing, electricity, gas, steam and air conditioning supply, and construction sectors.
[2] Last price of the daily series.
[3] Yield spread with respect to 10 year German government bond yield.
[4] Monthly average.
[5] See https://eabcn.org/dbc/peaksandtroughs/chronology-euro-area-business-cycles.
[6] EABCD committee: Euro Area Business Cycle Dating Committee.
[7] The last seven letters vary by forecast season and horizon.
[8] The ECB Macroeconomic Projection Database is available on the ECB website https://data.ecb.europa.eu/data/datasets/MPD

Table B.1: List of variables used for interpolation

Quarterly indicator	Monthly indicator	Source
Private final consumption		Eurostat
	Retail trade	SDW
	Imports of consumer goods	SDW
Government final consumption		Eurostat
Gross fixed capital formation		Eurostat
	Construction output	Eurostat
Change in business inventories and acquisitions less disposable values		Eurostat
	Stocks of finished products	Eurostat
	Volume of stocks	Eurostat
Net exports of goods and services		Eurostat
	Trade balance in goods with rest of world	FRED
	Volume of export order books	Eurostat
	Manufacturing new orders	SDW
GDP deflator		Eurostat
	HICP	SDW
	Domestic PPI	Eurostat

Notes: SDW: Statistical Data Warehouse, ECB. FRED: Federal Reserve Economic Data. PPI: Producer price index.

B.1 On core inflation

In our analysis we do not employ the seasonally adjusted series for core inflation from the ECB. A note in the ECB website explains how in 2015 the German price index for package holidays has changed the seasonal adjustment pattern.[3]

Eurostat has adjusted the series whereas the ECB series still display some distortion especially in 2015 (see Chart C in the ECB article).[4]

In Figure B.2, we report how from September 2015 up to December 2015 the seasonal pattern of the HICP core (Eurostat) displays a larger peak than usual. We decided to use the Core measure from Eurostat for the adjustment reported in the Eurostat series. The results of the paper with the Core measures of the ECB are similar but we decided to use the Eurostat series because we are sure of the adjustment as reported in the Eurostat note.

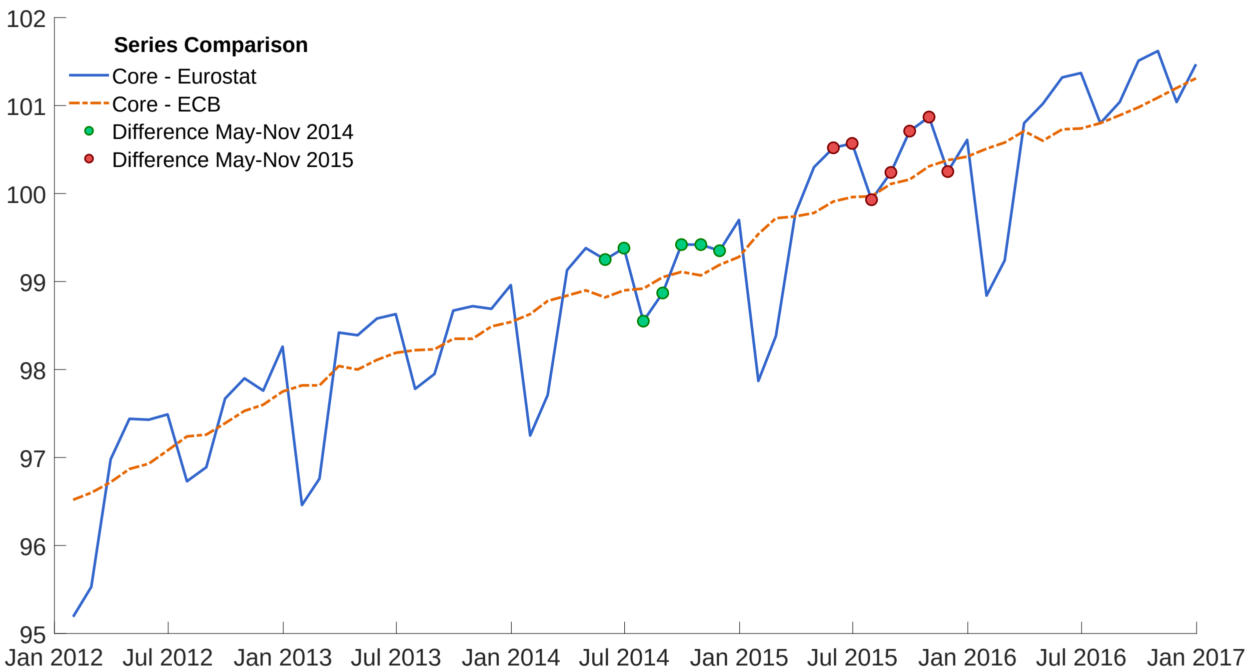
B.2 On industrial production

The series for industrial production we employ, which include constructions, is slightly different from the industrial production series excluding construction. The results in the paper are not affected by the choice of the series. For example, in Figure B.3 we report the IRFs of a 100 basis point tightening identified with the Target factor. We use the measure of industrial production excluding construction from the ECB ('STS.M.I9.Y.PROD.NS0020.4.000').

[3]See 'A new method for the package holiday price index in Germany and its impact on HICP inflation rates' published as part of the ECB Economic Bulletin, Issue 2/2019.

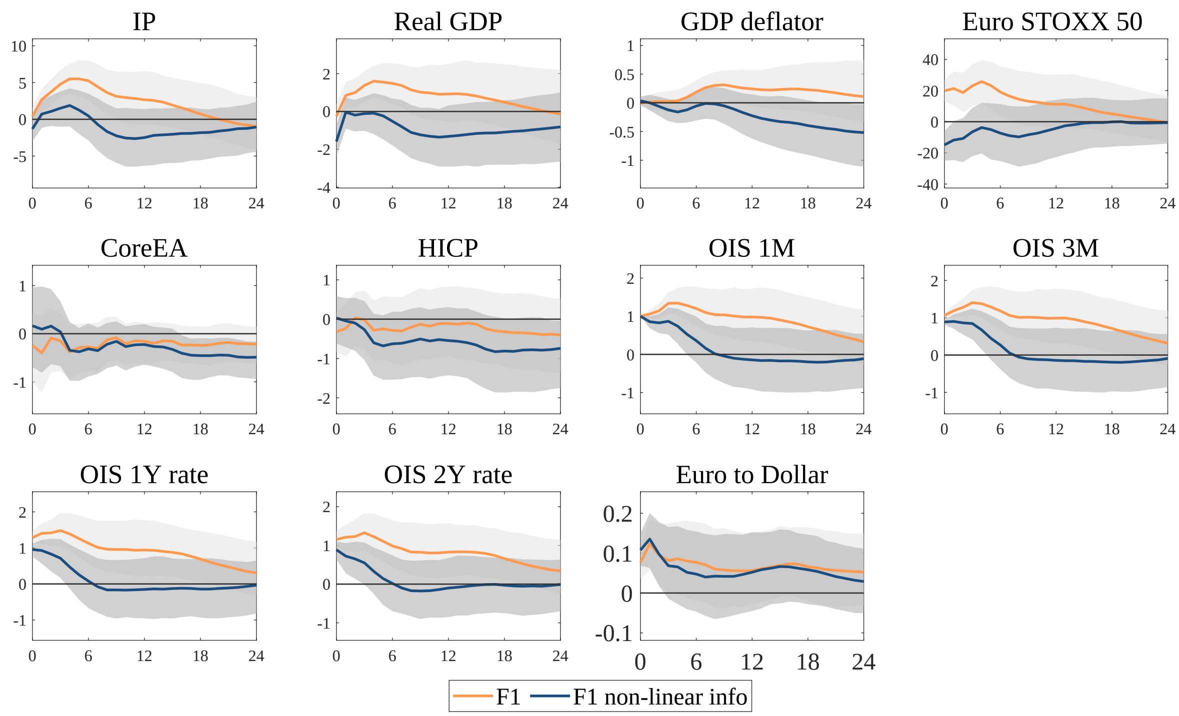
[4]See Eurostat, 'Improved calculation of HICP special aggregates and German package holidays methodological change', February 2019, p. 2 for the description of the changes

Figure B.2: Core in the Euro Area - ECB and Eurostat measures



Notes: The figure reports the difference in May-Nov 2015 of the ECB series (in orange) and Eurostat series (in blue). The blue circle shows how the peak in September 2015 for the Eurostat series was larger than the previous peaks during the same period of the year. This is consistent with the Chart C of the ECB note.

Figure B.3: IRFs to 100 basis points tightening in 1m-OIS - IP excluding construction



C Factor extraction

We employ the high-frequency price changes on 14 variables as reported in the Euro Area Monetary Policy Database (EA-MPD): 1-month OIS, 3-month OIS, 6-month OIS, 1-year OIS, 2-year OIS, 5-year OIS, 10-year OIS, 2-year SPREAD, 5-year SPREAD, 10-year SPREAD, EURGBP, EURJPY EURUSD, and STOXX50. We sum of the price changes in release and conference window. Differently to what done by Altavilla et al. (2019), we do not remove any observation in this time period.

The factor structure is:

$$Y = F\Lambda + \epsilon, \tag{48}$$

where Y is a $T \times 14$ matrix of surprises with T representing the number of ECB governing council meetings from 2002 to 2019. We extract four factors from these surprises. F represents the matrix of factors which, in our case, is $T \times 4$ and Λ is the loading matrix (4×14).

The factor structure is not unique. Consider an orthonormal matrix U (4×4) such that $UU' = I$:

$$Y = \tilde{F}\tilde{\Lambda} + \epsilon, \tag{49}$$

where $\tilde{F} = FU$ and $\tilde{\Lambda} = U'\Lambda$, which defines new matrices $\tilde{F}$ and $\tilde{\Lambda}$ consistent with the factor structure. Given the existence of 4 factors, 16 restrictions are needed to identify U, up to a sign.

Suppose $X_{.,j}$ is the j^{th} column of matrix X and $X_{i,.}$ is the i^{th} row of matrix X. The orthogonality of the columns provides 6 restrictions:

$$U'_{.,1}U_{.,2} = 0, U'_{.,1}U_{.,3} = 0, U'_{.,1}U_{.,4} = 0,$$
$$U'_{.,2}U_{.,3} = 0, U'_{.,2}U_{.,4} = 0, U'_{.,3}U_{.,4} = 0$$

The normalisation of the columns delivers 4 additional restrictions:

$$U'_{.,1}U_{.,1} = 1, U'_{.,2}U_{.,2} = 1, U'_{.,3}U_{.,3} = 1, U'_{.,4}U_{.,4} = 1$$

Thus, one has to define 6 additional restrictions to uniquely identify U (up to sign).

