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The Economic Impact of Yield Curve Compression:

Evidence from Euro Area Forward Guidance and Unconventional Monetary Policy

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Non-technical Summary

Motivation

Prior to the financial crisis of 2008, the ECB aimed to control inflation by changing its policy rates, which fed through to market short-term rates, as well as longer-term rates. However, in the period since the financial crisis of 2008, the ECB has been unable to rely on conventional tools alone to stimulate the macro-economy, since there is a limit to how far its policy rates can be lowered below zero.

This is why the ECB turned to unconventional monetary policies, with two key examples being asset purchase programmes, and forward guidance. The underlying logic of both policies is that, when a central bank can no longer lower short-term rates, it can still affect medium-term and long-term rates, i.e. it can still affect the yield curve (the relation between interest rates and the maturity of an asset). Lower long-term rates should stimulate the macro-economy. Asset purchase programmes achieve lower rates by driving up the price of certain assets, lowering their yields. Forward guidance programmes lower medium-term interest rates when central banks communicate that interest rates will remain low for periods of time.

It is of great importance for central banks to understand the impact of such policies on financial, and especially macro-economic variables. Accurate estimates of the effects of unconventional monetary policies are essential for their successful implementation. Given the complexity of the channels by which unconventional monetary policies operate, it is important to use frameworks that allow for the operation of these channels.

It is also of great interest to policymakers to know whether different unconventional policies were useful at different *times* in the post-crisis period, and whether their efficacy has risen or decreased. There has been a great deal of structural change in the wake of the financial crisis, as well as periods of heightened volatility. This study applies an empirical framework designed to also allow estimates to vary with time, while also incorporating information from a number of different channels.

Contribution

This study applies a novel decomposition of high-frequency asset price responses to ECB monetary policy statements. The decomposition is designed to separate between yield curve compression (induced by asset purchase programmes, or by other policies), forward guidance (including communication regarding future interest rates prior to the explicit adoption of forward guidance in July 2013), and other forms of information surprises (potentially regarding macro-economic forecasts). Restrictions (informed by theory) are placed on interest rates, the yield curve, and equities to achieve this.

The study also develops a time-varying parameter macro-econometric model which can incorporate information from these high-frequency responses to statements, and trace out their effects on financial and macro-economic variables. The model differs from existing approaches insofar that it includes an expanded number of variables, and also allows estimates to vary with time. To do this I incorporate recent advances in the estimation of time-varying parameter models (I employ non-parametric methods).

Results

The study first estimates a general model, where estimates do not vary with time, for the sample period 2002-2019. Forward guidance and yield curve compression surprises stimulate macro-economic activity and raise prices. Yield curve compression in fact leads to a greater effect on macro-variables than forward guidance, with a potential explanation being that spread compression surprises lead to a persistent flattening of the yield curve, and a persistent fall in corporate spreads. Yield curve compression also induces a strong depreciation in the exchange rate.

The time-varying model allows one to examine how these results vary over the sample period. Before the explicit forward guidance policy of the ECB in July 2013, markets were able to update their views of future interest rate changes in response to ECB statements, however results indicate that such surprises did not greatly affect inflation. This would reflect a narrative whereby the ECB was able to rely on conventional rate changes to control inflation in the pre-crisis period, though conventional policies are not quantified in this framework. In the post-European sovereign debt crisis period, however, forward guidance surprises have a particularly strong effect on inflation. Yield curve compression surprises raise inflation during the period of the asset purchase programme of the ECB, though there is some evidence of transmission in the period prior to this also. The effectiveness of these policies during this period is closely linked to their effects on the labour market (reducing unemployment). Some evidence of a breakdown in transmission of unconventional monetary policy measures to macro-economic variables in the financial crisis period of 2008-09 is also uncovered.

The Economic Impact of Yield Curve Compression: Evidence from Euro Area Forward Guidance and Unconventional Monetary Policy

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Abstract

This paper studies the effects of forward guidance and unconventional monetary policy on financial and macro-economic variables using euro area data. I decompose intra-daily variation in response to communication by the ECB Governing Council using sign-restrictions, with the key identifying assumption being whether expansionary communication shocks steepen the yield curve (a forward guidance shock) or flatten it (a spread compression shock). Central bank "information shocks" are extracted via an additional restriction on equities. I employ recently developed non-parametric estimation methods to estimate a medium-scale time-varying parameter SVAR model with high-frequency identification, allowing consideration of multiple transmission channels simultaneously. Expansionary spread compression shocks markedly reduce volatility and persistently lower spreads, and affect activity and prices in line with theory. Spread compression surprises affect macro-economic variables in a manner comparable to forward guidance surprises. The effects of both forward guidance and yield curve compression surprises on inflation increased in the post-European sovereign debt crisis period, as did their effect on unemployment.

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1 Introduction

During the period following the 2007-08 global financial crisis, many developed economy central banks turned to unconventional monetary policies to achieve their macro-economic stabilisation goals. These central banks faced the problem of a lower bound on interest rates, meaning they could not cut their policy rates to low enough levels to respond effectively to negative developments in the economic cycle.[1] One key example of such an unconventional monetary policy is termed quantitative easing (QE), and occurs when central banks create reserves in order to purchase various longer-maturity bonds.[2] By doing so, central banks aim to push up the prices of such bonds, lowering their yields and contributing to a general reduction of medium and longer-term interest rates (achieved without further cuts in short-rates). This compression of the yield curve is designed to stimulate productive long-term investments, which raise aggregate demand and therefore inflation. QE programmes have also been justified in terms of their effects at alleviating dysfunction in specific credit markets during crisis periods.[3] Another key example of unconventional monetary policy is termed "forward guidance", whereby central banks, when unwilling or unable to reduce short-rates any further, instead commit to hold rates at low levels for an extended period of time. Of course, at the time of implementation, unconventional monetary policies were experimental, and thus policy-makers could only estimate their effectiveness, and the relative importance of the channels through which they operate, *after* having introduced them.

Attempts to assess the effectiveness of unconventional monetary policies face three important empirical challenges. The first challenge is the complexity of the transmission mechanism, and a large literature has developed quantifying the importance of a plethora of different channels by which QE and forward guidance affect the economy. With respect to QE, an important role has been accorded to the portfolio re-balancing channel, by which central bank purchases raise asset prices, lower yields and stimulate market reallocation towards higher-yielding, and potentially more productive investments.[4] In situations of market dysfunction, the presence of a central bank as a committed buyer in the market for bonds can ensure smoother market operation via a liquidity channel. Researchers have also emphasised the potential importance of the "signalling channel", by which additional purchases induce lower interest-rate expectations, as well as channels that arise from any exchange rate depreciation induced by the purchases, channels that arise via the impact of central bank purchases on the supply of safe assets, as well as more general effects on uncertainty and confidence.

Forward guidance policies operate when economic agents anticipate a period of low interest rates, and thereby all of the traditional channels of interest-rate policy can be expected to play a role in their transmission. Recent work has emphasised that even traditional interest-rate policy itself can induce financial effects comparable to those of asset purchases, if smaller in magnitude, via their effects on term

[1]Because of the substitutability of central bank reserves for vault cash, there is a limit to how negative one can make the policy rate before banks begin to avoid the use of reserves.

[2]See Borio and Zabai (2018), Bhattarai and Neely (2020), Kuttner (2018) and Bernanke (2020) for review papers on the use of QE and other unconventional monetary policies by central banks.

[3]The degree to which policymakers have emphasised the role of QE for easing conditions in particular markets or emphasised its more general effects on the yield curve differs from case to case. The FOMC announcement of an expansion to the programme commonly known as QE1 on 18 March 2009 contains elements of both arguments. The ECB framed its purchases of sovereign bonds (beginning March 2015) more in terms of their general effects on the yield curve, see Cœuré (2015).

[4]This channel has two main forms, as discussed in Altavilla et al. (2015). The first is a "local" form by which purchases directly reduce the supply of particular assets available to investors, thereby lowering their yields and those of close substitutes. The second form is a duration extraction mechanism by which purchases remove duration-risk from private portfolios, reducing the valuation of the risk associated with longer-term bonds, which results in generally lower yields across longer-horizon bonds and across asset classes (Vayanos and Vila, 2009).

premia (Hanson and Stein, 2015). Additional factors will of course determine the strength of forward guidance, relative to conventional interest rate policies, in the sense that central bank statements about the future must be clear and credible if they are to change behaviour today. Of course, forward guidance policies have often been implemented at the same time as asset purchase policies, and their transmission channels may interact with each other (for example, the effects of asset purchases may be strengthened if the market knows that rates will remain low, and will not rise to offset increases in inflation generated by the purchases). What seems clear is that a good empirical model of the impact of unconventional monetary policy and forward guidance in the post-crisis period would need to incorporate information from a range of different financial variables, if the overall transmission through the financial sector to the macro-economy is to be estimated accurately.

The second important challenge facing quantification of the effects of unconventional monetary policies is the potential for structural change, since underlying relations between variables may differ in stressed or crisis periods. Moreover, in response to issues raised by the financial crisis (and European sovereign debt crisis), various regulatory and structural reforms were undertaken that may have impacted the relation between variables over time. A further complication is that the numerous forward guidance and asset purchase policies implemented by developed economy central banks underwent continual adaptation to changing circumstances, and exact details of their design were different in different stages of the crisis and recovery. Therefore, a successful estimation of the effectiveness of unconventional monetary policies would likely need to allow for changes in the relations between variables, even in the case the sample size is restricted to a relatively short period. This poses a difficulty from an econometric perspective, since the need to include both a sufficiently broad range of variables, as well as to model the time-varying relations between these variables, may be more than the majority of econometric approaches presently available can handle successfully, both due to computational limitations, as well as concerns regarding "over-fitting".

The third challenge is how to identify exogenous variation in unconventional and forward guidance policies. In the case that financial variables are included in a macro-economic model, conventional recursive identification schemes for monetary policy shocks are inappropriate, since they require that other variables in the system respond with a delay to policy surprises. However, policy announcements affect financial variables within seconds (Gürkaynak et al., 2005). One method is to move beyond recursiveness to apply additional structure to the residuals of a Vector Autoregression Model (VAR). One may apply an identification scheme involving sign-restrictions, magnitude restrictions, long-run restrictions, or narrative restrictions. However, under such approaches one can still face a deeper issue, relating to "non-fundamental shocks". In the case that there are large announcement effects of macro-economic polices (as is the case particularly for QE), it may not be possible to recover the structural shock of interest from the residuals of a VAR, irrespective of the identification scheme applied. And even were these issues overcome, one still needs a means to separate shocks to forward-guidance, asset purchases, and interest rates from each other.

This paper develops an empirical model designed to respond to these challenges. The paper quantifies the effects of forward guidance and unconventional monetary policies in the euro area, using a novel decomposition applied to intra-daily high-frequency surprise movements in asset prices on ECB policy announcement days. I use underlying data from the Euro Area Monetary Policy Event-Study Dataset (EA-MPD) of Altavilla et al. (2019), henceforth ABGMR, though the identification scheme used differs to the one of their study. The use of high-frequency responses to policy announcements should ensure that the surprises studied are unpredictable with respect to existing information (since expected moves are "priced in" to asset prices at the time of the statement). By directly including announcements into the identification, the approach alleviates concerns that ECB purchase programmes might represent news surprises that are not recoverable from the data available to the econometrician.