Following Gürkaynak et al. (2005) and Altavilla et al. (2019), we impose that all the factors apart from the target factor have zero effect on the 1-month OIS. This provides three additional restrictions:

$$U'_{.,2}\Lambda_{.,1} = 0, U'_{.,3}\Lambda_{.,1} = 0, U'_{.,4}\Lambda_{.,1} = 0$$

Following Swanson (2021) and Altavilla et al. (2019), we impose that the QE/QT factor has minimal variance in the pre-crisis period (January 2002-7 August 2008).[5]

We finally impose two restrictions on the fourth factor. First, we impose that it has zero effect on 10-year OIS to capture a factor that mainly influence sovereign yield:

$$U'_{.,4}\Lambda_{.,7} = 0$$

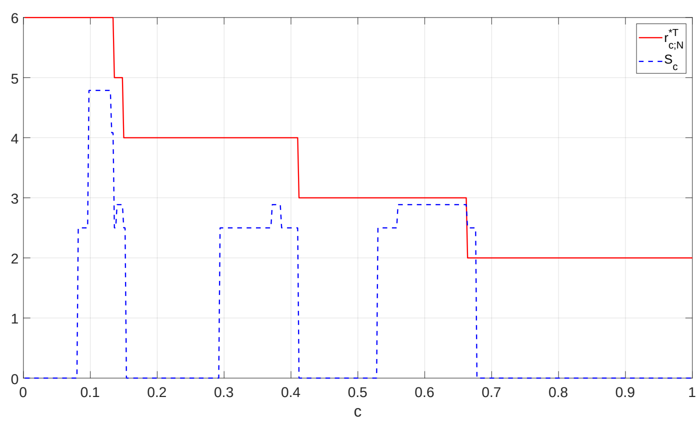
Second, we impose that country risk factor has the smallest variance in the pre-crisis period (January 2002-7 August 2008), as done for the QE/QT factor. This restriction is similar to what is imposed in Motto and Özen, 2022.

[5]Note that the uniqueness is up to a sign, so we have four scale normalisation. Altavilla et al. (2019) imposes that the three factors Target, Forward Guidance and Quantitative Easing are positively correlated with OIS 1 month, OIS 2 years and OIS 10 years, respectively. We do the same and we impose that the fourth factor, country risk factor, is positively correlated with 10-year Spread.

D Alessi et al. (2010)'s test

In Figure D.4, we report the result of the test of Alessi et al. (2010). The number of factor is determined by the second stability interval, i.e. the smallest value of c for which $r^{*T}_{c,N}$ is a constant function of the interval. Following Alessi et al. (2010), we have a stability interval when S_c is equal to zero. Thus, the second stability interval corresponds to a value of $r^{*T}_{c,N}$ equal to four, which indicates the existence of four statistically significant factors.

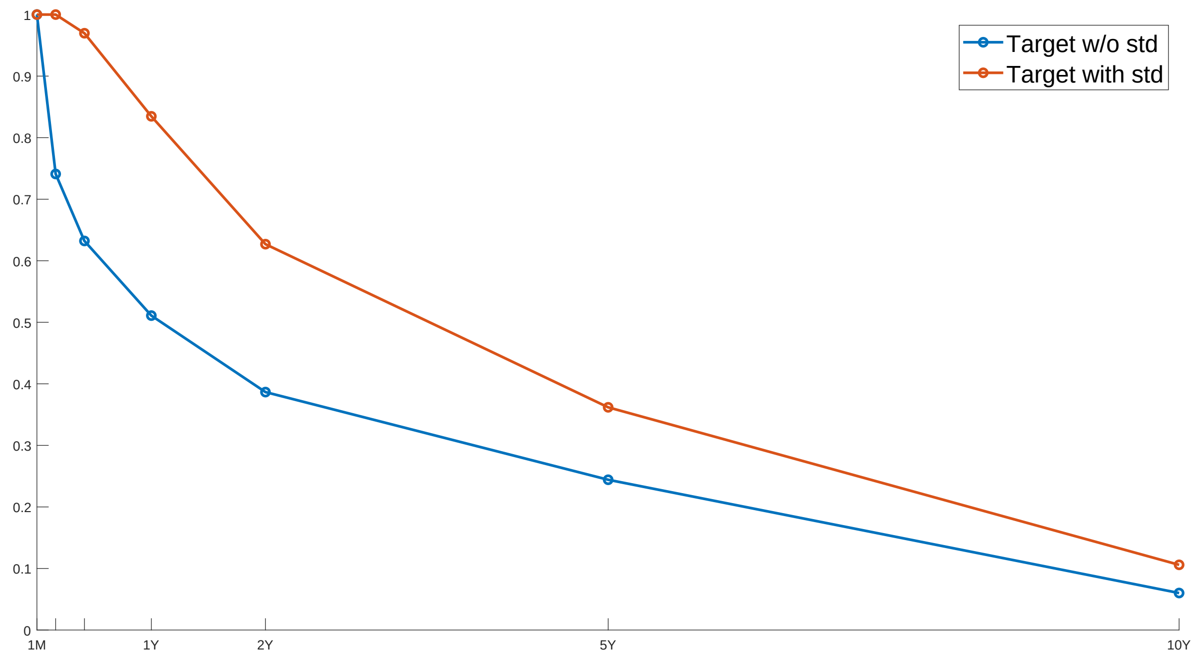
Figure D.4: Alessi et al. (2010) test for the number of factors



Notes: The figure reports the test proposed by Alessi et al. (2010). It plots $r^{*T}_{c,N}$ as a function of the parameter c, the penalisation term for the information criterion to evaluate the number of factors. The second stability interval for which S_c is equal to zero corresponds to $r^{*T}_{c,N} = 4$.

E Target factor loadings

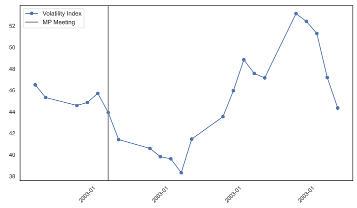
Figure E.5: Press release window



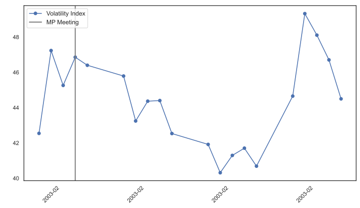
Notes: Figure E.5 reports the loadings of the Target factor as in Altavilla et al. (2019) (in blue) versus the loading of the same factor extracted with the standardisation of market surprises.

F VSTOXX in periods of high volatility

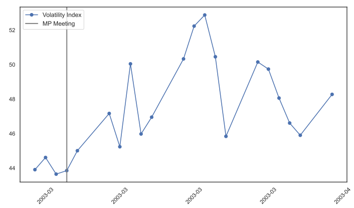
Figure F.6: Euro Stoxx Volatility Index for MP Meeting Dates 2003-2009



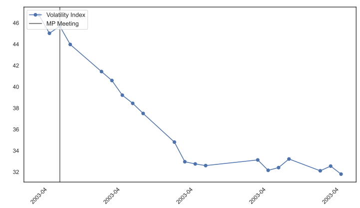
(a) MP Meeting Date: 2003-01-09



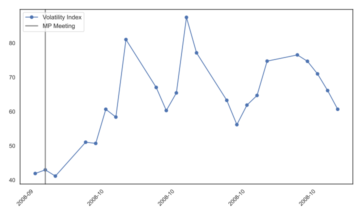
(b) MP Meeting Date: 2003-02-06



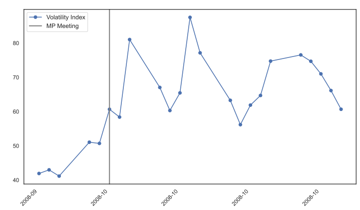
(c) MP Meeting Date: 2003-03-06



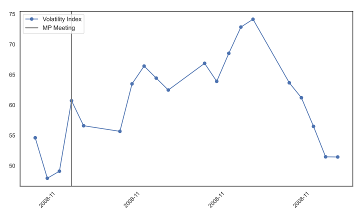
(d) MP Meeting Date: 2003-04-03



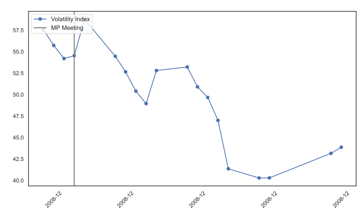
(e) MP Meeting Date: 2008-10-02



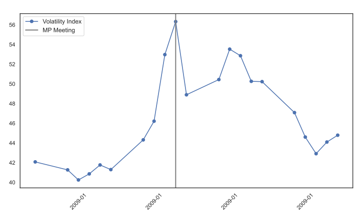
(f) MP Meeting Date: 2008-10-08



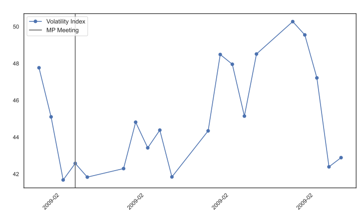
(g) MP Meeting Date: 2008-11-06



(h) MP Meeting Date: 2008-12-04



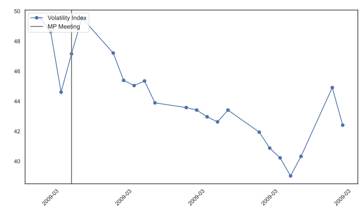
(i) MP Meeting Date: 2009-01-15

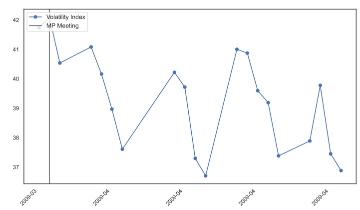


(j) MP Meeting Date: 2009-02-05

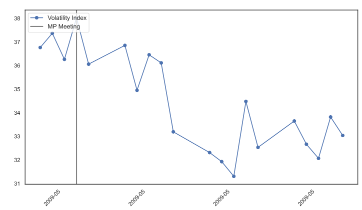
Notes: The figure displays the Euro Stoxx Volatility Index dynamics for the specified monetary policy meeting dates. Each subplot reports the volatility for the month of the MP meeting.

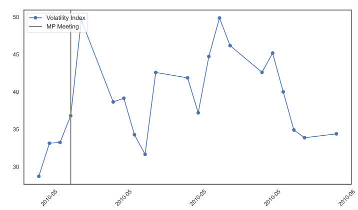
Figure F.7: Euro Stoxx Volatility Index for MP Meeting Dates 2009-2011



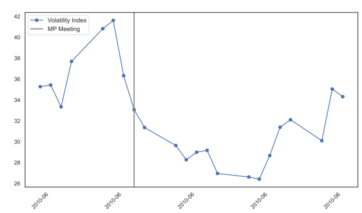


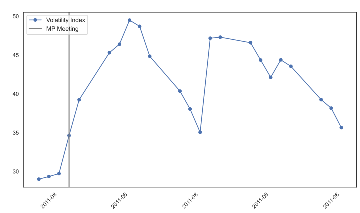
(a) MP Meeting Date: 2009-03-05 (b) MP Meeting Date: 2009-04-02



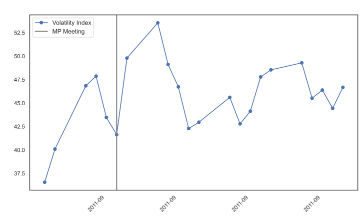


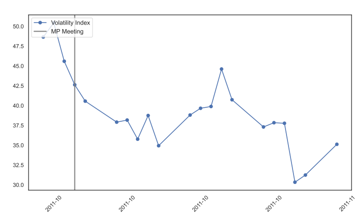
(c) MP Meeting Date: 2009-05-07 (d) MP Meeting Date: 2010-05-06



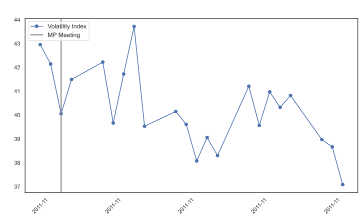


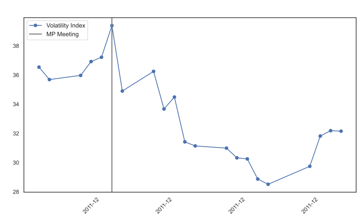
(e) MP Meeting Date: 2010-06-10 (f) MP Meeting Date: 2011-08-04





(g) MP Meeting Date: 2011-09-08 (h) MP Meeting Date: 2011-10-06





(i) MP Meeting Date: 2011-11-03 (j) MP Meeting Date: 2011-12-08

Notes: The figure displays the Euro Stoxx Volatility Index dynamics for the specified monetary policy meeting dates. Each subplot reports the volatility for the month of the MP meeting.