At this stage I make an important semantic and analytic distinction between "forward guidance", "yield curve compression" and "unconventional policy". The approach taken in this paper is to incorporate data from before the explicit implementation of a forward guidance policy by the ECB in July 2013, and before the start of net asset purchases under the Extended Asset Purchase Programme of the ECB in March 2015, which was implemented explicitly to compress the yield curve. However, ECB statements prompted changes in expectations regarding future interest rates before the formal adoption of forward guidance, and ECB statements prior to EAPP also affected long-rates. This paper extracts surprise series for a sample period between 2002 and 2019. To avoid confusion, the paper, and all of the discussions that follow, classifies pre-2013 statements by the ECB regarding future interest rates as "forward guidance" surprises. If anything, the post-2013 forward guidance of the ECB represents a development and enhancement of previous communication strategies, and in any case market participants have always inferred future policy rate moves from central bank statements. This paper also identifies surprise flattenings (or steepenings) of the yield curve induced by ECB statements, which are orthogonal to forward guidance surprises. I use the term "yield curve compression" surprises to refer to these movements. The yield curve compression surprises are identified in such a manner so as to mean that surprise changes to the extended-asset purchase programme represent a form of compression surprise, but not all identified compression surprises are a result of changes to the quantitative easing programme of the ECB. This is in the spirit of Baumeister and Benati (2013), who also study the implications of spread compression generally as a means to understand unconventional monetary policy specifically.

The identifying restriction employed is that expansionary forward guidance surprises lower shorter term-rates, but steepen the yield curve. Expansionary yield curve compression surprises lower shorter term-rates, and flatten sovereign yield curves. The measure of shorter term-rates is taken to be the two-year rate, so the response of overnight-rates to these policies is not restricted. I use only information from intra-daily movements in asset prices during the press conference following ECB decisions, and therefore the effects of conventional policy rate changes are *not* quantified in this study, since these are not announced by the ECB in the press conference (they appear on the website around 30 minutes beforehand). The reason for the use of the use of a sign-restrictions algorithm, as opposed to existing identification schemes, is to develop a series of term-premia responses that exist even prior to the adoption of the EAPP programme by the ECB in 2015, but obey theoretically informed sign-restrictions on average, which justifies the inclusion of a full time-series of proxies over the VAR sample period. This approach is informed by a recent literature documenting that even pre-crisis conventional monetary policy can affect the shape of the yield curve in ways similar to unconventional monetary policy.[5]

The decomposed surprise movements are employed in a medium-scale Bayesian Structural Vector Autoregression with exogenous proxy variables (BSVAR-X), in order to determine their effects on inflation and output. The use of a medium-scale (10 variable) model allows for a rich interaction between financial and macro-economic variables, befitting of the complexity of the channels at play in the transmission both of forward guidance, and of surprise yield curve compression policy. The use of Bayesian estimation allows for a degree of parameter shrinkage, enabling the study of a relatively large number of variables, with an appropriate lag structure.

While time-varying parameter Proxy VARs identified using high-frequency methods have been applied recently in other research, the models used thus far been limited to a consideration of a low number

[5] Hanson and Stein (2015), Inoue and Rossi (2018) and Kortela and Nelimarkka (2020).

of variables, for computational reasons. Uniquely for the time-varying Proxy-VAR literature to date, I use the non-parametric Quasi-Bayesian Local-Likelihood (QBLL) methodology of Petrova (2019) to estimate a medium-scale model. I use the simple VAR-X representation of a Proxy VAR used by Paul (2020) in order to achieve this. Paul (2020), who shows that a standard VAR, with suitable proxies incorporated in an exogenous block, is able to recover identical relative impulse response functions to those that result from the approach to the Proxy VAR estimation routines developed in Mertens and Ravn (2013) and Stock and Watson (2012). The simplicity of this setup makes it straightforward to incorporate time-varying parameters, and Paul (2020) exploits this to estimate time-varying impulse responses of asset prices to monetary policy shocks in the US case. This study combines the simple Paul (2020) Proxy VAR with the recently developed semi-parametric approach to VAR estimation developed in Petrova (2019).[6] I am therefore able to study the time-varying impact of conventional and yield curve compression shocks on a set of financial and macro-economic variables simultaneously, again while allowing for a reasonable lag structure. Both the impact effect of the identified shocks, and the parameters governing the reduced-form macro-economic relations within the VAR are allowed to vary. The framework also allows for stochastic volatility, which is arguably essential for an empirical study that traverses the financial crisis and European sovereign debt-crisis periods.[7]

As mentioned previously, this study relates to a recent literature seeking to understand the effects of responses in term-premia that occurred prior to the implementation of explicit unconventional monetary policies. Inoue and Rossi (2018) and Kortela and Nelimarkka (2020) identify shocks via their impact on various factors underlying the yield curve, arguing that communication by central bank monetary policy-makers regarding conventional interest rate policy, or forward guidance regarding future rates, can have a comparable impact on the yield curve to surprise announcements regarding purchase programmes. These studies relate to earlier findings of Hanson and Stein (2015), who document effects of conventional monetary policy announcements pre-crisis on forward rates far into the future (10 years or more). Such long-term effects are unlikely to come from changes to expectations regarding short-term rates, since few believe markets draw inference about central bank policy 10 years into future. Hanson and Stein (2015) reason that conventional interest changes induce portfolio-rebalancing towards higher yielding assets in the same manner as occurs in response to asset purchase policies. This view of the relationship between term-premia changes induced by policies enacted prior to asset purchase programmes is not uncontroversial; part of the contribution of this study is to quantify a sequence of such shocks, and study their role at explaining financial and macro-economic fluctuations in a time-varying parameter framework. Since little is known about the term-premia surprises that occur outside asset purchase programmes, the time-varying parameter approach taken in this study can provide additional information about how these surprises transmit, both in "conventional" and "unconventional" periods.

The idea that spread compression can be used to motivate a scheme of sign-restrictions to extract quantitative easing surprises is not itself new, however to the best of my knowledge sign restrictions such as the ones used in this paper have not been applied to intra-daily responses to announcements. Cieslak and Schrimpf (2019) employ identical restrictions to mine in their classification scheme for events, and use sign-restrictions to extract a continuous series of risk-premia shocks, but do not do the same for

[6] Liu et al. (2018) apply the estimation strategy of Petrova (2019) to the case of monetary policy, in an international framework including European data, though they do not use high-frequency identification methods and do not differentiate between different forms of monetary policy shock. Zakipour-Saber (2019) applies the approach of Petrova (2019) to a reduced-form study of the role of US long-rate innovations in explaining euro area macro-economic variables.

[7] Mumtaz and Petrova (2018) develop a time-varying Proxy VAR, developing on the constant parameter Bayesian Proxy-VAR of Caldara and Herbst (2019), however they specify transition equations for the time-varying parameters in a similar manner to earlier papers, and are thus limited to a small model for computational reasons.

quantitative easing surprises (nor do they study the effects of a continuous series of surprises on financial or macro-economic variables in a TVP-VAR system). Spread compression is used as an identification device in the TVP-VARs of Baumeister and Benati (2013), where US and UK unconventional monetary policy shocks are respectively extracted from a quarterly series of VAR residuals under the assumption that they compress the spread between long-term bond yields and the policy rate, and have a zero contemporaneous effect on the short-rate. A series of papers have applied similar identification schemes to SVAR models (for the UK case see also Kapetanios et al., 2012; for the euro area see Mandler and Scharnagl, 2020; Feldkircher et al., 2020; Lenza and Slacalek, 2018). Boeckx et al. (2017) also apply sign-restrictions to a VAR system to extract unconventional monetary policy shocks, adapted specifically to investigate the case of the liquidity policies pursued by the ECB since the financial crisis. These studies, and others like them, apply sign-restrictions to reduced-form residuals from VAR systems, which implies that the accuracy of the extracted surprises relies on the accuracy of the estimates regarding the underlying macro-model.[8] In studies that apply decompositions to asset-price responses to announcements, the reduced form movements (which are then decomposed) are isolated without specifying an econometric model, since in this case we need to assume only that the surprises that occur within the announcement window are monetary. The paper of Gambetti and Musso (2020) is closely related to this study, since these authors also contribute by offering a TVP-VAR study of unconventional monetary policy surprises in the euro area, though the identification strategy is different, since they use survey data to extract surprises, and focus on two events, whereas this study incorporates a continuous series of intra-daily surprise movements.[9] The paper of Gambetti and Musso (2020) uses conventional TVP-VAR estimation techniques, and therefore relies on a smaller model to the one used in this paper, which applies the semi-parametric approach of Petrova (2019).[10]

While the focus of this paper is on a comparison of the impact of forward guidance and unconventional monetary policy, I also contribute to the literature on the central bank "information effect", by estimating the time-varying impact of ECB information shocks, using the restriction applied in the identification scheme of Jarocínski and Karadi (2020) on equities. Recent papers have focussed on the role of central bank "hidden information" during press-conferences, arguing that policy-makers may reveal information about the state or expected evolution of macro-economic variables during press conferences, which can bias measures of monetary policy shocks derived from asset price responses to the statements. Campbell et al. (2012) and Nakamura and Steinsson (2016) study the case of the US. Barakchian and Crowe (2013), Miranda-Agrippino and Ricco (2019), and Goodhead and Kolb (2018) purge responses to Fed announcements of data from the Greenbook forecasts. Andrade and Ferroni (2020) and Jarocínski and Karadi (2020) employ sign-restrictions to extract Delphic forward guidance and information surprises respectively.

The approach broadly follows two steps: 1) separate forward guidance, yield curve compression, and

[8]Alternative applications of the sign-restriction approach to the identification of unconventional monetary policy shocks in VAR models can be found in the studies of Gambetti and Musso (2017), Weale and Wieladek (2016), Wieladek and Pascual (2016), Gambacorta et al. (2014), Joyce et al. (2011) and Peersman (2011). These studies do not apply sign-restrictions to intra-daily asset price responses to announcements, as is the case in this paper.

[9]This paper also contributes relative to Gambetti and Musso (2020) by separately identifying forward guidance and information surprises, and comparing responses in the same framework.

[10]The effects of ECB policy surprises identified at high-frequency on macro-economic variables are also quantified in the constant-parameter frameworks of Corsetti et al. (2020) and Hachula et al. (2020). This paper also relates to Skouralis (2020), who studies the impact of the ABGMR high-frequency surprises on euro area systemic risk in a GVAR framework. The approach I take in this paper is also related to that of Eberly et al. (2019), who also summarise unconventional monetary policies via their effects on the yield curve, in their case using a recursive scheme, and choose to term their measure "slope policy". See Rossi (2019) for a recent survey paper discussing methods for identifying the effects of quantitative easing.

information surprises using high-frequency (intra-daily) financial market movements around ECB monetary policy announcements; 2) model the impact of these policies on financial and macro-economic variables at monthly frequency, in respective constant-parameter and time-varying parameter frameworks.

Results from the constant-parameter model indicate that expansionary forward guidance and yield curve compression surprises both raise measures of activity, and the level of prices. Unconventional monetary policy surprises in fact have a greater impact than forward guidance surprises in the constant-parameter case. Part of the reason for this effectiveness is the persistent flattening of the yield curve induced by yield-curve compression policies, as well as the persistent effect on corporate spreads, and a reduction in volatility. A strong depreciation of the exchange rate in response to yield curve compression also plays a role.