G Information effects – Additional tables

Table G.7: Projection of yield curve surprises on forecasts - Linear specification

	(1) 1m-OIS	(2) 3m-OIS	(3) 6m-OIS	(4) 1y-OIS	(5) 2y-OIS	(6) 5y-OIS	(7) 10y-OIS
$MRO_{q=0}$	0.112	0.206	0.255	0.231	0.220	0.487	0.403*
	(0.245)	(0.264)	(0.314)	(0.389)	(0.396)	(0.393)	(0.241)
$\Delta MRO_{q=0}$	-5.036**	-4.497*	-4.820*	-3.947	-3.340	-1.175	0.390
	(2.419)	(2.438)	(2.529)	(2.729)	(2.730)	(2.355)	(1.395)
$HICP_{q=1}$	0.074	0.191	-0.229	-0.497	-1.430	-2.122	-0.708
	(1.023)	(0.999)	(1.202)	(1.546)	(1.634)	(1.558)	(1.146)
$GDP_{q=0}$	-1.779	-1.222	-1.219	-0.804	0.630	2.262	1.182
	(1.383)	(1.538)	(1.755)	(2.239)	(2.455)	(2.347)	(1.538)
$GDP_{q=2}$	2.768	1.257	0.791	0.563	-1.331	-2.342	-2.705
	(2.674)	(2.194)	(2.408)	(3.171)	(3.525)	(3.138)	(2.234)
$GDP_{y=0}$	0.399*	0.400*	0.457*	0.402	0.312	-0.008	-0.139
	(0.202)	(0.228)	(0.238)	(0.286)	(0.338)	(0.334)	(0.275)
$HICP_{y=0}$	0.009	0.248	0.523	0.471	0.693	0.963	0.324
	(1.178)	(0.945)	(1.018)	(1.255)	(1.326)	(1.287)	(0.907)
$HICP_{y=1}$	-2.401*	-3.185**	-2.974	-3.015	-2.513	-2.117	-1.917
	(1.315)	(1.565)	(1.820)	(2.189)	(2.409)	(2.389)	(1.748)
$\Delta HICP_{y=0}$	1.709*	1.272	1.463	1.364	0.789	0.629	1.064
	(0.928)	(0.947)	(1.045)	(1.247)	(1.302)	(1.267)	(0.899)
$HICP^{ECB}_{q=0}$	1.268	0.681	0.961	1.329	2.370	3.391*	1.808
	(0.895)	(1.072)	(1.317)	(1.854)	(2.050)	(1.954)	(1.351)
$\Delta HICP^{ECB}_{q=0}$	-1.292**	-0.625	-1.088	-0.671	-0.375	0.461	1.077
	(0.583)	(0.621)	(0.741)	(0.991)	(1.108)	(1.163)	(0.925)
$GDP^{ECB}_{y=0}$	-0.047	0.012	0.049	0.168	-0.039	-0.162	0.045
	(0.200)	(0.231)	(0.295)	(0.407)	(0.500)	(0.440)	(0.349)
$HICP^{ECB}_{y=0}$	-1.163	-0.491	-0.590	-0.675	-1.537	-2.628	-1.390
	(1.045)	(1.230)	(1.518)	(2.098)	(2.283)	(2.137)	(1.453)
$Constant$	2.657	3.579*	3.417	3.848	4.371	4.370	3.706*
	(1.775)	(1.929)	(2.258)	(2.668)	(2.920)	(2.819)	(2.176)
$\mathcal{R}^2_{adj}$	0.074	0.057	0.060	0.023	0.017	0.008	0.015
N	197	197	197	197	197	197	197

Notes: The table reports regression results for a test of linear information effects along the yield curve surprises.

Table G.7: Projection of spreads, exchange rates and stock market surprises on forecasts - Linear specification

	(1) 2y-Spread b/(se)	(2) 5y-Spread b/(se)	(3) 10y-Spread b/(se)	(4) EURGBP b/(se)	(5) EURJPY b/(se)	(6) EURUSD b/(se)	(7) STOXX50 b/(se)
$MRO_{q=0}$	0.148	-0.495	-0.474	0.040	0.053	0.081*	-0.007
	(0.553)	(0.588)	(0.614)	(0.035)	(0.043)	(0.046)	(0.066)
$\Delta MRO_{q=0}$	-2.512	-5.853***	-4.918**	0.064	0.274*	0.186	0.961***
	(1.987)	(2.173)	(2.231)	(0.132)	(0.152)	(0.168)	(0.249)
$HICP_{q=1}$	1.839*	1.923	1.540	-0.032	-0.091	-0.091	-0.052
	(1.097)	(1.198)	(1.124)	(0.163)	(0.185)	(0.215)	(0.271)
$GDP_{q=0}$	-0.898	-2.574	-3.108	-0.094	0.183	-0.090	0.399
	(2.980)	(3.048)	(2.664)	(0.214)	(0.210)	(0.236)	(0.352)
$GDP_{q=2}$	-1.164	1.038	1.618	0.256	-0.189	0.183	-0.434
	(3.233)	(3.108)	(3.064)	(0.238)	(0.281)	(0.302)	(0.509)
$GDP_{y=0}$	0.208	-0.048	0.005	-0.038	-0.025	-0.028	0.036
	(0.315)	(0.441)	(0.384)	(0.031)	(0.043)	(0.036)	(0.069)
$HICP_{y=0}$	-0.943	-1.323	-1.541	-0.027	0.171	0.101	-0.003
	(1.141)	(1.092)	(1.068)	(0.131)	(0.152)	(0.175)	(0.246)
$HICP_{y=1}$	-0.002	3.324	3.913	-0.029	-0.452	-0.340	-0.011
	(2.599)	(2.375)	(2.644)	(0.284)	(0.303)	(0.343)	(0.467)
$\Delta HICP_{y=0}$	0.685	2.036	1.058	-0.024	-0.052	0.068	-0.242*
	(1.134)	(1.322)	(0.961)	(0.114)	(0.118)	(0.130)	(0.142)
$HICP^{ECB}_{q=0}$	-0.233	-0.005	-1.852	-0.043	-0.037	0.043	-0.125
	(2.378)	(2.456)	(2.236)	(0.213)	(0.218)	(0.229)	(0.318)
$\Delta HICP^{ECB}_{q=0}$	-0.406	0.836	1.161	0.072	0.283**	0.128	-0.017
	(1.379)	(1.508)	(1.205)	(0.125)	(0.126)	(0.124)	(0.172)
$GDP^{ECB}_{y=0}$	-0.206	0.033	0.047	0.010	0.031	0.045	-0.031
	(0.524)	(0.536)	(0.491)	(0.058)	(0.053)	(0.052)	(0.078)
$HICP^{ECB}_{y=0}$	0.141	-0.103	1.692	0.079	0.084	-0.018	0.162
	(2.808)	(2.619)	(2.292)	(0.224)	(0.230)	(0.247)	(0.346)
$Constant$	-1.286	-5.583*	-5.519	0.026	0.536	0.348	0.034
	(3.422)	(3.319)	(3.829)	(0.361)	(0.414)	(0.466)	(0.673)
$\mathcal{R}^2_{adj}$	-0.022	0.020	0.003	-0.024	-0.002	-0.022	0.026
N	197	197	197	197	197	197	197

Notes: The table reports regression results for a test of linear information effects in spreads, exchange rates, and stock market surprises.

Table G.7: PROJECTION OF SPREADS, EXCHANGE RATES AND STOCK MARKET SURPRISES ON FORECASTS - NON-LINEAR SPECIFICATION

	(1) 2y-Spread b/(se)	(2) 5y-Spread b/(se)	(3) 10y-Spread b/(se)	(4) EURGBP b/(se)	(5) EURJPY b/(se)	(6) EURUSD b/(se)	(7) STOXX50 b/(se)
$MRO_{q=0}$	0.256	-0.275	-0.394	0.050	0.023	0.062	-0.060
	(0.524)	(0.575)	(0.543)	(0.039)	(0.048)	(0.053)	(0.068)
$\Delta MRO_{q=0}$	-8.910**	-12.285**	-11.156*	0.282	0.257	0.189	1.069**
	(3.775)	(5.274)	(5.658)	(0.205)	(0.225)	(0.275)	(0.512)
$HICP_{q=1}$	1.045	0.967	0.550	0.001	-0.002	-0.022	0.141
	(1.275)	(1.584)	(1.385)	(0.193)	(0.216)	(0.258)	(0.310)
$GDP_{q=0}$	-0.089	-4.143	-4.572	-0.100	0.281	0.010	0.390
	(3.912)	(4.467)	(4.071)	(0.241)	(0.260)	(0.281)	(0.398)
$GDP_{q=2}$	-1.116	0.274	2.022	0.023	-0.166	0.162	0.374
	(3.790)	(4.181)	(3.467)	(0.285)	(0.351)	(0.384)	(0.463)
$GDP_{y=0}$	0.105	0.109	-0.069	-0.007	-0.015	-0.012	0.015
	(0.318)	(0.524)	(0.396)	(0.033)	(0.047)	(0.038)	(0.076)
$HICP_{y=0}$	-0.298	-0.906	-1.478	-0.044	0.123	0.060	-0.132
	(1.437)	(1.536)	(1.481)	(0.174)	(0.194)	(0.235)	(0.304)
$HICP_{y=1}$	0.377	4.170	6.361	-0.133	-0.440	-0.328	-0.016
	(3.098)	(3.579)	(3.958)	(0.318)	(0.350)	(0.389)	(0.559)
$\Delta HICP_{y=0}$	1.952	2.658	1.845	-0.072	-0.094	-0.020	-0.098
	(1.490)	(1.826)	(1.356)	(0.156)	(0.169)	(0.183)	(0.163)
$HICP^{ECB}_{q=0}$	0.812	-1.548	-2.744	0.117	-0.015	0.072	-0.400
	(2.974)	(3.060)	(2.883)	(0.241)	(0.324)	(0.329)	(0.367)
$\Delta HICP^{ECB}_{q=0}$	-0.139	2.258	2.593	-0.062	0.280	0.119	0.089
	(1.878)	(1.887)	(1.656)	(0.150)	(0.191)	(0.187)	(0.169)
$GDP^{ECB}_{y=0}$	-0.220	0.133	0.222	-0.016	0.007	0.016	-0.049
	(0.538)	(0.599)	(0.563)	(0.054)	(0.056)	(0.052)	(0.084)
$HICP^{ECB}_{y=0}$	-1.279	1.098	2.156	-0.057	0.073	-0.029	0.496
	(3.391)	(3.236)	(2.884)	(0.252)	(0.335)	(0.347)	(0.398)
$I(index) * MRO_{q=0}$	0.154	-0.666	-1.224	-0.033	0.201	-0.051	0.124
	(2.387)	(1.545)	(0.873)	(0.110)	(0.204)	(0.152)	(0.315)
$I(index) * \Delta MRO_{q=0}$	9.611**	8.510	8.686	-0.168	0.246	0.194	0.579
	(4.424)	(5.878)	(5.503)	(0.266)	(0.357)	(0.341)	(0.713)
$I(index) * HICP_{q=1}$	9.200	13.305*	-0.396	0.667	0.851	0.993	-0.581
	(9.856)	(7.693)	(4.797)	(0.556)	(0.898)	(0.604)	(1.311)
$I(index) * GDP_{q=0}$	5.485	17.812***	11.365**	-0.811	-0.933*	-0.835*	0.218
	(6.048)	(6.149)	(4.395)	(0.623)	(0.510)	(0.493)	(1.526)
$I(index) * GDP_{q=2}$	-22.679**	-26.069***	-14.598***	3.001***	1.816*	2.578***	-0.770
	(10.545)	(8.380)	(3.956)	(1.149)	(1.073)	(0.951)	(2.901)
$I(index) * GDP_{y=0}$	0.386	-2.723*	0.924	-0.500***	-0.444**	-0.612***	-0.214
	(2.101)	(1.618)	(1.010)	(0.183)	(0.206)	(0.148)	(0.335)
$I(index) * HICP_{y=0}$	-11.411*	-11.193**	-2.577	0.476	0.110	0.337	1.029
	(5.971)	(4.874)	(3.079)	(0.341)	(0.481)	(0.387)	(0.696)
$I(index) * HICP_{y=1}$	8.342	5.965	6.428***	-1.525**	-1.318**	-1.487***	-0.448
	(5.323)	(4.124)	(2.250)	(0.632)	(0.575)	(0.444)	(1.172)
$I(index) * \Delta HICP_{y=0}$	-0.949	-0.317	-1.247	-0.213	-0.170	-0.148	-0.780*
	(2.241)	(2.544)	(1.577)	(0.240)	(0.258)	(0.243)	(0.470)
$I(index) * HICP^{ECB}_{q=0}$	-3.930	3.590	0.002	0.261	-0.065	-0.097	1.149
	(5.474)	(5.534)	(3.718)	(0.576)	(0.562)	(0.605)	(0.861)
$I(index) * \Delta HICP^{ECB}_{q=0}$	-7.466**	-13.293***	-6.790**	-0.425	-0.323	-0.605	-0.678
	(3.653)	(4.206)	(3.027)	(0.370)	(0.309)	(0.389)	(0.539)
$I(index) * GDP^{ECB}_{y=0}$	4.839*	5.439**	0.172	0.652**	0.370*	0.474*	0.237
	(2.512)	(2.519)	(1.497)	(0.279)	(0.209)	(0.279)	(0.437)
$I(index) * HICP^{ECB}_{y=0}$	3.024	-5.238	0.763	-0.668	-0.149	-0.218	-1.627*
	(5.982)	(6.224)	(4.020)	(0.641)	(0.596)	(0.673)	(0.948)
$Constant$	-1.794	-5.656	-7.565	0.214	0.441	0.265	-0.302
	(3.793)	(4.334)	(4.667)	(0.407)	(0.466)	(0.521)	(0.768)
$\mathcal{R}^2_{adj}$	0.021	0.053	-0.001	-0.022	-0.041	-0.061	0.038
N	197	197	197	197	197	197	197