When the time-varying parameter impulse response functions are studied, results indicate a strong transmission to prices in the post-European sovereign debt crisis period for both forward guidance and yield curve compression surprises. This may indicate the strengthening of the ability of the ECB to control the yield curve, as it adopted explicit forward guidance policies, and implemented its EAPP programme. The fact that forward guidance surprises had a limited pass-through to inflation during the 2008 financial crisis and during the preceding number of years is noteworthy. This may indicate that forward guidance policies can benefit from being explicit, as opposed to the previous regime whereby markets would interpret ECB statements in order to learn about the path of future interest rates. Both yield curve compression surprises and forward guidance surprises had a more pronounced impact on unemployment in the post-European sovereign debt crisis period, suggesting a key role for conventional transmission of such policies to inflation via decreases in unemployment. The stock of loans also responds strongly to both policies during this period, suggesting an important role for the credit channel. Time-varying impulse response functions for the information surprise demonstrate a great deal of heterogeneity in transmission across the sample period, especially during the period of the EAPP programme, when responses display some evidence that ECB information surprises affected risk premia.

Section 2 discusses the decomposition applied to extract high-frequency forward guidance, compression, and information surprises from the EA-MPD of ABGMR. Section 3 describes the constant parameter Bayesian Proxy-VAR model, and discusses the approach to identification in the paper. Section 4 discusses impulse response functions in the constant parameter case. Section 5 discusses the estimation method for the time-varying parameter model. Section 6 discusses the results in the time-varying parameter case. Section 7 concludes.

2 Decomposition of Forward Guidance and Yield Curve Compression

This paper uses an event study approach to identify surprise movements in financial markets that arise in response to communication by monetary policy markers. By using intra-daily surprises, one can ensure that the financial market movements are responses to monetary policy news only, and do not reflect changes in underlying macro-economic variables. Such an approach was introduced by Kuttner (2001) using daily changes in Federal Funds futures contracts for the US case. Gürkaynak et al. (2005) were the first to study intra-daily surprises, and to separate surprises into components relating to rate surprises and surprises relating to communication regarding the path of future policy, using data from the US.[11]

As mentioned, the approach taken in this paper, which applies sign-restrictions to yield curve movements to separate surprises, is very similar to that of Cieslak and Schrimpf (2019). Cieslak and Schrimpf

[11] High frequency identification methods, using alternative decompositions to the one used in this paper, have been applied to the euro area in the studies of Brand et al. (2010), Jardet and Monks (2014), Ellen et al. (2020), and Leombroni et al. (2020).

(2019) offer a categorization of monetary policy events and separate unconventional monetary policy events from conventional ones by their overall effects on the yield curve under the same logic as that used in the continuous decomposition employed in this paper. The papers of Swanson (2020) and ABGMR offer continuous decompositions of unconventional monetary policy shocks, and this study uses the raw intra-daily asset movements provided by ABGMR as part of their EA-MPD. In both of these studies the unconventional monetary surprise is essentially uncovered as residual variation relative to other surprises, with an additional restriction requiring the surprise to explain only post-crisis variation in asset-price movements, with the intuition being that the QE surprise should only be "active" after the implementation of QE policies.[12] Such a restriction has the appealing feature of parsimony, and both studies report the effects of the surprise on the yield curve to be in line with theoretical predictions regarding the financial impact of QE.

This paper employs an alternative identification scheme for several reasons. The Swanson (2020) shock is not identified via restrictions on the compression of the yield curve, and therefore it is possible it contains confounding movements in the responses of financial variables on announcement days. One example of such a confounding movement would be the "risk-premia" shocks discussed in Cieslak and Schrimpf (2019), which are non-monetary news shocks that flatten the yield curve (while simultaneously depressing equity prices). The decomposition used in this study separately identifies potentially confounding "information effects" during the ECB statements, whereby market participants may gain information about the state and projected evolution of macro-economic variables during the discussion, which could bias the measurement of monetary policy surprises. I use the sign-restriction on equities introduced by Jarocínski and Karadi (2020) (i.e. that equities fall in response to unexpected, contractionary policy, and rise in response to "good news", for example about aggregate demand).[13] This restriction is not included in the ABGMR approach, and it is of interest to study the results of decompositions that control for information effects.

At a deeper level, however, the reason for the use of sign-restrictions to uncover forward guidance and compression surprises is to create a series of movements in term-premia that "mimic" the effects of unconventional monetary policy, with respect to their effects on the yield curve, even prior to the explicit adoption of such policies. Recent evidence has suggested that variation in term-premia associated with pre-crisis monetary policy can have qualitatively comparable effects on the yield curve to unconventional policy (Hanson and Stein, 2015; Inoue and Rossi, 2018). This motivates the application of a general decomposition between forward guidance and unconventional policy, without applying a restriction to the time-period, and a yield curve compression shock series is therefore developed for the ECB that is active prior to the adoption of the Extended Asset Purchase Programme in 2015. The use of sign-restrictions implies the shock series will preserve the theoretically justified effects on the yield curve on average, and this justifies the inclusion of a series of term-premia surprises for the period 2002-2019.

The EA-MPD, created by ABGMR, gathers intra-daily price movements in a selected group of financial contracts on meeting days of the ECB Governing Council. The EA-MPD offers shock series derived from the window around the policy announcement, which is a short description of major policy changes released on the website of the ECB at 13:45 CET. The dataset also offers surprises derived from the window around the press conference, which follows the policy announcement and usually commences at 14:15 CET. Changes to the policy rate are revealed in the press release, meaning "action" surprises

[12] Technically, Swanson (2020) imposes a criterion by which the unconventional monetary policy shock explains minimal variation in the pre-effective lower bound period; ABGMR impose a similar criterion for the euro area case.

[13] Matheson and Stavrev (2014) apply similar sign-restrictions to a daily VAR system in their examination of the "taper tantrum" period in the US case.

Table 1: Sign Restrictions

	Information	Forward Guidance	Yield Curve Compression
2Y DE Yield	−	−	−
10Y - 2Y DE Yield		+	−
Stocks	−	+	+

can be extracted from this window. Until March 2016, changes to forward guidance and to unconventional monetary policies were discussed in the press conference, while the press statement only revealed information regarding policy rates.[14] After the increase in the rate of net asset purchases in March 2016, press statements would include details regarding both forward guidance and unconventional monetary policy (including both net asset purchases, re-investment of existing purchases, and discussion of liquidity operations such as the Targeted Long-Term Refinancing Operations).

In this study I use intra-daily movements from the press conference window on the ECB statement days, and exclude information from the announcement window. Therefore, all of the shocks considered are "communication" shocks, in the sense that they should be distinct from the impact of policy rate changes. This decision is taken to avoid an attempt to estimate the effects of "action" shocks during the period of the effective lower bound, during which short-rates rarely moved.

This study employs a simple and general distinction between forward guidance and yield curve compression surprises. I decompose yield curve compression from forward guidance by applying sign-restrictions to a vector of surprises in financial market variables. I take a vector of surprise movements comprised of changes in the two-year German sovereign yield, a measure of the yield curve (ten-year minus two-year German yield), and stock prices (Eurostoxx50). The sign-restrictions applied are detailed in Table 1. I assume that both forward guidance and expansionary compression surprises reduces the two-year German sovereign yield. This is a reasonable assumption, since changes in short-rate expectations ought to transmit to the two-year rate. Orthogonal variation in ECB unconventional monetary policies, for example asset-purchases or the securities market programme, should also reduce the two-year rate.

I also assume that that both conventional and yield curve compression boost stock prices. This follows the argument of Jarocínski and Karadi (2020) and Andrade and Ferroni (2020), in the sense that the surprises may contain an "information effect", whereby markets can receive positive or negative information regarding the macro-economy during the statements–restricting the behaviour of stock prices is a means to control for this.[15] While both papers also apply sign-restrictions to vectors of high-frequency surprises, neither separately identifies unconventional monetary policy shocks in the sense of policies undertaken to flatten the yield curve.

The key sign-restriction for the purpose of identification is to assume that an expansionary forward guidance shock steepens the yield curve, while an expansionary yield curve compression shock flattens

[14] As ABGMR mention, between January 2015 and January 2016 the press statement would indicate whether new measures were to be introduced in the subsequent press conference, since it would occasionally reference "further measures" to be revealed. Prior to this, the press statement would state the policy rates of the ECB in a concise manner only, even when further measures were to be announced 30 minutes later. One exception is the case of the emergency rate cut of October 2008, when there is a fairly detailed discussion of the rationale for such a move included in the press statement. However, in this case there was no press conference, and therefore this surprise is not included in the shock series used in this paper.

[15] Jarocínski and Karadi (2020) show that restricting the monetary policy surprises to push stock prices and interest-rates in opposing directions is a means to control for these effects, and Andrade and Ferroni (2020) follow a similar logic using market-implied inflation expectations.

it. A forward guidance monetary policy shock ought to affect short-term rates relatively more than long-term rates for three reasons: 1) forward guidance statements by the ECB are typically thought to be relevant for the one or two-year horizon; 2) the effects of a temporary shock should dissipate with the horizon; 3) long-term rates contain a large term-premium component that is not strongly affected by transitory movements in short-rate expectations. A yield curve compression surprise, on the other hand, is designed to uncover surprises relating to asset-purchase policy, which ought to push term-premia down at the long-end of the yield curve via portfolio re-balancing.[16]

The sign-restrictions are implemented using the QR-decomposition, following the algorithm in Rubio-Ramírez et al. (2010). Formerly, I define u_t to be the (3×1) vector of high-frequency movements in: (1) the two-year German Bund yield; (2) the ten-year minus the two-year German Bund yield (the yield curve); and (3) the Eurostoxx 50 index. I compute the variance-covariance matrix of the chosen vector of variables over the set of meeting days, Σ_u. I assume further that u_t is a linear combination of structural shocks, ε_t. One permissible decomposition is $u_t = P'\varepsilon_t^*$, where $\Sigma_u = P'P$, and P is the upper-triangular matrix from a Cholesky decomposition of Σ_u. Here I refer to a decomposition as "permissible" in the sense that the variance-covariance matrix of these structural shocks, when they are multiplied by P', is equal to that of u_t. I find many other permissible decompositions using repeated QR-decompositions of random orthonormal matrices, creating new decomposition matrices according to the relation $P^Q = QP$, where Q is orthonormal. I then keep only those decompositions that satisfy the sign-restrictions in Table 1. Of this set, I choose the particular decomposition with elements closest to their median values within a set of 1,000 draws.[17] I do not consider the uncertainty over shock decompositions ("identification uncertainty") in the subsequent macro-econometric model, and take the shocks as data. Properly accounting for identification uncertainty is left for future work. A full discussion of the implementation of the QR-decomposition algorithm is provided in Online Appendix Section 2.

The shocks themselves are plotted in Figure 1. One point of interest is that the series display evidence of heteroskedasticity, with periods of elevated variance that broadly correspond to the state of the business cycle in the euro area. The volatility of the forward guidance shock can be seen to increase with the onset of the financial crisis, and also during the sovereign debt crisis. In the period post 2017, expectations regarding the two-year rate became fixed, as a result of the official ECB forward guidance policy. This is reflected in the reduced variance of the conventional monetary policy shock series in the final years of the sample. The variance of the yield curve compression surprise increases to a degree from around 2013-2014, and most markedly from 2015, the date at which the ECB commenced its Public Sector Purchase Programme, the main constituent programme of its QE policy. The increased volatility of the yield curve compression surprise in the post-2015 period supports its interpretation as an unconventional monetary policy shock.

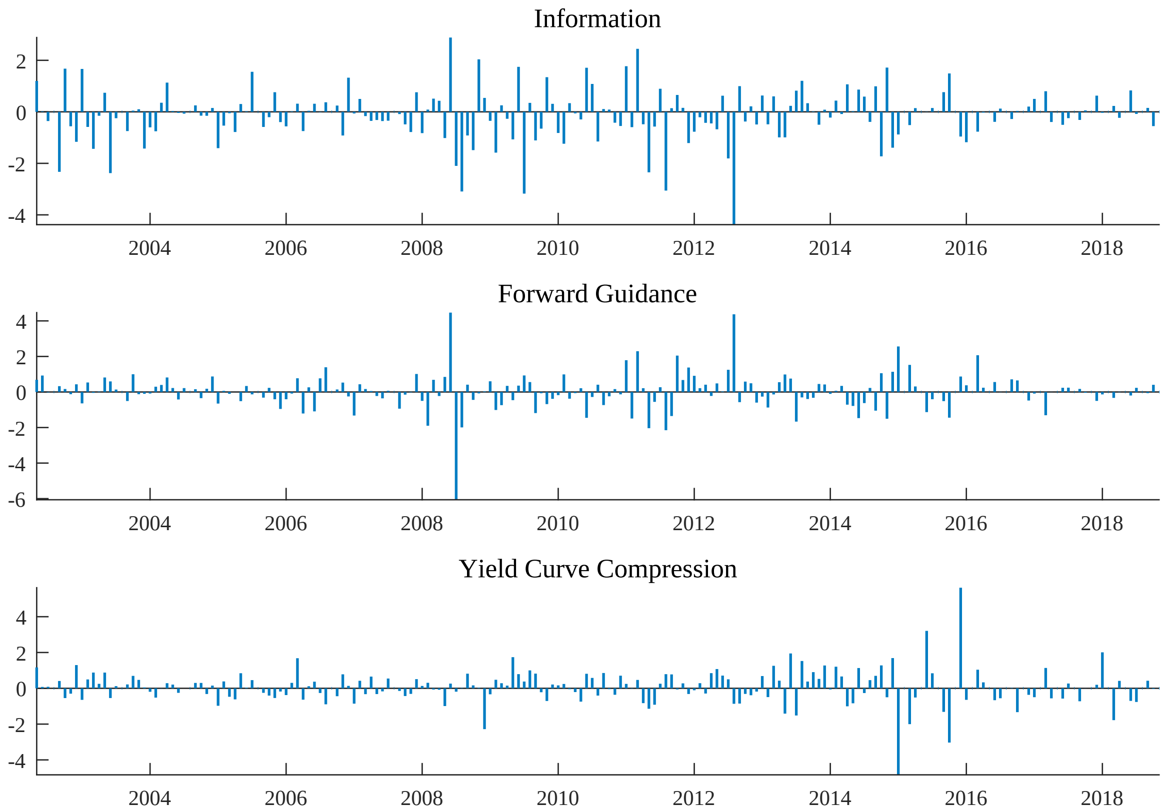
Figure 2 displays the distributions of the estimated information, forward guidance, and yield curve compression shocks for three dates of interest. It is important to emphasise that surprise movements during press-conferences often do not move in the same direction as the actual stance announced, since markets frequently expect greater stimulus than was actually delivered (see Gürkaynak et al., 2005).

The July 2009 meeting represented a large expansionary conventional monetary policy surprise, despite a rise in rates, since, as ABGMR argue, "[t]he press conference was taken as signalling that no

[16]For formal treatments of the portfolio-rebalancing effect, see Vayanos and Vila (2009) and Hamilton and Wu (2012).

[17]Technically, the chosen decomposition matrix is such that the distance between its parameters, and the median parameters across draws is minimised (in terms of squared deviation). This ensures the chosen decomposition matrix is within the set of drawn matrices.

Figure 1: Shock Series



Notes: Figure shows the shock series derived from decomposition matrix that minimizes the squared deviation between itself and the matrix formed of median elements across 1,000 draws. A positive surprise is normalised to increase the two-year rate at impact by construction.

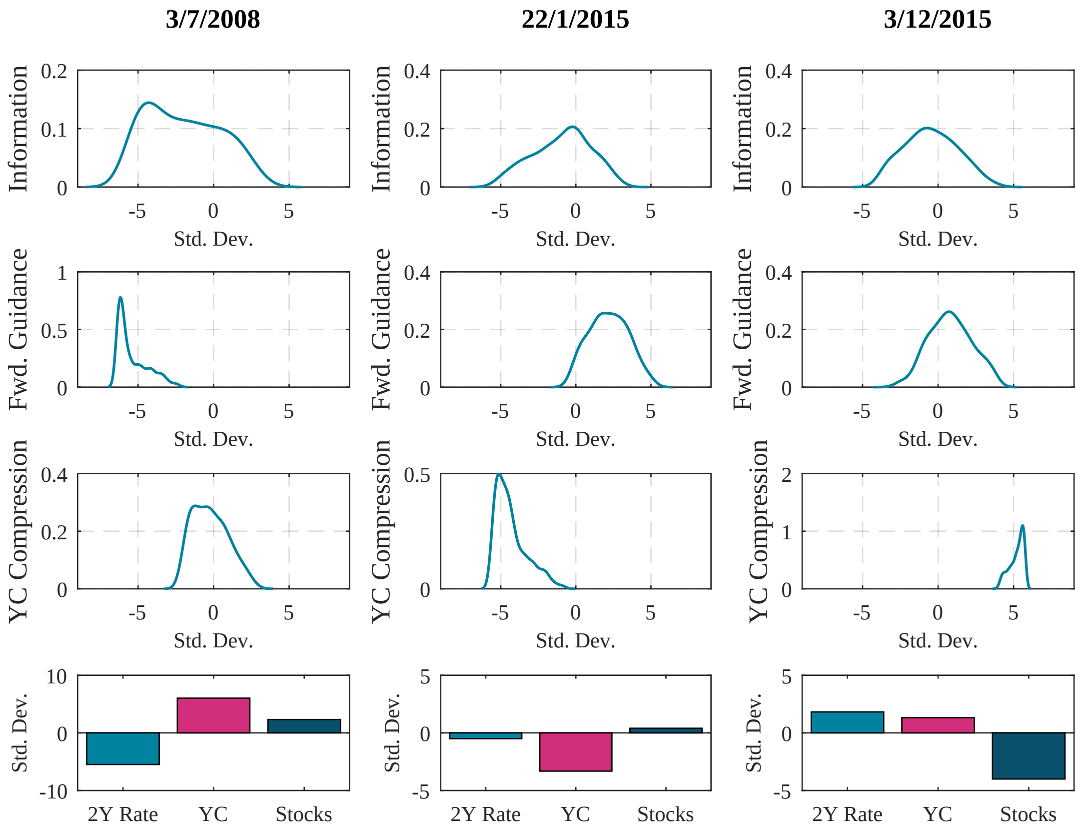
more hikes were intended".[18] The January 2015 announcement of the commencement of the Expanded Net Asset Purchase Programme resulted in a very large flattening of the yield curve, as can be seen in the second column of Figure 2. This resulted in a very large expansionary yield curve compression surprise. The December 2015 case is an interesting one, since, although the ECB cut its deposit facility rate extended its asset purchases, the market expected greater action, and this is interpreted by the decomposition as a large contractionary yield curve compression surprise.[19] Generally, therefore, the extracted surprises cohere with the narrative around the events they respond to, and an additional set of examples are presented and discussed in Online Appendix Section 3.

3 The (Constant-Parameter) Macro-Econometric Model

The identified shocks are used as external instruments to estimate a Structural Vector Auto-Regression (SVAR), in order to study their effects on macro-economic variables. Such an approach, which can be termed a "Proxy-SVAR" approach, was pioneered in the papers of Stock and Watson (2012) and Mertens and Ravn (2013), who showed the usefulness of instrumental variables for identifying the effects of shocks within a VAR system. The approach was first applied in a monetary policy context by Gertler and

[18]Section G of the Online Appendix to ABGMR.
[19]This was widely reported by financial journalists at the time, for one example see FT (2015).

Figure 2: Examples of Estimated Shocks



Notes: Figure shows movements in asset prices on key dates of interest. The upper three rows show the distributions of the estimated Information, Forward Guidance, and Yield Curve Compression shocks. The distributions are constructed from 1,000 accepted draws of decomposition matrices, with acceptance depending on whether sign-restrictions are met. The final row shows the raw movements from which the surprises are extracted, i.e. measures of the change in the two-year DE rate, yield curve (10-year subtract two-year DE rate), and the Eurostoxx50 index. These movements are taken from the dataset of Altavilla et al. (2019). A positive surprise is normalised to increase the two-year rate at impact by construction. This means a positive yield curve “compression” surprise steepens the yield curve.

Karadi (2015).

This study follows the specification of Paul (2020), who demonstrates that the Proxy-SVAR specification is identical to that of a standard VAR, when the surprise series is entered in as an exogenous variable (a VAR-X specification). I discuss the equivalence result of Paul (2020) in the latter part of this section, and note here that the Proxy VARs used in this paper incorporate multiple instruments, while the paper of Paul (2020) employs a single instrument. Otherwise the specification of the constant-parameter VAR is identical, other than the use of Bayesian estimation in my system (on account of the larger number of variables and lags).[20]

The VAR-X is specified as follows, given T observations over time for y_t, a $(n_y \times 1)$ vector of variables of interest:

$$y_t = B_0 + B_1 y_{t-1} + \ldots + B_p y_{t-p} + A z_t + e_t, \tag{1}$$

where the variance-covariance matrix of the $(n_y \times 1)$ vector of Gaussian errors, e_t, is given by Σ_e. Thus $e_t \sim \mathcal{N}(0, \Sigma_e)$. We take $\{y_t\}_{t=1}^{p}$ to be given as initial conditions. We assume B_0 is an $(n_y \times 1)$ vector of intercepts, and $\{B_i\}_{i=1}^{i=p}$ are the $(n_y \times n_y)$ coefficient matrices associated with each lag of the vector of endogenous variables. Here z_t is a $(n_z \times 1)$ vector of exogenous instruments, and A is a $(n_y \times n_z)$ matrix of coefficients, which I refer to as "impact coefficients" since they govern the period 0 response of the system to the instrument. In this study $n_z = 3$, but in principle any number of proxies could be added.

The VAR-X model specified in Equation 1 can be written in matrix notation as

$$Y = XB' + E, \tag{2}$$

where $Y \equiv [y_{p+1} \ldots y_T]'$, $X = [X_p', \ldots, X_{T-1}']'$, with $X_{t-1} \equiv (y_{t-1}', \ldots, y_{t-p}', z_t', 1)$, $B \equiv [B_1, \ldots, B_p, A, B_0]$, and $E \equiv [e_{p+1}, \ldots, e_T]'$. Let $\beta = vec(B')$.

The data are at monthly frequency, and the sample period is from May 2002 to December 2019. In order to assess the impulse responses of a broad range of macro-economic and financial variables, the vector includes 10 variables and the VAR is thus of "medium" size. I include the following financial variables: the two-year German bond yield, a measure of the yield curve (the ten-year German bond yield minus the two-year yield), the US/EUR exchange rate (in logarithms), the Eurostoxx index (in logarithms), a measure of implied volatility in equity markets, and measures of corporate spreads.[21] The included macro-economic variables are: industrial production (in logarithms), unemployment, the nominal stock of loans (in logarithms), and HICP (in logarithms).[22] The lag length is set equal to 12. A full discussion of the data is available in Online Appendix Section 1.[23]

Given the relatively short-data series, and the fact the VAR is of medium scale, there is a clear issue regarding over-parameterisation (the "curse of dimensionality"). I follow the approach of Bańbura et al. (2010), who demonstrate that Bayesian shrinkage is appropriate in such cases, provided one strengthens the prior view on the relation between variables as the number of variables increases. I therefore estimate

[20] Paul (2020) uses frequentist estimation for his baseline constant-parameter VAR, though the time-varying parameter VAR is he uses is estimated with Bayesian techniques. The algorithms used to estimate the time-varying VAR of this paper are very different to those of Paul (2020), as will be discussed.