Notes: The table reports regression results for a test of non-linear information effects in spreads, exchange rates, and stock market surprises.

Table G.7: PROJECTION OF YIELD CURVE SURPRISES ON FORECASTS - LASSO OVER LARGER SET OF FORECASTS

	(1) 1m-OIS	(2) 3m-OIS	(3) 6m-OIS	(4) 1y-OIS	(5) 2y-OIS	(6) 5y-OIS	(7) 10y-OIS
$\Delta HICP^{ECB}_{q=4}$	-2.623**	-1.869	-2.471	-3.024			
	(1.064)	(1.663)	(1.778)	(2.277)			
$\Delta MRO_{q=1}$	-3.135**						
	(1.518)						
$\Delta HICP_{q=4}$	-3.565						
	(2.200)						
$\Delta MRO_{q=0}$		-2.740	-2.992*	-4.637*	-3.150		
		(1.787)	(1.770)	(2.461)	(2.504)		
$\Delta GDP_{q=4}$		-6.221					
		(3.880)					
$\Delta GDP^{ECB}_{q=4}$			-7.481	-13.089**	-8.300		
			(4.930)	(6.575)	(5.606)		
$HICP^{ECB}_{y=0}$			0.530*				
			(0.318)				
$HICP^{ECB}_{q=4}$				1.123***	1.126**	1.013**	0.722***
				(0.431)	(0.449)	(0.423)	(0.415)
$\Delta HICP^{ECB}_{y=0}$				2.325**			
				(1.010)			
$\Delta MRO_{q=3}$				3.790			
				(2.527)			
$\Delta HICP_{q=0}$				-0.439	-0.751	-0.827	
				(0.430)	(0.574)	(0.505)	
$GDP_{q=4}$					-1.665		
					(3.019)		
$\Delta GDP^{ECB}_{q=0}$							3.641**
							(1.824)
$\Delta HICP^{ECB}_{q=3}$						1.999	1.421
						(1.219)	(1.003)
$\Delta HICP_{q=2}$							1.843*
							(1.052)
$GDP_{q=2}$							-6.593**
							(3.298)
$HICP_{y=1}$							-1.134
							(0.731)
Constant	0.007	-0.023	-0.299	0.133	1.136	0.697	1.390
	(0.189)	(0.194)	(0.262)	(0.641)	(1.277)	(0.808)	(1.238)
$\mathcal{R}^2_{adj}$	0.124	0.081	0.090	0.097	0.063	0.056	0.111
N	197	197	197	197	197	197	197

Notes: The table reports regression results for a test of linear information effects along yield curve surprises when we use LASSO over a larger set of forecasts with respect to the baseline. Specifically, we include forecast for longer horizons (up to four quarters for quarterly forecasts and two years for yearly forecasts). By including a larger set of forecasts, especially those at longer horizons, we are able to capture more than 11% of the variability of the 10y-OIS and larger variability for longer maturities of the yield curve.

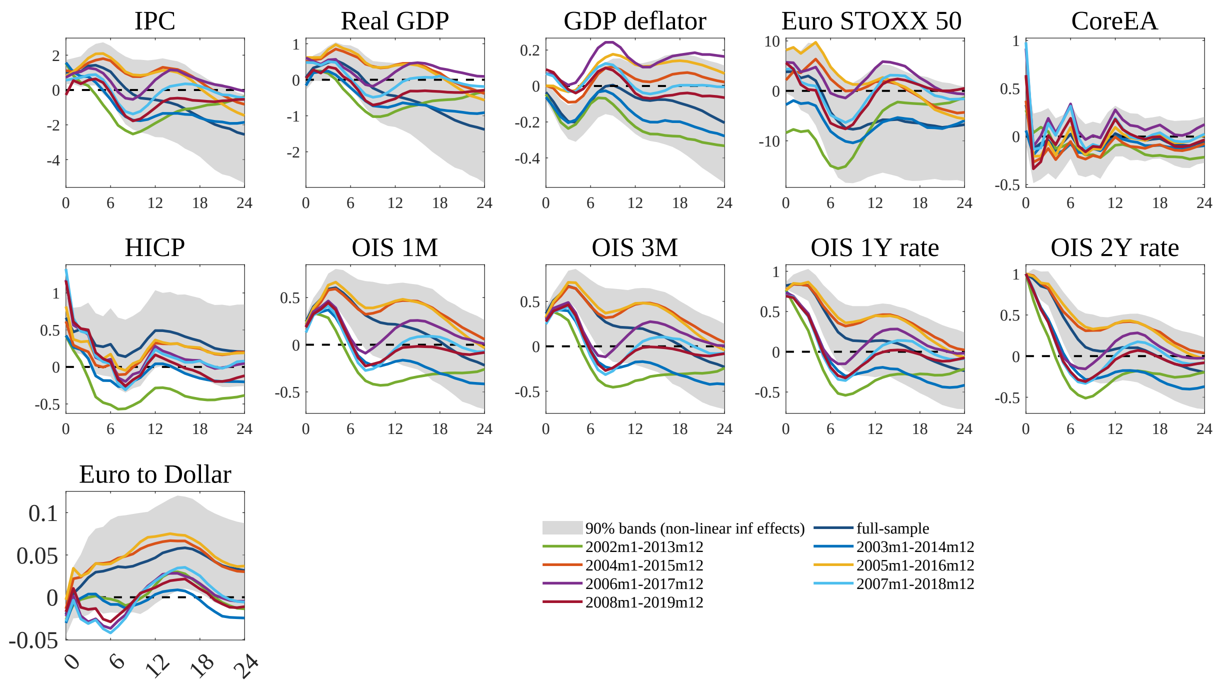
Table G.7: Projection of spreads, exchange rates and stock market surprises on forecasts - Lasso over larger set of forecasts

	(1) 2y-Spread b/(se)	(2) 5y-Spread b/(se)	(3) 10y-Spread b/(se)	(4) EURGBP b/(se)	(5) EURJPY b/(se)	(6) EURUSD b/(se)	(7) STOXX50 b/(se)
$HICP_{q=0}$	0.861***						
	(0.286)						
$\Delta GDP^{ECB}_{q=3}$		-8.520					
		(7.622)					
$\Delta HICP^{ECB}_{q=3}$		3.354**					
		(1.633)					
$\Delta MRO_{q=0}$		-3.258*	-4.143*				0.657***
		(1.823)	(2.127)				(0.215)
$\Delta MRO_{q=4}$		-1.213					
		(1.496)					
$GDP_{q=1}$		-1.947					
		(2.387)					
$\Delta GDP_{q=3}$		-9.544					
		(8.812)					
$HICP_{q=1}$		1.166***					
		(0.432)					
$\Delta GDP^{ECB}_{q=0}$				0.719***			
				(0.247)			
$\Delta HICP_{q=2}$						0.371***	
						(0.136)	
$\Delta MRO_{q=2}$							0.341*
							(0.194)
Constant	-1.667***	-1.540*	-0.090	-0.004	-0.015	-0.031	-0.093**
	(0.461)	(0.816)	(0.310)	(0.026)	(0.033)	(0.034)	(0.046)
$\mathcal{R}^2_{adj}$	0.025	0.077	0.021	0.050	0.000	0.024	0.060
N	197	197	197	197	197	197	197

Notes: The table reports regression results for a test of linear information effects in spreads, exchange rates, and stock market surprises when we use LASSO over a larger set of forecasts with respect to the baseline. Specifically, we include forecast for longer horizons (up to four quarters for quarterly forecasts and two years for yearly forecasts). By including a larger set of forecasts, we have qualitatively the same results as the baseline where we observe limited information effects for these surprises.