[21] To be completely clear, the exchange rate is defined as the number of dollars that can be purchased in exchange for 1 euro, and a fall in this measure represents a depreciation of the euro.

[22] All variables are seasonally adjusted where appropriate.

[23] One point worth mentioning here is that I use end-of-the-month values for the financial series in the VAR, when aggregating variables available at daily frequency to monthly (with the exception of the spreads variable). The reason for this is that, were I to take a monthly average, the impact effect of the surprises on monthly asset prices might be artificially weakened, since an average of asset prices within the month would include data prior to the statement (which could take place at the very end of a given month).

the model using Bayesian methods, and set a Normal-Inverse Wishart prior, which is implemented using dummy observations.

The prior for the VAR is implemented in a largely standard manner, following a normal-Inverse Wishart scheme, and implemented using dummy observations. More detailed information about the implementation of the prior can be found in Online Appendix Section 5. The prior mean for each variable in the system is that it depends only on its own lag, meaning the prior for all of the coefficients is set to equal zero, with the exception of the first-order auto-correlation parameter for each variable. I vary the prior for the mean of the auto-correlation coefficient depending on whether the variable is stationary (when the prior mean is also set to zero), non-stationary (in which case the prior mean is set to equal one), or highly-persistent (the prior mean is set to 0.9).[24] The variances of the prior for the coefficients are set according to the Litterman scheme. The key argument of Bańbura et al. (2010) is that the tightness of the priors, which in my scheme is governed by the parameter λ, should increase as the number of variables in the system increases (i.e. λ should be lowered). I set λ to 0.108, which is the value used by Bańbura et al. (2010) for their medium-scale VAR. The prior for the intercept has a zero mean, and a large variance (10^5), determined by the parameter λ_4.

It is also necessary to specify a prior for the coefficients of the impact matrix associated with the exogenous block (A). These coefficients are vitally important when constructing the relative impulse response functions to the exogenous shocks, since the impulse response at the 0 horizon (immediate) will be determined by A. In principle, one could set the prior on these parameters to zero, since one might not want to place a prior on the effects of the shocks, given that part of the objective of our enquiry is to learn whether there are effects or not. I choose to set the prior mean for A to equal the parameters from respective OLS regressions of $\{y_{i,t}\}_{i=1}^{i=n_y}$ on z_t.[25] In any case, the prior variance for this parameter is set to a large number (10^5), determined by the parameter λ_z. The scale matrix for the Inverse-Wishart prior distribution of the error term is set to $diag(\sigma_1^2, \ldots, \sigma_n^2)$. The parameter governing the degrees of freedom of the Inverse-Wishart distribution, υ_0, is set to equal 20.[26] To construct estimates I draw directly from the posterior distribution, using Monte Carlo sampling.

3.1 Relative Impulse Response Functions

In this study I estimate a single Proxy-VAR model, with multiple instruments included in the exogenous block.[27] Paul (2020) demonstrates in the single-proxy case, where there is only one structural shock of interest, that the VAR-X representation uncovers the true *relative* impulse response functions. Formally, assume without loss of generality that the shock of interest is the final shock of the structural shock vector η_t. In the case that we have one proxy variable series ($n_z = 1$), Paul (2020) makes the following assumption:

$$E[z_t \eta_t'] = \begin{bmatrix} 0_{[1,n_y-1]} & \phi \end{bmatrix},$$

[24] In fact I set the prior for two variables to 0.9, German yields and unemployment, and here deviate from Bańbura et al. (2010). I made this decision in response to the issue that for euro area data 2002-2019, German bond yields exhibit seeming downward trends, and the behaviour of euro unemployment appears highly persistent. The assumption of white noise is not appropriate for such series. However, for neither variable is the assumption of a random-walk plausible: we have good reason to believe interest rates are broadly mean-reverting, and it is logically inconsistent for an unemployment rate to have a stochastic trend (since it is bounded between 0 and 1 by construction). Thus I set the prior to a highly-persistent value strictly below one.

[25] I.e. $A_0' = \hat{A}' = (Z'Z)^{-1}Z'Y$, where $Z = [z_{p+1}, \ldots, z_T]'$.

[26] Jarociński and Maćkowiak (2017) argue in favour of a relatively high value for υ_0, in the Appendix to their paper. They find the marginal likelihood (of their unrestricted BVAR model) falls markedly with lower υ_0.

[27] Note that in months where there are no meetings, the shocks are set to zero. In the months where there are multiple meetings, the shocks are cumulated.

and also that $\phi \neq 0$. These conditions resemble instrument relevance and instrument exogeneity assumptions. Paul (2020) shows that, under these conditions it is possible to use the VAR-X representation to identify the columns of the impact matrix from the structural representation of the VAR in Equation 1.

We therefore assume that the VAR-X of Equation 1 is structural, and the reduced form error from this model is a linear combination of shocks with an economic interpretation, i.e. that $u_t = D_0^{-1}\eta_t$, where η_t is a $(n_y \times 1)$ vector of structural shocks, with variance-covariance matrix I_{n_y}. In this case, still assuming a single instrument, Paul (2020) shows that the impact matrix A is related to the n_yth column of D_0^{-1} by the relation:

$$A = [D_0^{-1}]_{[:,n_y]}\frac{1}{\phi},$$

where the $[M]_{[:,j]}$ notation indicates the jth column of a matrix M. In this case we are able to identify relative impulse functions by dividing the coefficients of the estimate of A by any of the estimated parameters in this vector, which causes the $(1/\phi)$ term to cancel out.

In the Online Appendix to this paper (Section 6) I demonstrate, by a straightforward extension of the logic of Paul (2020), that in the case that we have multiple shocks of interest, and multiple instruments, we are able to identify multiple relative impulse response functions in the case the following assumption holds:

$$E[z_t\eta_t'] = \begin{bmatrix} 0_{[n_z,n_y-n_z]} & \Phi_{n_z,n_z} \end{bmatrix}, \quad \Phi_{n_z,n_z} = diag(\phi_1,\ldots,\phi_{n_z}),$$

where z_t is a $(n_z \times 1)$ vector, and we assume that we are interested in identifying the final n_z shocks of the vector η_t (without loss of generality). We further require that each of the $\{\phi_j\}_{j=1}^{j=n_z}$ are strictly positive. This is obviously a simple case for the Proxy SVAR-X to handle, since each of the instruments correlates with only one structural shock of interest, and the instruments are uncorrelated with each other. However, this assumption is also clearly satisfied by the shock series I enter into the SVAR-X, since, as described previously, the instruments were extracted via an algorithm employing sign-restrictions, and are uncorrelated with each other *by construction*. In this case, the estimate of the A matrix uncovers

$$A = \begin{bmatrix} [D_0^{-1}]_{[:,n_y-n_z+1]}\phi_1^{-1} & [D_0^{-1}]_{[:,n_y-n_z+2]}\phi_2^{-1} & \ldots & [D_0^{-1}]_{[:,n_z]}\phi_{n_z}^{-1} \end{bmatrix}.$$

This means that one can identify the relative impulse responses to each of the shocks, by normalising the response of one of the endogenous variables to a given value (and therefore cancelling out the respective $\{\phi_i^{-1}\}_{i=1}^{i=n_z}$. A full discussion of the way the SVAR-X specification allows one to identify relative impulse response functions, which is a generalisation of the derivations of Paul (2020), can be found in the Online Appendix Section 6 (one difference is that the derivations I use do not invoke asymptotic arguments, for consistency with the Bayesian approach employed in this investigation throughout).

In order to evaluate the impulse-response functions to monetary policy shocks, the shocks must be normalised relative to the impulse-response of one of the variables within the system. The forward guidance shock is normalised with respect to the two-year German Bund yield, and is scaled to reduce the rate by 10 basis points on average. The yield curve compression shock is normalised to reduce the yield curve by 10 basis points on average.[28] This decision has the implication that the impulse response functions reported for information and rate guidance shocks undergo a different normalisation to that of the unconventional monetary impulse response. While results are robust to the case that the yield curve compression impulse response is normalised with respect to the two-year rate, in practice the estimates under the yield curve normalisation are more precise. This results from the fact that the relation between the yield curve compression shock and the yield-curve is less uncertain in the data, relative to its relation

[28] Note that this is similar to the average compression in the German sovereign yield curve on APP announcement days as reported in Altavilla et al. (2015), see Table 3, pp. 34.

to the two-year rate changes. In any case, the point is somewhat moot, as will be discussed, since the unconventional monetary surprise happens to deliver an approximately 10 basis point fall in the shorter-rate at the median.

4 Impulse Response Functions in the Constant Parameter Case

Impulse responses for the macro-economic variables, loans and equities are displayed in Figure 3, while the responses for financial variables are displayed in Figure 4. In this discussion I will focus first on the results for the forward guidance and yield curve compression shocks, before discussing the information surprise.

With respect to the macro-economic variables, we can see that both forward guidance and yield curve compression (expansionary) shocks raise the level of industrial production, reduce the unemployment rate, and raise the price level in ways consistent with theory (though industrial production does fall at impact in response to the forward guidance shock). The effects of yield curve compression shocks are larger in magnitude for all three variables. The peak median effect of the unconventional monetary surprise on the price level is 0.16% after 28 months, while the peak median effect of the forward guidance surprise is 0.07%. With respect to unemployment, the peak impact of yield curve compression is a fall of 0.17pp., while the forward guidance surprise induces a reduction of 0.04pp. The unconventional monetary surprise increases the level of industrial production by 0.88% after 16 months at peak, while the forward guidance surprise increases industrial production by 0.27%. The yield curve compression shock also stimulates a larger response in the stock of loans relative to the forward guidance shock. The responses of equities are partly determined by the identification scheme applied, since by construction the forward guidance and yield curve compression surprises raise stock prices within the intra-daily window.[29] However, the unconventional monetary surprise raises equities by 3.13% at impact, while the forward guidance surprise raises the stock index by only 0.5% (and a zero response is within the 68% credible set, even at impact, for the case of forward guidance).

From Figure 4 we can study the impact of the shocks on interest rates and the yield curves. Recall that the impulse responses are normalised to deliver a 10bp fall in the two-year rate to the forward guidance shock, and a 10bp fall in the yield-curve to the yield curve compression shock. We can see that, with respect to the median impulse response function at least, the yield curve compression surprise ends up delivering a 9.5bp fall in the two-year rate, meaning that both surprises deliver similar responses to the shorter-rate at impact, even though they undergo different normalisations. However, there is a greater degree of uncertainty with respect to the response of the two-year rate in response to the yield curve compression surprise.

One feature of the responses of interest rates which is particularly noteworthy is the medium-term response of the two-year rate to the yield curve compression shock. The shorter-rate falls in response to the shock (which follows from the sign-restrictions), but there is a medium-term *rise* in the shorter-rate (before it falls again to some extent). One explanation for this finding is that the unconventional

[29] It must also be emphasised that the responses of the monthly variables in the system are not *directly* affected by sign-restrictions. In a traditional sign-restriction algorithm, restrictions would be applied to the variance-covariance matrix of the VAR model, as we sample from its posterior distribution, meaning the sign-restrictions would be satisfied across every draw. In the model studied, the sign-restrictions are applied at the intra-daily frequency in the first stage, not the second stage VAR. This means that it is in principle possible for a shock which is restricted to reduce a variable on meeting days *not* to do so at the monthly frequency, which could occur if the effects of the surprises dissipate before the end of the month. For certain endogenous variables in response to certain surprises, we do see a portion of the posterior distribution where this is indeed the case.

policy shock is sufficiently stimulative towards inflation and real variables that it induces a counteracting increase in the shorter-rate by the policymaker in the medium-run. Essentially, the VAR has embedded two reaction functions, one for interest-rate guidance, and another for asset purchases. The reaction function with respect to interest rate guidance could imply an endogenous "dampening" of the effects of unconventional policy. While at first it may seem odd to envisage a central bank actively suppressing the effectiveness of its asset purchase policy with its forward guidance policy, it could also reflect a rational strategy. In a sense, successful expansionary unconventional monetary policies could imply a faster path to "normalization" of the level of the policy rate and escape from the effective lower bound, meaning asset purchases prompt medium-term increases in short-rate expectations. In the case of the ECB faster normalisation may be additionally desirable given the potentially negative implications of a sustained period of negative rates.[30] A similar response of shorter-horizon rates in the medium-term to an expansionary unconventional monetary policy shock is also reported in Boeckx et al. (2017), in their study of ECB liquidity operations, so such a result is not unique to this study.

However, it is possible that the path of the shorter-rate in the VAR system is influenced by the fact that we are using a two-year rate in place of an actual policy rate of the ECB.[31] Therefore, one must be cautious when interpreting the two-year rate equation in the VAR as a "typical" monetary policy reaction function, since its dependent variable is derived from sovereign bonds and is therefore influenced by unconventional policy to some extent.[32] It is possible that the estimated path of the two-year rate could be influenced by (unmodelled) changes in the *composition* of the portfolio of the ECB over time across short-term and long-term bonds, or equally by the composition of the "free-float" of available public sector debt. It would be of interest to study the endogenous response of the two-year rate in more detail in future work.

As we would expect from the sign-restrictions applied, the yield curve steepens in response to the expansionary forward guidance surprise, and flattens in response to the yield curve compression surprise. The steepening of the yield curve in response to the forward guidance surprise, which disappears before one year has elapsed, is less persistent than the flattening induced by unconventional policy, which remains below zero even after two years. This suggests that part of the explanation for the strength of the effect of yield curve compression comes from the persistence of its effect on the yield curve. Note that results do not indicate a medium-term steepening of the yield curve in response to expansionary ECB unconventional policy, which is a finding of Gambetti and Musso (2020), and the median response remains persistently below the zero line.[33]

Part of the reason for the effectiveness of the yield curve compression shock seems to be the depreciation in the exchange rate. In a result counter to the predictions of theory, the US/EUR exchange rate does

[30] Negative interest rates could potentially suppress lending, if the net-interest-margins of banks are compressed by their inability to pass negative rates to deposit holders. The existence of a "reversal interest rate", below which further rate cuts are contractionary for lending, and which in principle can be positive or negative, is discussed in the paper of Brunnermeier and Koby (2019). To date, the empirical literature examining the impact of negative interest rates in the euro area has found little evidence that banks have restricted lending in response to these policies, once the general equilibrium effects of lower rates on demand have been taken into account (Altavilla et al., 2018). It is possible this could change with the duration of the negative interest rate period.

[31] This decision was made since there is insufficient variation in overnight rates during the effective lower bound (ELB) period to permit their use in the analysis.

[32] Forward guidance and expectations would also be important for movements in the two-year rate during the sample period.

[33] The proxy for an unconventional monetary policy surprise is different in this study, relative to that of Gambetti and Musso (2020). The proxy developed by Gambetti and Musso (2020), created using Bloomberg survey data, reflects two separate events (January 2015 and March 2016), whereas the proxy for unconventional monetary policy in this paper is a time-series of yield curve compression surprises (2002-2019).

not depreciate significantly in response to the expansionary forward guidance shock. The depreciation at impact in response to the yield curve compression shock is 2.22%. The expansionary forward guidance shock appears to raise corporate spreads at impact, though the impact effect is measured with a high degree of uncertainty. However, there is a fall in corporate spreads after around 6 months, which persists for around a year, consistent with the "credit" channel of monetary policy (and forward guidance), as quantified by Gertler and Karadi (2015). The yield curve compression shock reduces corporate spreads in the short-term and in a persistent manner, with the falls in corporate spreads lasting for around two years. This suggests that there is an important credit channel to yield curve compression in the short to medium-term. However, there is a subsequent increase in spreads after around three years. This increase is perhaps induced by the response of the shorter-term rate to the yield curve compression shock, which rises in the medium-run, as has been discussed. Forward guidance seems to reduce measures of stock market volatility with a lag of around one year, however the yield curve compression surprise reduces volatility strongly at impact, though the effect dissipates quickly. The differences in the timing of impact of forward guidance and yield curve compression on corporate spreads and uncertainty suggest that forward guidance reduces financial stress via its salutatory effect on the macro-economy (which occurs with a lag), while unconventional policies reduce stress more directly, since they involve purchases of assets from stressed sectors.

The information surprise can be seen to reduce the two-year German rate by 10bp at the median (by construction), and equities fall by 1.13%. The fall in equities reflects the restriction placed on the intra-daily movements at the point at which the information shock was identified. The yield curve steepens by 1.6 basis points at impact in response to the information surprise. This response was actually left unrestricted in the identification scheme, but supports the interpretation of this surprise as a information surprise, as opposed to a "risk premia surprise" of the kind studied by Cieslak and Schrimpf (2019). Cieslak and Schrimpf (2019) argue that information surprises (which they call "growth" surprises) during monetary policy press-statements, perhaps regarding the level of aggregate demand in an economy, for example, should inherit the property of mean-reversion, implying that contractionary surprises steepen the yield curve.

With respect to the other financial variables, the responses seem consistent with a "bad news" interpretation of the information surprise (in the case that it reduces interest rates). There is an increase in implied volatility and corporate bond spreads (the response of spreads is consistent with Jarocínski and Karadi, 2020). There is also a depreciation in the USD/EUR exchange rate. However, the information surprise has only weak effects on macro-economic variables, and seems primarily to affect financial variables. A zero response for unemployment lies within the credible set at all horizons, and the level of industrial production briefly increases in response to the information surprise.[34]

Given the construction of the information surprise uses the same approach to identification used in Jarocínski and Karadi (2020), albeit with a larger Proxy VAR model, one would expect the impulse responses in the constant parameter VAR case to be similar and this is largely true (of course, part of the contribution of this study relative to Jarocínski and Karadi (2020) is to separate forward guidance from unconventional surprises, as opposed to the composite of forward guidance and rate change surprises studied in their paper).[35] The exception is the responses of the price level, since in the paper of Jarocínski

[34]The low significance is also in evidence in certain of the responses to the information surprise in Figure 8A of Jarocínski and Karadi (2020), as discussed by the authors.

[35]There are some differences in the set-up for this paper, where the impulse-responses to the information shock is concerned. I use the EA-MPD of ABGMR whereas Jarocínski and Karadi (2020) use a novel dataset of their own construction; Jarocínski and Karadi (2020) sum responses from the press-releases and press-conferences, whereas I use only the conference window; I

and Karadi (2020) results indicate that an information surprise that lowers interest rate would lower their measure of the monthly price level (though the significance of their responses is low after around 12 months). The information surprise of this paper lowers interest rates, and while the level of prices falls at impact, there is a larger *increase* in the price level in the medium run. From my investigations this result seems to be a feature of medium-scale constant parameter VAR systems only, and may reflect the impact of the depreciation of the exchange rate on prices, which would be expected to transmit with a delay. Results for smaller constant parameter VAR specifications, where the price level is shown to fall in response to the contractionary information surprise, are displayed and discussed in Online Appendix Section 8.

4.1 Robustness

One concern is the use of the German two-year rate in the VAR as a measure of euro area shorter-term interest rates. During the European sovereign debt crisis, the German Bund was widely observed to earn a time-varying safe asset premium, and thus decreases in this rate could reflect flight-to-safety effects, rather than changes in short-rate expectations, or the effects of policy programmes on term-premia. Results are essentially the same if I replace this rate with the two-year OIS rate, which is a measure of the expected path of the EONIA, and should not be directly impacted by German "specialness".

In the baseline model, the overall level of shrinkage was set to equal 0.108. I experiment with $\lambda_1 = 0.05$ without much change in impulse response functions. Conclusions are also robust to setting $\lambda_1 = 0.2$, though the credible sets are wider for these specifications. The baseline prior value for υ_0 was set to a relatively high value of 20, though results look essentially the same with $\upsilon_0 = 2$ (this is the minimum value under which the prior mean for the variance-covariance matrix exists, and is a typical value chosen by researchers).

The shocks used in this paper are related to those derived in ABGMR, though the approach to decomposition differs, as discussed previously. To assess whether the shock series of this paper lead to different results, I have estimated versions of the Proxy-VAR model where I use the timing, forward guidance and unconventional monetary policy surprises of ABGMR. The results of this investigation are presented in Online Appendix Section 7, with a full discussion. While results do look similar, as one might expect, given conceptual similarities between the surprise series and the fact this study uses the EA-MPD, there are some interesting differences. The forward guidance surprise of this paper has a larger, and more significant effect on the price level than the forward guidance surprise of ABGMR. This may be a result of the additional restriction this paper places on equities, which is designed to separate information effects. The responses of macro-variables to the yield curve compression surprise of this paper is also larger, when compared to responses to the ABGMR unconventional monetary policy surprise. However, the median IRFs of macro-variables in response to their QE surprise lies within the 68% credible set for IRF to the yield curve compression surprise, suggesting that the differences are not large statistically.[36] This finding is consistent with the study of Bu et al. (2019), who find a reduced importance of the information channel for long rates (which the yield curve surprise of this paper disproportionately affects).[37]

use the German two-year rate as the measure of short-rates, whereas Jarocínski and Karadi (2020) use the three-month EONIA swap. The sample of Jarocínski and Karadi (2020) ends in December 2016, whereas my sample ends in December 2019 and therefore includes three more years during which asset purchases occurred (aside from the period January-September 2019 when net purchases were halted).

[36]Of course, the unconventional monetary policy surprise of ABGMR was not designed to cover this period, this is part of the motivation for applying an alternative decomposition in this paper, to allow some level of comparability pre- and post-crisis.

[37]Kim et al. (2020) find some role for information effects in explaining variation in the Swanson (2020) unconventional

This paper has argued that the complexity of the transmission channels of unconventional monetary policy necessitates the inclusion of a reasonable number of variables, for both the financial sector and macro-economy. If this claim is true, one would expect smaller VAR systems to deliver different results to the 10-variables system used as the baseline of this paper. I have experimented with smaller VAR systems, and found that VAR(4) and VAR(6) systems deliver very different, and occasionally "puzzling" results. For example, the VAR(4) and VAR(6) specifications display puzzling responses of the price level to the forward guidance surprises, in the sense they have a sign inconsistent with theory. The results of these investigations, with an accompanying discussion, are presented in Online Appendix Section 8. The lack of robustness of smaller systems is part of the reason why time-varying parameters are implemented in this paper using a semi-parametric approach, since parametric approaches have been largely limited to VARs with 6 variables or below (with few lags).