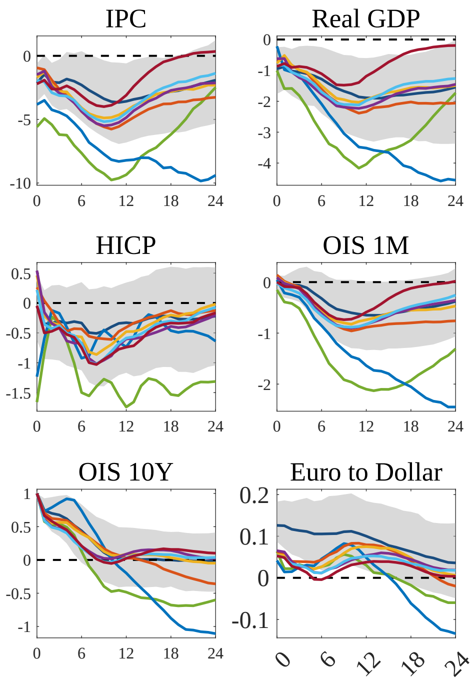
H Rolling subsamples for IRFs

Figure H.8: Forward Guidance factor – rolling sample



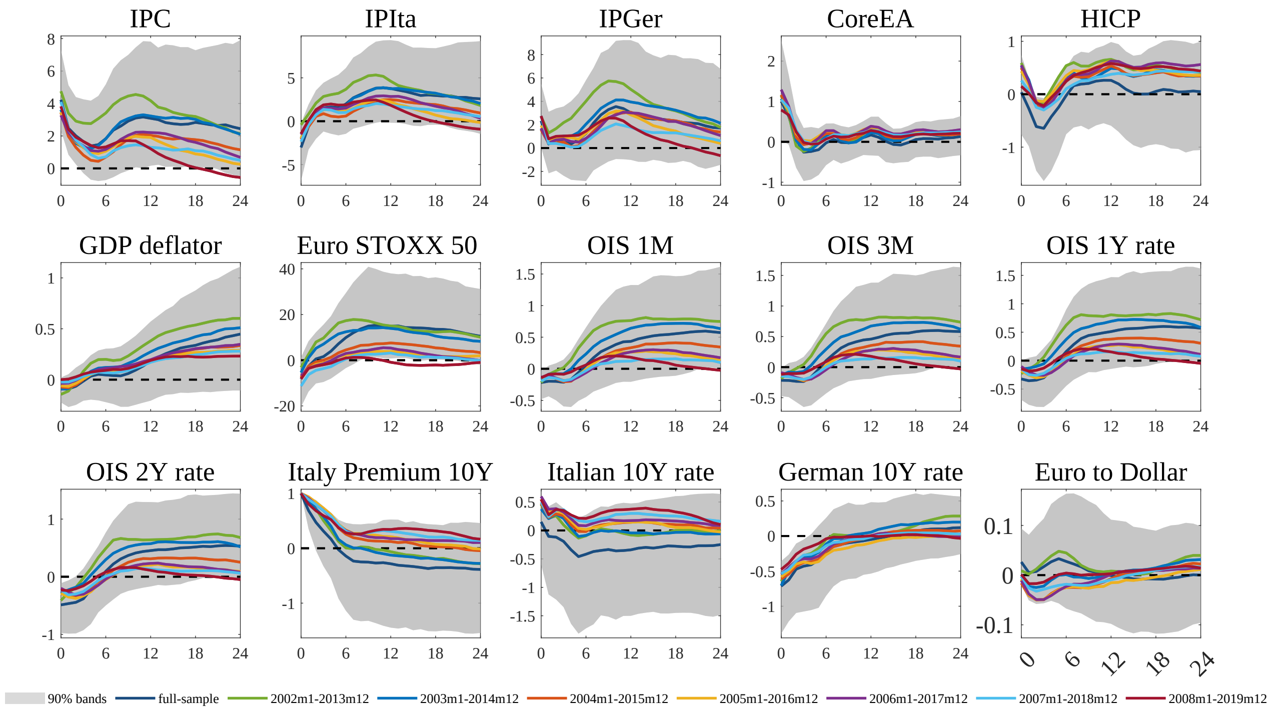
Notes: The figure reports the IRFs to a forward guidance shock on the baseline sample and on a set of rolling subsamples. The shock is identified with the informationally robust forward guidance factor, corrected for non-linear information effects, and normalised to induce a 100 basis points increase in the 2y-OIS rate. The grey areas are 90% coverage bands of the baseline specification.

Figure H.9: QE factor – rolling sample



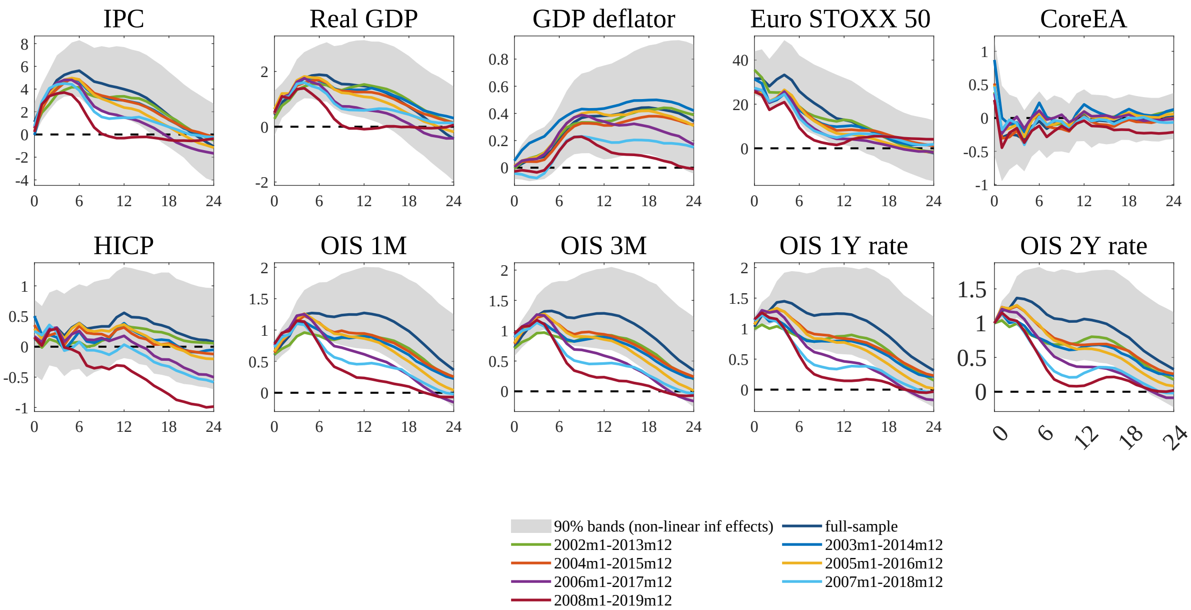
Notes: The figure reports the IRFs to a quantitative tightening shock on the baseline sample and on a set of rolling subsamples. The shock is identified with the QE/QT factor, corrected for non-linear information effects, and normalised to induce a 100 basis points increase in the 10y-OIS rate. The grey areas are 90% coverage bands of the baseline specification.

Figure H.10: Asymmetric country risk factor – rolling sample



Notes: The figure reports the IRFs to a asymmetric country risk shock on the baseline sample and on a set of rolling subsamples. The shock is identified with the asymmetric country risk factor, corrected for non-linear information effects, and normalised to induce a 100 basis points increase in the spread between the 10Y Italian government bond yield and the 10Y German government bond yield. The grey areas are 90% coverage bands of the baseline specification.

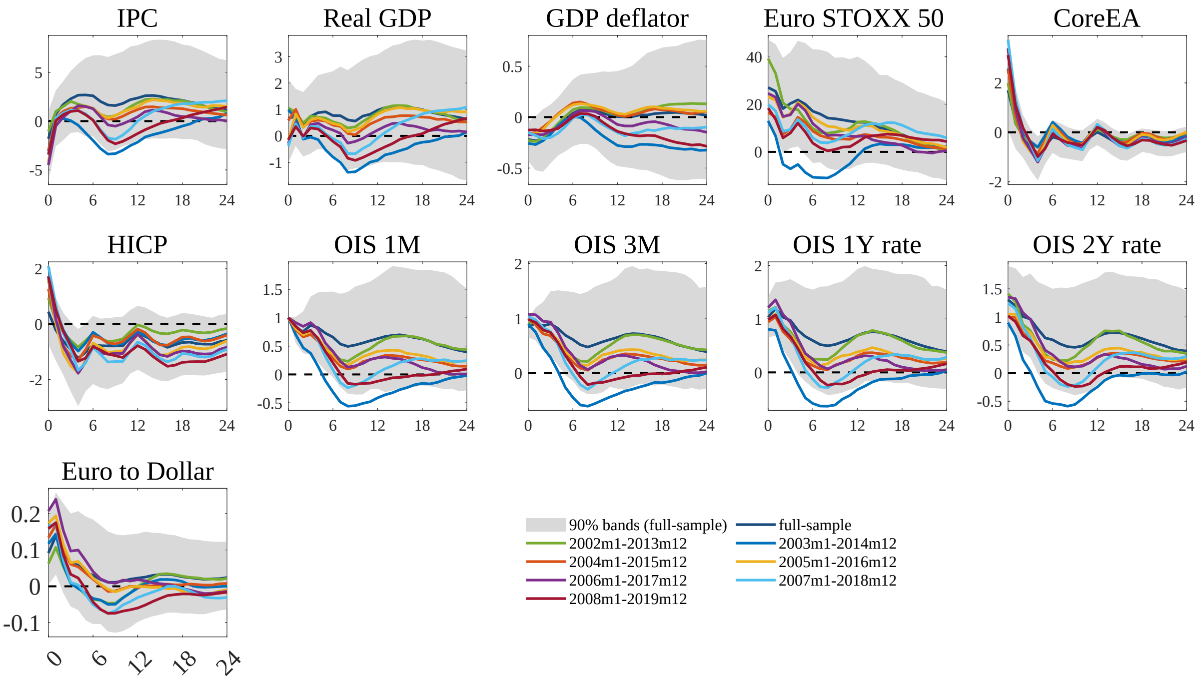
Figure H.11: Information factor – rolling sample



Notes: The figure reports the IRFs to an 'information shock' on the baseline sample and on a set of rolling subsamples. The shock is identified with an information factor defined as the sum of the first two principal components of the fitted values of the non-linear information effects regressions, and normalised to induce a 100 basis points increase in the 2y-OIS rate. The grey areas are 90% coverage bands of the baseline specification.

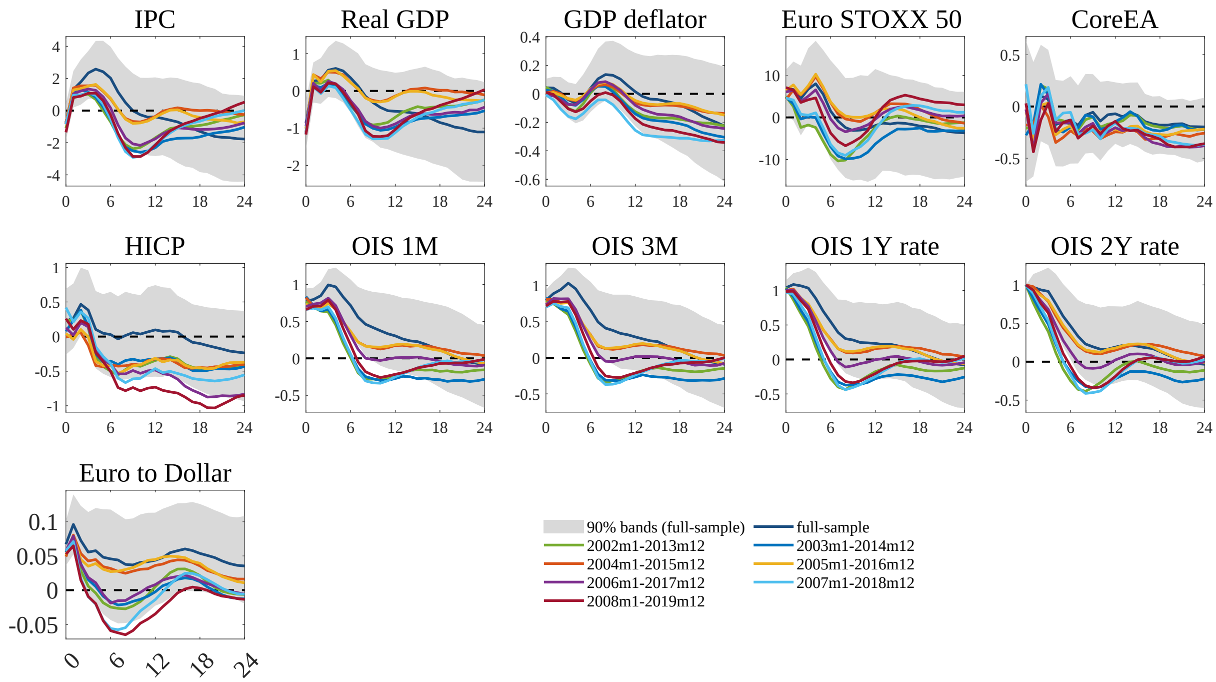
I Rolling subsamples for IRFs Altavilla et al. (2019)