5 The Time-Varying Parameter Model

This section discusses the time-varying parameter model, and the non-parametric approach used in estimation. The TVP-SVAR-X is specified as follows:

$$y_t = B_{0,t} + B_{1,t}y_{t-1} + \ldots + B_{p,t}y_{t-p} + A_t z_t + e_t, \tag{3}$$

where $e_t = R_t^{-1/2}\eta_t$, $\eta_t \sim \mathcal{N}(0, I_{n_y})$. Here we assume that R_t is a positive-definite matrix, governing the time-varying covariances of the structural shocks.

We can re-express the TVP-SVAR-X of Equation 3 as follows:

$$y_t = (I_{n_y} \otimes X_{t-1})\beta_t + e_t,$$

where $\beta_t = vec(B_t')$, $B_t = [B_{1t}, \ldots, B_{p,t}A_t, B_{0,t}]$, and we recall from the definition of Equation 2 that $X_{t-1} = [y_{t-1}', \ldots, y_{t-p}', z_t', 1]$.

Under the Quasi-Bayesian Local Likelihood approach of Petrova (2019), we augment the prior distribution (NIW) with a "quasi-posterior", which replaces the *true* log-likelihood with a log-likelihood comprised of a weighted sum of log-likelihoods over time, where the weights are given by a kernel function. The methodology of Petrova (2019) builds on the quasi-Bayesian approach of Chernozhukov and Hong (2003), and the non-parametric approach to the estimation of time-varying parameter VAR models developed in Giraitis et al. (2018).

Denote the log-density of y_t by $l_t(y_t \mid y^{t-1}, \theta_t)$, where y^{t-1} is the history $y^t = \{y_t, y_{t-1}, \ldots\}$ and θ_t denotes the entire vector of parameters at time t, i.e. $\theta_t = [\beta_t', vec(R_t)']'$. The local-likelihood is given by:

$$l_{Tj}(\theta_j) \equiv \sum_{t=1}^{T} \vartheta_{jt} l_t(y_t \mid y^{t-1}, \theta_j). \quad j \in \{1, \ldots, T\}.$$

Here the key point is that ϑ_{jt} is proportional to a kernel function $\mathcal{K}\left(\frac{j-t}{H}\right)$. The underlying intuition for the procedure is that we down-weight data from periods further backwards (and further forwards) in time, when estimating parameters at a given point in time. This allows us to estimate variation in parameters over the sample period, without specifying a parametric form for parameter evolution. We do not employ a random walk assumption regarding the ways in which parameters evolve over time, as used by Cogley and Sargent (2005) and Primiceri (2005), and thus the approach will not suffer from

monetary policy (LSAP) surprise, however in their system this is limited to two variables, industrial production and the excess bond premium.

bias associated from misspecifying the functional form of structural change, since structural change is uncovered non-parametrically. Petrova (2019) shows the approach is consistent under the assumption that parameter change is sufficiently "slow" across time.[38]

The exact way in which the log-likelihood functions are weighted is given by the following relations:

$$\begin{aligned}
\vartheta_{jt} =& \varkappa_{Tj} w_{jt}, \\
w_{jt} =& \tilde{w}_{jt} \left(\sum_{t=1}^{T} \tilde{w}_{jt} \right)^{-1}, \\
\tilde{w}_{jt} =& \mathscr{K}\left(\frac{j-t}{H} \right), \\
\varkappa_{Tj} =& \left(\sum_{t=1}^{T} w_{jt}^2 \right)^{-1},
\end{aligned}$$

for $j \in \{1, \dots, T\}$. Petrova (2019) employs the Gaussian kernel, therefore

$$\mathscr{K}\left(\frac{j-t}{H} \right) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2} \left(\frac{j-t}{H} \right)^2 \right),$$

where H is set equal to $\sqrt{T}$.

We then combine the prior density, $\pi_j(\theta_j)$, defined over parameter space Θ, with the objective function to obtain the quasi-posterior:

$$p_{Tj} = \frac{\pi_j(\theta_j) \exp(l_{Tj}(\theta_j))}{\int_\Theta \pi_j(\theta) \exp(l_{Tj}(\theta)) d\theta}.$$

In the Gaussian VAR-X case, under the definitions of Y and X as were used in Equation 2, we have the following local-likelihood function:

$$l_{Tj}(y \mid \beta_j, R_j X) \propto |R_j|^{tr(D_j)/2} \exp\left[-\frac{1}{2} (y - (I_{n_y} \otimes X)\beta_j)'(R_j \otimes D_j)(y - (I_{n_y} \otimes X)\beta_j) \right],$$

where D_j is a diagonal matrix comprised of the normalised kernel weights, i.e. $D_j = diag(\vartheta_{j1}, \dots, \vartheta_{jT})$.

One of the advantages of the Petrova (2019) approach is that priors can be applied in the time-varying parameter case that are coherent with the typical Minnesota schemes applied to constant parameter VARs. I therefore maintain the same Normal-Wishart prior distribution over parameters as was applied in the constant-parameter case.[39] We assume that β_j and R_j have a Normal-Wishart prior distribution for $j \in \{1, \dots, T\}$:

$$\beta_j \mid R_j \sim \mathscr{N}(\beta_{0j}, (R_j \otimes \kappa_{0j})^{-1}), \quad R_j \sim \mathscr{W}(\gamma_{0j}^{-1}, \alpha_{0j}),\ j \in \{1, \dots, T\}.$$

Here γ_{0j} and α_{0j} respectively represent the scale matrix and degrees of freedom parameter of the Wishart distribution. The approach also allows the prior to differ over time-periods, though I do not exploit this feature in this study, and $\beta_{0j} = \beta_0$, $\kappa_{0j} = \kappa_0$, $\gamma_{0j} = \gamma_0$, $\alpha_{0j} = \alpha_0$ $\forall j \in \{1, \dots, T\}$. Here I parameterise

[38] Technically, the process θ_t must satisfy one of two conditions:

1. θ_t is a deterministic process $\theta_t = \theta(t/T)$, where $\theta(\cdot)$ is a piecewise differentiable function;
2. θ_t is a stochastic process satisfying: $\sup_{j:|j-t|\leq h} ||\theta_t - \theta_j||^2 = O_p(h/t)$ for $1 \leq h \leq t$ as $t \to \infty$.

The process θ_t can feature any combination of trends satisfying (1) and persistent stochastic components satisfying (2). See Petrova (2019) for a full discussion.

[39] Technically, there is a small difference on account of the fact that the prior was implemented in the constant-parameter case via dummy observations, whereas I follow Petrova (2019) in the time-varying case, where dummy observations are not used.

α_{0j} according to $\alpha_{0j} = \upsilon_{0j} + n_y + 1$. I discuss the exact parameterisation of the prior distribution below, when I discuss the empirical set-up in the time-varying case.

Petrova (2019) derives the quasi-posterior in closed form by combining l_{Tj} with the Normal-Wishart prior. The quasi-posterior is available in closed-form and is given by:

$$\beta_j \mid R_j, X, Y \sim \mathcal{N}\left(\tilde{\beta}_j, (R_j \otimes \tilde{\kappa}_j)^{-1}\right), \\ R_j \sim \mathcal{W}(\tilde{\gamma}_j^{-1}, \tilde{\alpha}_j),$$

for $j \in \{1, \ldots, T\}$. Here the quasi-posterior means are given by:

$$\tilde{\beta}_j = (I_{n_y} \otimes \tilde{\kappa}_j^{-1}) \left[(I_{n_y} \otimes X' D_j X) \hat{\beta}_j + (I_{n_y} \otimes \kappa_{0j}) \beta_{0j} \right], \tag{4}$$

where

$$\tilde{\kappa}_j = \kappa_{0j} + X' D_j X, \\ \hat{\beta}_j = (I_{n_y} \otimes X' D_j X)^{-1} (I_{n_y} \otimes X' D_j) y.$$

The final expression, $\hat{\beta}_j$ is the local likelihood estimator for β_j in the frequentist case of Giraitis et al. (2018). One can see that $\hat{\beta}_j$ looks similar to the OLS estimator $(I_{n_y} \otimes X'X)^{-1}(I_{n_y} \otimes X')y$, however the contribution of data from different parts of the sample-period are weighted according their proximity to period j by the matrix D_j. One can interpret Equation 4 as a weighted sum of the prior (β_{0j}) and the frequentist estimator ($\hat{\beta}_{0j}$).

Further, the quasi-posterior degrees of freedom parameter is given by:

$$\tilde{\alpha}_j = \alpha_{0j} + \sum_{t=1}^{T} \vartheta_{jt}.$$

The quasi-posterior scale matrix is given by:

$$\tilde{\gamma}_j = \gamma_{0j} + Y' D_j Y + B_{0j} \kappa_{0j} B_{0j}' - \tilde{B}_j \tilde{\kappa}_j \tilde{B}_j'.$$

Since the quasi-posterior is available in closed form, estimation can proceed by sampling from the quasi-posterior for the parameters at each point in time $j \in \{1, \ldots, T\}$. The computational demands are therefore minimal, which is part of the attractiveness of the approach with respect to existing methods.

With respect to the empirical set-up of the model, I maintain the specification as close as possible to the specification in Section 3. One important difference is that the estimation procedure of Petrova (2019) requires stationarity of the series, so I enter the series in year-on-year differences where appropriate. The lag order of the SVAR-X is set to 6. I use the same 10 series in the time-varying parameter model as in the constant-parameter model, with the exception of industrial production, which I replace with the €-coin real-time monthly GDP measure of CEPR/Banca d'Italia (see Altissimo et al., 2010). The reason is that €-coin is arguably a better measure of aggregate production at a monthly frequency than industrial production, since it applies more broadly across sectors, and lacks the idiosyncratic volatility of industrial production.[40] However, it was unclear as to the interpretation of a cumulated €-coin measure, which is why I used industrial production in the VAR in levels.

With respect to the prior, the specification of β_0 differs in the time-varying case, since the series are differenced. I maintain the prior that all coefficients on the endogenous variables are zero in the model, with the exception of the first auto-regressive coefficient for unemployment and the two-year interest

[40] €-coin is also used as a measure of aggregate activity in Gambetti and Musso (2020).

rate, which are set to 0.9 as before, due to their high serial correlation. The overall level of shrinkage is set to the same value as before, i.e. $\lambda_1 = 0.108$. I maintain the same Inverse Wishart prior regarding the variance-covariance matrix as in the constant-parameter case, with γ_0 set to equal a diagonal matrix with the variances derived from OLS auto-regressions placed in the diagonal elements. The parameter υ_0 is set to equal 20, as before.

With respect to identification, the argument of Paul (2020) still holds in the time-varying parameter case (indeed, Paul, 2020 also uses a TVP SVAR-X, estimated using a parametric approach). However, we require the additional assumption that the relevance parameters $\{\phi\}_{i=1}^{i=n_z}$ do not vary over time. One argument in favour of this assumption is that the "structure" by which the ECB makes its policy statements (namely, a press release followed by a conference) has remained essentially unchanged over the sample period. Perhaps, if the ECB were to begin lengthen its press statements considerably, for example, an argument could be made for potential fluctuations in instrument relevance. However, there seems little evidence *a priori* to support concern regarding time-varying relevance, though it could be an interesting subject for future research.