Figure I.12: Target factor Altavilla et al. (2019) – rolling sample



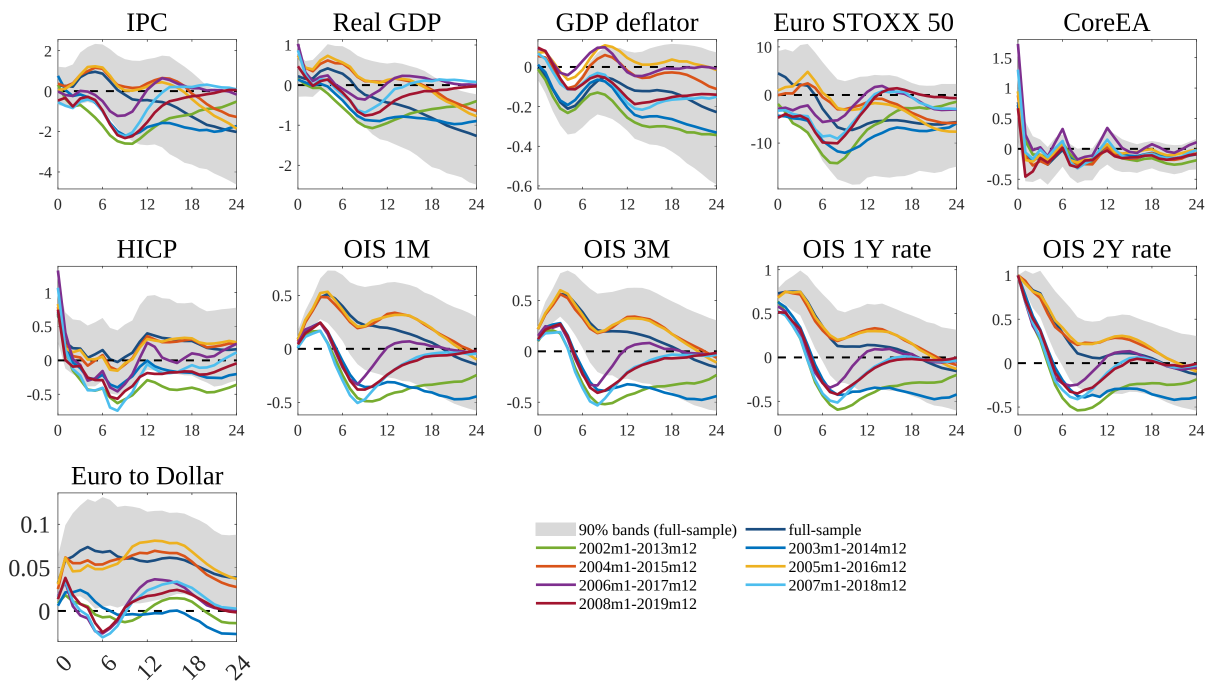
Notes: The figure reports the IRFs to a conventional monetary policy shock on the baseline sample and on a set of rolling subsamples. The shock is identified with the target factor of Altavilla et al. (2019), and normalised to induce a 100 basis points increase in the 1m-OIS rate. The grey areas are 90% coverage bands of the sample 2002-2019.

Figure I.13: Timing factor Altavilla et al. (2019) – rolling sample



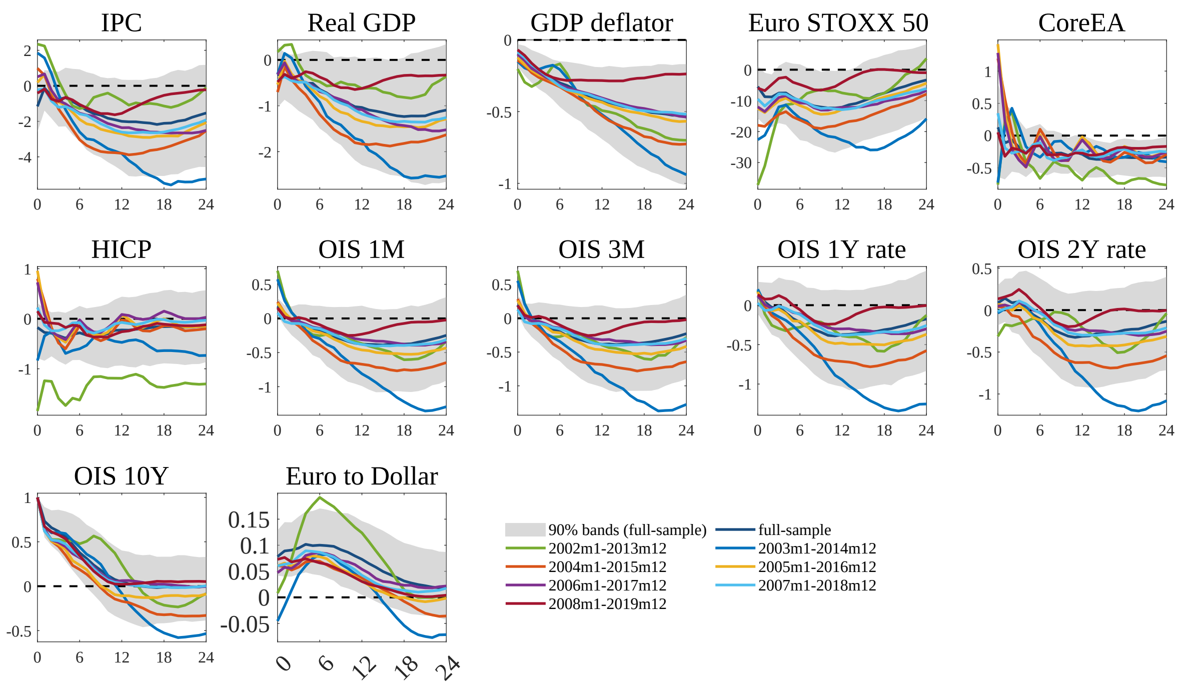
Notes: The figure reports the IRFs to a timing shock on the baseline sample and on a set of rolling subsamples. The shock is identified with the timing factor of Altavilla et al. (2019), and normalised to induce a 100 basis points increase in the 2y-OIS rate. The grey areas are 90% coverage bands of the sample 2002-2019.

Figure I.14: Forward guidance factor Altavilla et al. (2019) – rolling sample



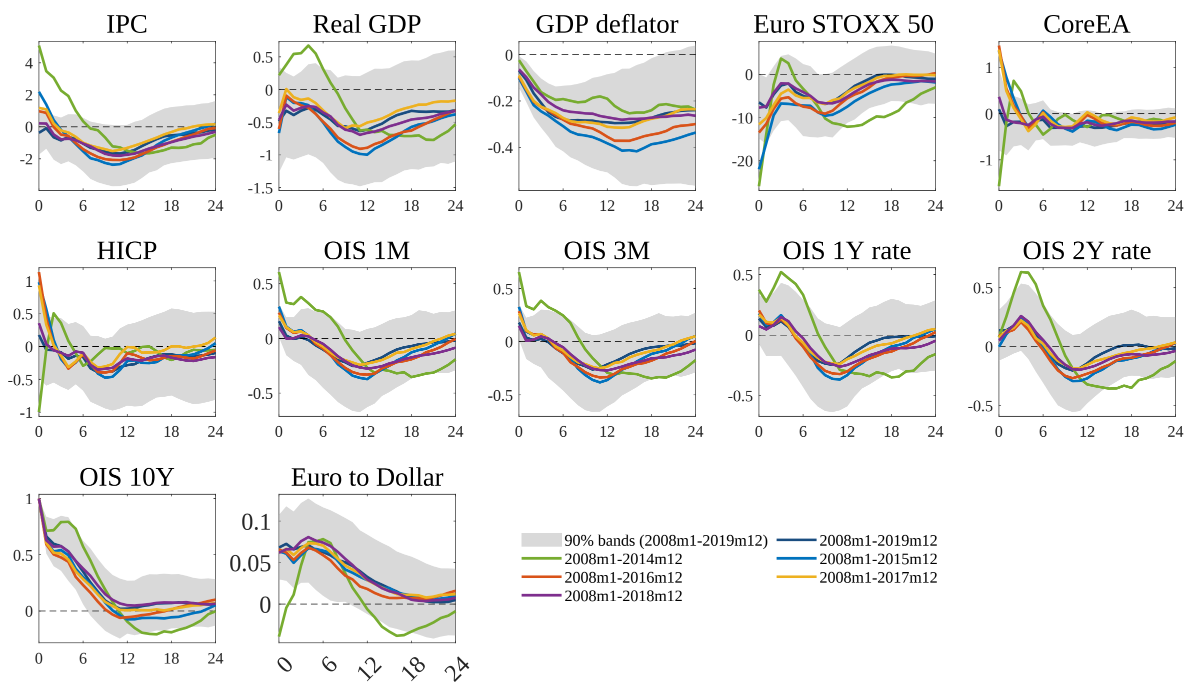
Notes: The figure reports the IRFs to a forward guidance shock on the baseline sample and on a set of rolling subsamples. The shock is identified with the forward guidance factor of Altavilla et al. (2019), and normalised to induce a 100 basis points increase in the 2y-OIS rate. The grey areas are 90% coverage bands of the sample 2002-2019.

Figure I.15: Quantitative easing/tightening factor Altavilla et al. (2019) – rolling sample



Notes: The figure reports the IRFs to a quantitative tightening shock on the baseline sample and on a set of rolling subsamples. The shock is identified with the QE/QT factor of Altavilla et al. (2019), and normalised to induce a 100 basis points increase in the 10y-OIS rate. The grey areas are 90% coverage bands of the sample 2002-2019.

Figure I.16: Quantitative easing/tightening (Altavilla et al. (2019) factor) – extending samples



Notes: The figure reports the IRFs to a quantitative tightening shock on a set of subsamples starting from 2008. The shock is identified with the QE/QT factor of Altavilla et al. (2019), and normalised to induce a 100 basis points increase in the 10y-OIS rate. The grey areas are 90% coverage bands of the sample 2008-2019.

J Variance decomposition – Additional tables

Table J.16: Variance Decomposition at a short run horizon

Variables	*Target*	*Forward Guidance*	*QE*	*Asymmetric Country Risk*	*Information*
IP	5.67	14.55	5.46	9.78	13.33
	(3.67, 8.23)	(8.43, 20.51)	(2.73, 9.14)	(5.88, 13.86)	(8.60, 18.90)
Real GDP	5.54	14.24	6.83	–	7.86
	(3.48, 8.65)	(3.34, 11.44)	(1.59, 15.35)	–	(4.48, 11.81)
Stock Market	4.49	9.88	11.38	5.69	37.77
	(2.86, 6.70)	(5.66, 13.97)	(7.43, 15.59)	(2.55, 8.50)	(28.96, 45.40)
HICP	3.02	7.01	2.63	3.28	3.95
	(1.73, 4.79)	(4.56, 9.73)	(1.36, 4.18)	(1.77, 5.26)	(1.90, 6.33)
1m-OIS	16.92	20.19	5.24	8.61	26.24
	(11.69, 22.26)	(13.08, 27.78)	(1.86, 10.10)	(3.67, 13.87)	(19.14, 34.27)
1y-OIS	12.23	39.40	5.12	8.12	31.62
	(8.29, 16.12)	(29.46, 46.90)	(2.10, 8.86)	(3.80, 12.13)	(23.48, 39.60)
2y-OIS	8.87	43.14	5.71	8.06	27.16
	(5.93, 12.40)	(33.53, 50.45)	(2.77, 9.32)	(4.07, 12.41)	(19.29, 34.25)
10y-OIS	–	–	17.86	–	–
	–	–	(12.72, 22.87)	–	–
Spread 10Y	–	–	–	10.32	–
	–	–	–	(6.65, 15.65)	–
IP Italy	–	–	–	5.61	–
	–	–	–	(3.07, 8.45)	–
IP Germany	–	–	–	4.26	–
	–	–	–	(2.36, 6.69)	–

Notes: The table reports the percentage share of the variance for each variable considered as due to each monetary policy shock, in the range of short-term frequencies (i.e. 2 and 16 months), following the approach of Forni et al. (2022). 68% confidence bands are reported in parenthesis.

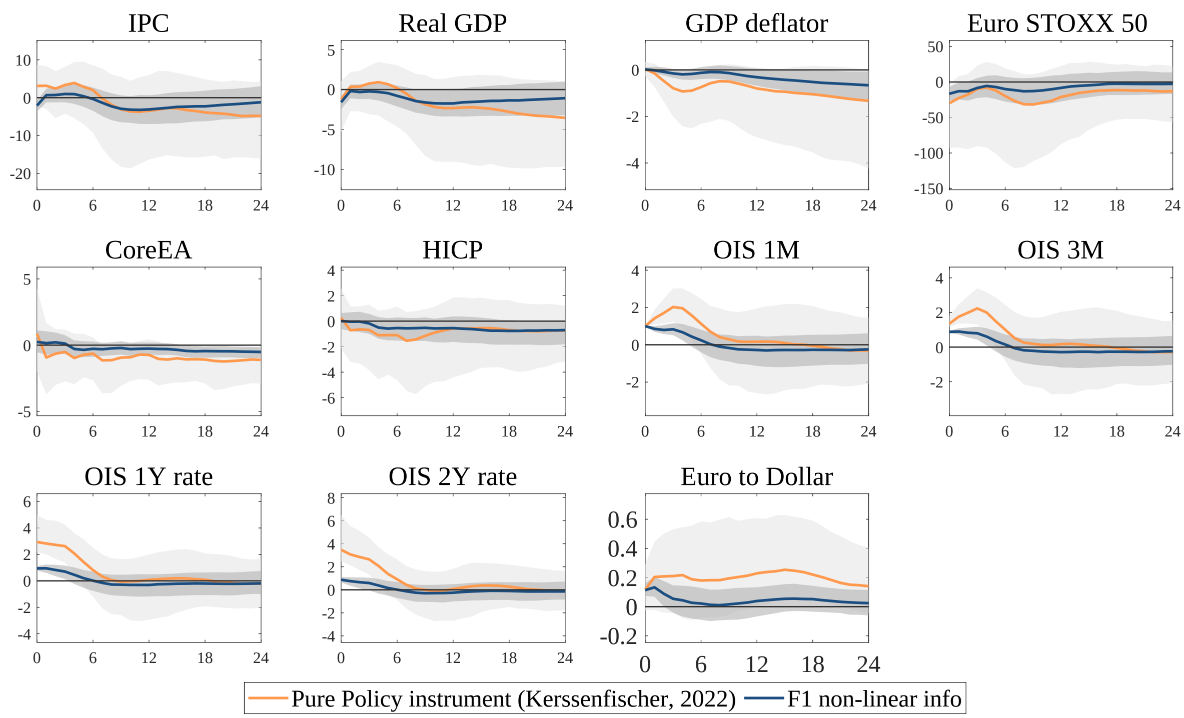
Table J.16: VARIANCE DECOMPOSITION – OVERALL VARIANCE

Variables	*Target*	*Forward Guidance*	*QE*	*Asymmetric Country Risk*	*Information*
IP	3.16	7.36	9.45	7.52	23.99
	(1.25, 6.73)	(3.39, 12.90)	(3.89, 16.99)	(2.84, 13.38)	(15.70, 34.66)
Real GDP	4.71	9.29	13.79	–	14.82
	(1.56, 9.40)	(3.81, 16.06)	(6.60, 21.80)	–	(8.35, 23.02)
Stock Market	3.35	6.50	14.86	6.79	32.19
	(1.31, 6.78)	(2.45, 11.97)	(7.42, 22.44)	(2.70, 12.74)	(21.33, 43.89)
HICP	4.10	6.59	3.23	2.50	5.05
	(1.21, 8.66)	(3.41, 12.03)	(1.19, 7.70)	(1.23, 4.67)	(1.94, 11.82)
1m-OIS	4.72	8.62	7.12	5.24	44.42
	(2.70, 7.86)	(5.36, 12.90)	(1.89, 14.46)	(1.45, 10.21)	(32.89, 56.13)
1y-OIS	3.91	12.58	6.25	5.70	42.85
	(2.11, 6.70)	(8.47, 17.03)	(1.87, 12.63)	(1.80, 10.45)	(31.24, 54.25)
2y-OIS	3.58	15.10	5.38	5.61	40.21
	(1.78, 6.00)	(10.46, 19.55)	(1.99, 10.57)	(2.25, 10.22)	(29.20, 51.23)
10y-OIS	–	–	10.83	–	–
	–	–	(6.41, 15.72)	–	–
Spread 10Y	–	–	–	3.85	–
	–	–	–	(1.79, 7.01)	–
IP Italy	–	–	–	5.51	–
	–	–	–	(2.16, 10.95)	–
IP Germany	–	–	–	3.66	–
	–	–	–	(1.32, 8.34)	–

Notes: The table reports the percentage share of the overall variance (i.e. 2+ months) for each variable considered as due to each monetary policy shock following the approach of Forni et al. (2022). 68% confidence bands are reported in parenthesis.

K A comparison with Kerssenfischer (2022)

Figure K.17: Conventional monetary policy shock – comparison with Kerssenfischer (2022)



Notes: The figure reports the IRFs to a conventional monetary policy shock, normalised to induce a 100 basis points increase in the 1m-OIS rate. In amber, it reports the responses obtained with the pure policy instrument identified by Kerssenfischer (2022). In blue, it reports the IRFs by using the informationally robust F1 factor. The grey areas are 90% coverage bands. The sample considered is 2002m3-2019m12.

L List of 10 largest surprises in identified factor series

The tables below reports the largest surprises in the four identified factors, presented in chronological order. Specifically:

- Column 2 of each table records the magnitude of the surprise on the particular date.
- Column 3 contains any changes in the key interest rates of the ECB: the Main Refinancing Operations (MRO) rate, the Marginal Lending Facility (MLF) rate and the Deposit Facility (EDF) rate. Prior to the Global Financial Crisis, in case of a change in the policy rate, all policy rates moved by the same magnitude. After October 2008, there were some instances where this was not the case. On such dates, we specify the rates which were changed.
- Column 4 provides the authors' summary of the economic analysis mentioned in the Introductory Statement of the ECB president in the press conference held to announce the policy decision. The economic analysis typically contains details about real GDP growth and inflation as well as their outlook.
- Column 5 provides additional notes on the events. These combine insights from high frequency surprise data in OIS rates and sovereign bonds on policy announcement dates, the median expected MRO forecast data, and reading the transcripts of the Q&A session held with journalists on the day of the policy announcement after the ECB president's Introductory Statement.[6]

[6]The transcripts of the ECB's monetary policy decisions can be found on the ECB website. They contain the Introductory Statement delivered by the ECB president and the Q&A session held with journalists. Reuters conducts polls for the median expected MRO multiple times for a specific quarter. We create a h quarter(s) ahead fixed event forecast from these polls.

L.1 Target factor

Table L.17: 10 largest surprises in the target factor

Date	Surprise	Rate Change	Introductory Statement	Notes
Nov 2002	1.85	0	Less than expected real GDP growth in Q3:2002 due to heightened uncertainty from "geopolitical tensions, evolution of oil prices and developments in stock markets." Inflation is close to 2% target.	Forecasters expected ECB to reduce rates due to subdued economic growth. A journalist commented, "Mr. Duisenberg, I think it is fair to say that you, the ECB, disappointed a lot of people today by not cutting interest rates."
Mar 2003	2.34	-25bps	Economic growth remained sluggish in previous months. Further, modest growth is expected in 2003 owing to geopolitical tensions and rise in oil prices. Inflation is likely to be on target in the medium term.	OIS yields rose at the short end of the yield curve. A journalist commented, "the markets have reacted somewhat badly to this rate decision and there seems to be some suspicion that it was a rather unhealthy compromise, possibly between those that wanted to cut by 50 basis points and those who maybe wanted to cut by 25 basis points or leave rates unchanged."
Jun 2008	1.63	0	Real GDP growth in the first half of the year was above expectations. Inflation was above 3% for several months and there were elevated risks to price stability over the medium term due to energy and food prices.	In the press conference, a journalist commented: "Markets are now, after your comments, pricing in a 65% chance of an increase in July, next month."
Oct 2008	-5.61	-100bps MLF -50bps MRO with fixed tender	Collapse of large banks in the US led to heightened uncertainty about real GDP growth and inflation.	Policy response to the turmoil in financial markets.
Nov 2008	5.16	-50bps	Financial market tensions caused a break in economic growth momentum. Prices and wages should moderate in light of weak domestic and global economy.	The ECB decision followed in the wake of larger rate cuts by the Federal Reserve and the Bank of England.
Aug 2011	-2.89	0	ECB concerned about deceleration in real GDP growth amidst heightened uncertainty. Inflation in the short term is a concern with upside risks to its medium term outlook.	Announcement of monetary easing measures such as the Long-term Refinancing Operations at 3 months and 6 months maturity, and continuing MROs at fixed rate until Jan 2012.
Oct 2011	4.69	0	Lacklustre economic growth due to slowing global demand, falling business confidence and deteriorating conditions in sovereign debt markets. Elevated inflation in previous months along with lacklustre growth.	OIS yields rose despite announcement of various policy measures such as Longer-term Refinancing Operations (LTRO) and Covered Bonds Purchase Programme (CBPP2). The median MRO forecast indicated an expectation of 25bps rate cut, but there was no change in the policy rate.
Nov 2011	-3.45	-25bps	Expectation of low real GDP growth due to sovereign debt crisis and slower global economic growth. Inflation is expected to decline from 3% in October to below 2% in 2012.	During the Q&A, the ECB president talked about the Euro Area "heading towards a mild recession by the end of the year."
Jul 2012	-2.79	-25bps	Real GDP growth remained weak. Risks to higher inflation subsided due to a cooling of futures price of oil.	The ECB president pointed out that risks surrounding the economic outlook continue to be on the downside.
Sep 2014	-1.73	-20bps	Real GDP growth saw a modest expansion but was weaker than expected. Inflation remained lower than the medium term target.	The ECB announced a reduction in policy rates, and purchases of non-financial private sector bonds and covered bonds.

L.2 Forward guidance factor

Table L.17: 10 largest surprises in the forward guidance factor

Date	Surprise	Rate Change	Introductory Statement	Notes
Mar 2003	-1.85	-25bps	Economic growth remained sluggish in previous months. Further, modest growth was expected in 2003 owing to geopolitical tensions and rise in oil prices. Inflation was expected to be on target in the medium term.	ECB president revealed new set of forecasts where economic growth figures were revised downwards.
Jun 2003	-2.98	-50bps	Economic growth remained very modest. Inflation expected to decline below the 2% target due to sluggish demand and exchange rate appreciation.	Downgrade of real GDP growth forecast for 2003 prompted the ECB to provide a monetary stimulus.
Jul 2005	1.65	0	Economic growth remained subdued. Rising oil prices seem to be hampering demand and confidence. However, several indicators, such as favourable financial conditions and corporate earnings, point to a gradual recovery. Prices are stable around the 2% target.	
Jun 2008	2.64	0	Real GDP growth in the first half of the year was above expectations. Inflation was above 3% for several months and there were elevated risks to price stability over the medium term due to energy and food prices.	In the press conference, a journalist remarked: "Markets are now, after your comments, pricing in a 65% chance of an increase in July, next month."
Jul 2008	-2.62	25bps	Real GDP growth expected to slow down in coming quarters. Inflation reached 4% in Jun 2008, well above the 2% target. High energy and food prices present an upside risk to price stability over the medium term.	In the press conference, the ECB president did not commit to future increase in the policy rate while markets had priced in a series of rate hikes.
Aug 2008	-2.21	0	Real GDP growth expected to be weaker in Q2:2008. Inflation remained well above the target with upside risks to price stability over the medium term.	The ECB's concern about economic growth prevented them from further increasing the policy rate. During the Q&A, a journalist asked, "Just a quick question. After this press conference investors will have certainly priced out any possibility of a rate increase this year and early next year. Are you comfortable with that?"
Mar 2011	1.84	0	Positive momentum in real GDP growth, although uncertainty was elevated. ECB flags upside risks to price outlook.	ECB staff projections for Mar 2011 signalled an uptick in HICP inflation relative to Dec 2010. The central bank signalled that rates could increase soon if the incoming data suggests that inflation will remain high.
May 2011	-1.47	0	Economic growth was on a positive trajectory since Q4:2010. Inflation rate was above target and under upward pressure from higher than expected fuel prices.	The ECB left the policy rate unchanged due to which markets reversed their bets on an aggressive tightening cycle.
Aug 2011	-1.44	0	ECB concerned about deceleration in real GDP growth. Inflation in the short term was a concern with risks to its medium term outlook on the upside.	Liquidity measures announced in the form of supplementary LTROs with 3 months and 6 months maturity. Additionally, MRO to be conducted at fixed rate until Jan 2012.
Dec 2016	1.84	0	Economic growth continued into Q4:2016. It was further expected to expand at a "moderate but firming pace." Inflation still below 2% target and will see a gradual recovery towards the 2% target.	Reduced pace of APP from 80 billion until Mar 2017 to 60 billion until the end of Dec 2017 or beyond, if necessary.

L.3 Quantitative easing factor

Table L.17: 10 largest surprises in the quantitative easing/tightening factor

Date	Surprise	Rate Change	Introductory Statement	Notes
May 2003	1.41	0	A review of monetary policy and communication.	N/A
May 2009	1.76	-25bps MRO -50bps MLF	Lack of global economic growth that was expected to remain subdued. Inflation was low primarily due to global commodity prices, but ECB confident of maintaining medium-term price stability.	ECB president termed covered bond purchases as "enhanced credit support" and ruled out quantitative easing. This signalled that the ECB did not intend to target long term OIS yields with this programme.
Jan 2011	1.23	0	ECB worried about negative spillover of financial sector into the real economy. There was short term pressure on inflation, but price stability expected to be maintained over the medium term.	ECB president warned about upside risks to inflation and that rates may be raised despite ongoing economic conditions, reminding journalists about 2008 where the ECB raised rates during the economic slowdown. This hawkish tone raised medium and long term OIS rates.
Aug 2012	-1.35	0	Real GDP growth remained flat and was expected to remain weak. Inflation was expected to decline below the 2% target well into 2013. ECB additionally commented on irreversibility of the Euro.	The ECB committed to undertaking further non-standard measures for repairing monetary policy transmission in the Euro Area.
Feb 2013	-1.34	0	QoQ EA real GDP growth contracting since H2:2012 and likely to stay weak. Loan growth to non-financial sectors also remained negative. Prices hovering around 2% target.	
Jan 2015	-1.76	0	Lacklustre economic growth accompanied by low credit growth. In addition, weak inflation dynamics due to fall in energy prices.	ECB announced Extended Asset Purchase Programme (APP). Targeted LTRO pricing to be reduced by removing spread over MRO.
Oct 2015	-1.43	0	Real GDP growth continued its recovery in 2015, but was likely to decline owing to weaker foreign demand. Inflation remained near zero, but was expected to rise due to base effects.	ECB credited asset purchases with reducing cost of borrowing for firms and households in the Euro Area. Reaffirmation of APP to run till Sep 2016.
Dec 2015	3.44	-10bps EDF	ECB: "Today's decisions were taken in order to secure a return of inflation rates towards levels that are below, but close to, 2% and thereby to anchor medium-term inflation expectations."	APP extended till Mar 2017. Journalist asks in the Q&A, "You've just explained your reasoning, but nevertheless, financial markets appear to be disappointed."
Dec 2016	-1.24	0	Economic growth continued into Q4:2016. It was further expected to expand at a "moderate but firming pace."	Reduced pace of APP from €80 billion until Mar 2017 to €60 billion until the end of Dec 2017 or beyond, if necessary. However, ECB committed to increasing the pace if the outlook became less favourable, or if financial conditions became inconsistent.
Jun 2018	-1.42	0	Slow, but broad based real GDP growth. Inflation expected to remain below 2%, but expected to increase towards the end of the year.	Pace of APP to continue at €30bn. ECB provided a roadmap for reducing pace of asset purchases. Further, it provided date and state dependent forward guidance on policy rates.

L.4 Asymmetric country risk factor

Table L.17: 10 largest surprises in asymmetric country risk factor

Date	Surprise	Rate Change	Introductory Statement	Notes
Aug 2011	1.97	0	ECB concerned about deceleration in real GDP growth. Short term inflation was a concern with risks to its medium term outlook on the upside.	Longer-term refinance operations (LTRO) with three and six months maturity. MRO to continue to be conducted at fixed rate with full allotment till Jan 2012. However, none of these announcement reduced sovereign spreads that were already high since the EU summit on Jul 21
Dec 2011	3.14	-25bps	Dampened economic growth as well as outlook due to financial market tensions. Going forward, downward revision in 2012 real GDP growth.	Introduced liquidity enhancing measures to improve financial conditions. These included a three year LTRO, reducing the rating threshold for certain asset-backed securities (ABS) and reducing reserve ratio. Despite these assurances, yield spread increased.
Jul 2012	3.28	-25bps	Real GDP growth remained weak. Risks to higher inflation were subsiding.	ECB president pointed to tensions in some euro area sovereign debt markets. However, no additional measures were discussed by the Governing Council to tackle fragmentation in financial markets.
Aug 2012	6.21	0	Real GDP growth remained flat and was expected to remain weak. Inflation expected to decline below the 2% target well into 2013. ECB additionally commented on irreversibility of the Euro, "Risk premia that are related to fears of the reversibility of the euro are unacceptable, and they need to be addressed in a fundamental manner. The euro is irreversible.."	Italian and Spanish yields jumped higher during the press conference while German yields declined.
Sep 2012	-3.18	0	Economic growth remained weak, inflation above 2%, but likely to subside in the medium term. Heightened uncertainty in financial markets.	ECB introduced Outright Monetary Transactions (OMT) for secondary bonds, "OMTs will enable us to address severe distortions in government bond markets which originate from, in particular, unfounded fears on the part of investors of the reversibility of the euro." This announcement was effective in reducing sovereign bond spreads.
Jan 2013	-1.74	0	Economic weakness in the euro area was expected to continue well into 2013. Inflation declined from summer of 2012, owing to a cooling of oil prices.	ECB highlighted that accommodative monetary policy will further reduce fragmentation. Moreover, it was "not thinking about an exit" for non-standard policies that were introduced to reduce fragmentation in Euro Area financial markets.
Jul 2013	-3.10	0	Economic growth, labour market, credit expansion remained subdued. There was an emergence of a few green shoots of economic growth. Inflation is likely to remain below 2%.	ECB focussed on improving transmission of monetary policy by further reducing fragmentation of Euro Area credit markets.
Dec 2015	2.17	-10bps EDF	ECB: "Today's decisions were taken in order to secure a return of inflation rates towards levels that are below, but close to, 2% and thereby to anchor medium-term inflation expectations."	A journalist in the Q&A asked, "You've just explained your reasoning, but nevertheless, financial markets appear to be disappointed." Sell-off in bond markets with Italian and Spanish yields increasing more than the German yields.
Jun 2018	-2.41	0	Slow, but broad based real GDP growth. Inflation likely to remain below 2%, but expected to increase towards the end of the year.	ECB stressed that the situation in sovereign bonds was localised and not as extreme as the 2011 episode associated with redenomination risk. Sovereign yields of Italy declined more than all other major member countries.
Sep 2019	-1.98	-10bps	Inflation remained far from the 2% target. Outlook for real GDP growth and inflation revised downwards.	ECB restarted the Asset Purchase Programme (APP). Italian and Spanish yields declined while French and German yields increased.

M Non-conventional monetary policy in the euro area

Since the 2007 financial crisis, the ECB has adopted a number of non-conventional monetary policy measures.

Long-term refinancing operations (LTROs) aimed at providing liquidity to the financial system have been carried out more frequently, including very long-term financing operations (VLTROs), with maturities of up to three years, conducted from December 2011 to February 2012.

Since September 2014, the ECB has conducted three series of targeted longer-term refinancing operations (TLTROs), designed to stimulate bank lending to the real economy. During the COVID-19 pandemic, the pandemic emergency longer-term refinancing operations (PELTROs) provided emergency liquidity to the money markets.

The Outright Monetary Transactions (OMT) is a programme allowing for conditional purchases of sovereign bonds in secondary markets, introduced in line with President Draghi's July 2012 commitment to do 'whatever it takes' to preserve the euro. It was never activated but provided a backstop to countries under market pressures.

The ECB's first explicitly defined quantitative easing programme with a price stability goal, the asset purchase programme (APP), was launched in March 2015. Additional ECB asset purchase programs initiated in 2014 include (i) the corporate sector purchase programme (CSPP), (ii) the public sector purchase programme (PSPP), (iii) the asset-backed securities purchase programme (ABSPP), (iv) the third covered bond purchase programme (CBPP3), and (v) the pandemic emergency purchase programme (PEPP). Further details are available on the ECB website.

The ECB has adopted different types of conditional forward guidance, providing at different points in time guidance about the path of the interest rates or of the asset purchases. The ECB?s first instance of forward guidance was in July 2013, when the Governing Council said that it expected 'interest rates to remain low for an extended period of time'.

In June 2014, The ECB was the first major central bank to adopt a negative interest rate policy (NIRP), setting one of its key rates below zero. NIRP has been maintained till September 2022.

The Transmission Protection Instrument (TPI), approved in July 2022, is an additional instrument in the ECB toolkit, that and can be activated ‘to counter unwarranted, disorderly market dynamics that pose a serious threat to the transmission of monetary policy across the euro area’. In the event of market tensions causing some countries to experience sharp deteriorations in financing conditions, ‘not warranted by country-specific fundamentals’, the ECB can make targeted secondary market purchases of securities of those countries.

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