6 Results from the Time-Varying Parameter VAR-X Model

Before describing the impulse response functions, I discuss some of the features of the time-varying estimates of the parameters. Figure 5 plots the conditional volatilities of the endogenous variables over the sample-period. What is immediately apparent is a marked increase in volatility during the financial crisis periods, as one would expect given the the behaviour of the underlying series as the credit crunch and global recession unfolded. We see a decrease in the volatility of the two-year German interest rate over time post-crisis, which again seems plausible, given the increasing use of forward guidance by the ECB, which kept short-rate expectations low. In the presence of the effective lower bound, one would expect the volatility of interest rates to reduce mechanically, given that they cannot fall far below zero in response to financial or macro-economic shocks. The volatility of HICP remains elevated post-crisis, and declines at slower rate than the majority of the financial variables. The volatility of unemployment also remains elevated post-financial crisis, and in fact shows an additional peak around 2015. This seems to map closely to the double-dip recession experienced by the euro area, and the elevation in unemployment after 2011, which began to reduce relatively quickly after a lag.

Figure 6 shows the parameters of the impact matrix A_t, as they evolve over time, for several key variables. These estimates will inform the responses we see in the time-varying impulse response functions, since they represent the period zero-response. Note that technically any plot of the parameters of A_t include the (unknown) relevance parameters $\{\phi_i\}_{i=1}^{i=3}$ as well as the true structural parameters. However, we have maintained an assumption that the relevance parameters do not change over time, and they therefore are assumed to govern only the level of the estimated parameters, not their changes over time. An interesting point is that, though sign-restrictions were placed on the instruments on average across meetings, we do see fluctuations in the *strength* by which the sign-restrictions influence the estimates of A_t over the sample period. Note also that, since the approach to identification is two-stage, it is not necessarily the case that the impact responses of the monthly IRFs to the surprises adhere to the sign-restrictions applied to intra-daily surprises, though we have good reason to expect the sign-restrictions to hold in this case. For example, the yield curve compression surprise has a particularly clear relation to the yield curve during the 2015-2017 period, during which the ECB commenced its asset purchases. However, during the earlier period the relation is estimated with more uncertainty. The forward guidance surprise likewise exhibits larger impact parameters in the post-2014 period, after which the official forward guidance policy of the ECB was estimated. These results prefigure the strength of the effects of forward guidance and unconventional monetary policy in the post-sovereign debt crisis period, as will be seen.

When constructing the impulse-response functions, I follow Paul (2020) and normalise the impulse response functions to set the responses of endogenous variables at a given point in time, as opposed to doing so at each and every period, in order to avoid studying the effects of shocks to z_t of different sizes across time. I choose to normalise the impulse responses for the information surprise and forward guidance surprise in order to ensure a 10bp fall in the two-year rate at the median in January 2015, when the ECB APP programme was announced. I also choose to normalise the yield curve compression surprise with to give a 10bp fall in the yield curve in January 2015. In each case, the degree of uncertainty of the respective impact parameter in January 2015 is low, as can be seen from Figure 6, which will reduce the overall uncertainty of the impulse response function. I also cumulate the impulse response functions of the differenced variables, although since these variables enter the model as annual growth rates I first convert these growth rates to monthly by dividing through by 12.[41]

The impulse-response functions are displayed in Figures 7, 8, 9, 10, and 11. I will first compare and contrast the responses to forward guidance and yield curve compression surprises, before turning to a discussion of the information surprise. From Figure 7 we can see that the effect of the forward guidance surprise on the two-year German sovereign yield does fluctuate over time, though the median impact response is always below zero. In the pre-crisis period the transmission of ECB forward guidance statements to the monthly German yield was therefore slightly weaker. The effect of the yield curve compression surprise on the two-year rate prior to 2010 is more irregular, as one would expect since prior to the financial crisis this surprise is essentially a linear combination of term-premia responses to press-statements regarding conventional monetary policy. However, when we examine the effect on the yield curve, we see that these unconventional surprises do affect the curve in a consistent manner. This strengthens the argument for the using these premia responses as representative of the effects of QE programmes on the yield curve, as made, for example, in the constant-parameter framework of Inoue and Rossi (2018).

Figure 8 shows the time-varying responses of inflation and nominal loans. We can see that both the forward guidance surprise and the yield curve compression surprise have their greatest effects on inflation in the post-euro crisis period. Interestingly, the effectiveness of the forward guidance surprise is limited prior to the financial crisis. While this may seem unsurprising, given that an explicit forward guidance policy by the ECB was adopted in July 2013, the relative strength of communication about future rate changes during "normal times" and communication during forward guidance periods is an open question and subject to debate. As I have expressed previously, the ECB did offer guidance relating to future rate movements prior to 2013, and the forward guidance surprise is constructed in such a manner to isolate the surprise components of these statements. These results are consistent with the argument that the explicit forward guidance policy of the ECB did indeed enhance its ability to control inflation. The impulse response to the yield curve compression surprise also result in a second peak before 2015, suggesting that ECB statements during the period were able to transmit to inflation in some degree. Forward guidance statements by the ECB seem to increase loan growth to a maximal extent at about the same period in time forward guidance is most effective for inflation (around 2016). The effect of yield curve compression on loan growth is mostly positive, though there is a puzzling sharp decline in loans to expansionary surprises in the pre-crisis sample.

Figure 9 displays the time-varying responses of equities and the USD/EUR exchange rates. Forward

[41] The response of €-coin is not cumulated.

guidance surprises have their greatest effects on equities in the post-2015 period. The yield curve compression surprise has comparable positive effects on equities in the crisis and post-crisis period, though there is a large effect on equities in the immediate pre-crisis period. It is likely that equities were particularly sensitive to ECB statements in the wake of the dot-com boom and bust, and that this results in the high estimates at the beginning of the sample. In the TVP-SVAR-X model, the effects of the surprises on the exchange rate is hard to interpret, with appreciations often being recorded. Gürkaynak et al. (2020) document puzzling responses of exchange rates to monetary policy surprises in certain cases for the Fed and the euro area, though their results are consistent with theory when considered on average over the sample. The time-varying impulse response functions of this study may be picking up some of these counter-intuitive exchange rate responses.

Figure 10 shows the responses of unemployment and €-coin. The forward guidance and the yield curve compression surprise seem to reduce unemployment in the pre-crisis and post-crisis sample, though there is a breakdown in the transmission of monetary policy communication to unemployment in the financial crisis period, with an unemployment "puzzle" arising around 2011 for the yield curve compression surprise. The effects of forward guidance on €-coin are greatest in the post-2015 period, while the effects of unconventional monetary surprises on €-coin are muted. Figure 11 shows that the effects of forward guidance on corporate spreads are also stronger in the post-crisis period. The effects of yield curve compression surprises are fairly consistent across the time-period of study, though there are periods where spreads actually rise at impact, before falling at later horizons.

With respect to the results for the information surprise, we can see from Figure 7 that the "bad news" information surprise has a fairly consistent negative effect on the two-year rate, consistent with the sign-restrictions imposed that markets anticipate policy rate easing in response to information regarding weak data (which lowers equities). Despite this, the effects on financial and macro-economic variables differ markedly across time. This suggests that the information surprise may reflect discussions of different features of the information set of the ECB at different times. As we would expect given the sign-restrictions imposed, equities fall at impact for the majority of the sample, with the exception of an anomalous increase at the very beginning of the time period. €-coin falls at impact for the sample period prior to 2015, indicating that the information surprises are associated with depressed activity. One notable feature is that the information surprise, though defined to reduce short-term rates, in fact raises the price level substantially in the post-European crisis period, with a similar effect on loans, as can be seen in Figure 8. The "bad news" information surprise also appears to reduce unemployment at impact, and in a persistent manner for a period post-2015. Though equities fall at impact, and the exchange rate depreciates, there is evidence for medium-run increases in these variables during this period. However, there are also increases in implied volatility at impact during this period. These results appear puzzling, in the sense that in the post-2015 period the information surprise has both contractionary and expansionary features.

One explanation could be that the information surprises could have become multi-dimensional during this period, in a manner the identification scheme of Table 1 is not able to handle. Results indicate that the information surprise has certain effects comparable to those of "risk-premium" surprises studied by Cieslak and Schrimpf (2019) in the post-2015 period, since it reduces rates, reduces equities, and increases implied volatility. However, the positive risk-premium surprise of Cieslak and Schrimpf (2019) would be expected to flatten the yield curve. This occurs in response to the information surprise for 2014-2016, but not for 2017-2019. In any case, if expansionary information surprises were associated with increases to the risk-premium, this could account for the complexity of the estimates during this period, since responses would encapsulate both expansionary and contractionary forces. In principle the IRFs could reflect a short-term financial impact of risk-premia surprises and a medium-term expansionary impact of correlated information surprises.[42] Another explanation could be that markets changed their views as to the reaction function of the ECB, in particular the endogenous component of the response of the ECB to its information, perhaps underestimating the extent to which the ECB would use expansionary policy to boost inflation in the medium-term (accounting for the medium-term expansion of prices and equities). The ECB began to reduce the scale of its monthly net asset purchases in December 2016, with a gradual tapering down of the scale of purchases until they ended in December 2018. During this period, many commentators and policy researchers focussed on the question of when the ECB would "normalise" its interest rate and balance sheet policy.[43] Such debates proved premature, as ultimately the ECB resumed net asset purchases in September 2019. It is possible that during the latter part of the initial EAPP of the ECB, when there was policy uncertainty regarding the path to normalisation, markets updated their views of the reaction function in ways that affect the information surprise. The focus of this paper is on the transmission channels of forward guidance and unconventional monetary policies, but the evidence for time-variation in the transmission of the information surprise could be a fruitful subject for future research.

As in the constant-parameter VAR case, the use of the German two-year rate as a measure of the shorter-term interest rate risks may incorporate fluctuations in safe-asset premia, which could be especially relevant during the sovereign debt crisis period. Results look comparable when I replace this series with the two-year OIS rate. Results are also robust to tightening the prior to $\lambda = 0.05$, which is the baseline value used in the paper of Liu et al. (2018). Results are also similar when the shrinkage parameter λ is set to 0.2, implying a weaker level of shrinkage. The baseline TVP-VAR use 6 lags, I also experimented with specifications using 2 lags, and 12 lags, with little change.

7 Conclusion

This paper has decomposed forward guidance and spread compression surprises from the high-frequency surprise dataset for the euro area, created by ABGMR. The study used sign-restrictions to differentiate forward guidance and spread compression policies by their effects on the yield curve, respectively steepening and flattening it. The study used a macro-econometric Proxy SVAR model in both constant-parameter and time-varying cases to study the effects of the two shocks, and found that the shocks that act to flatten the yield curve affect macro-economic variables in a comparable manner to forward guidance surprises. Time-varying evidence suggests that the impact of these two shocks on inflation increased in the post-European sovereign debt crisis period.

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[42]However, the risk-premium is typically thought to be counter-cyclical, making it unclear as to how expansionary information surprises in response to ECB statements could be associated with increases in the risk-premium. Paoli and Zabczyk (2012) show that a standard asset pricing model augmented with habit persistence can generate procyclical risk-premia in certain cases where habits are sufficiently nonpersistent, and consumption is trend-stationary, since agents in bad states of the world reduce their expectations regarding the probability of future recessions. While this is a theoretical special case, much of the dialogue surrounding ECB policy in 2018-2019 concerned the potential for an imminent slowdown, or even a recession, and ECB statements may have influenced these probabilities (see FT, 2019 for an example of such market commentary).

[43]See Claeys and Demertzis (2017) for an example of such discussion.

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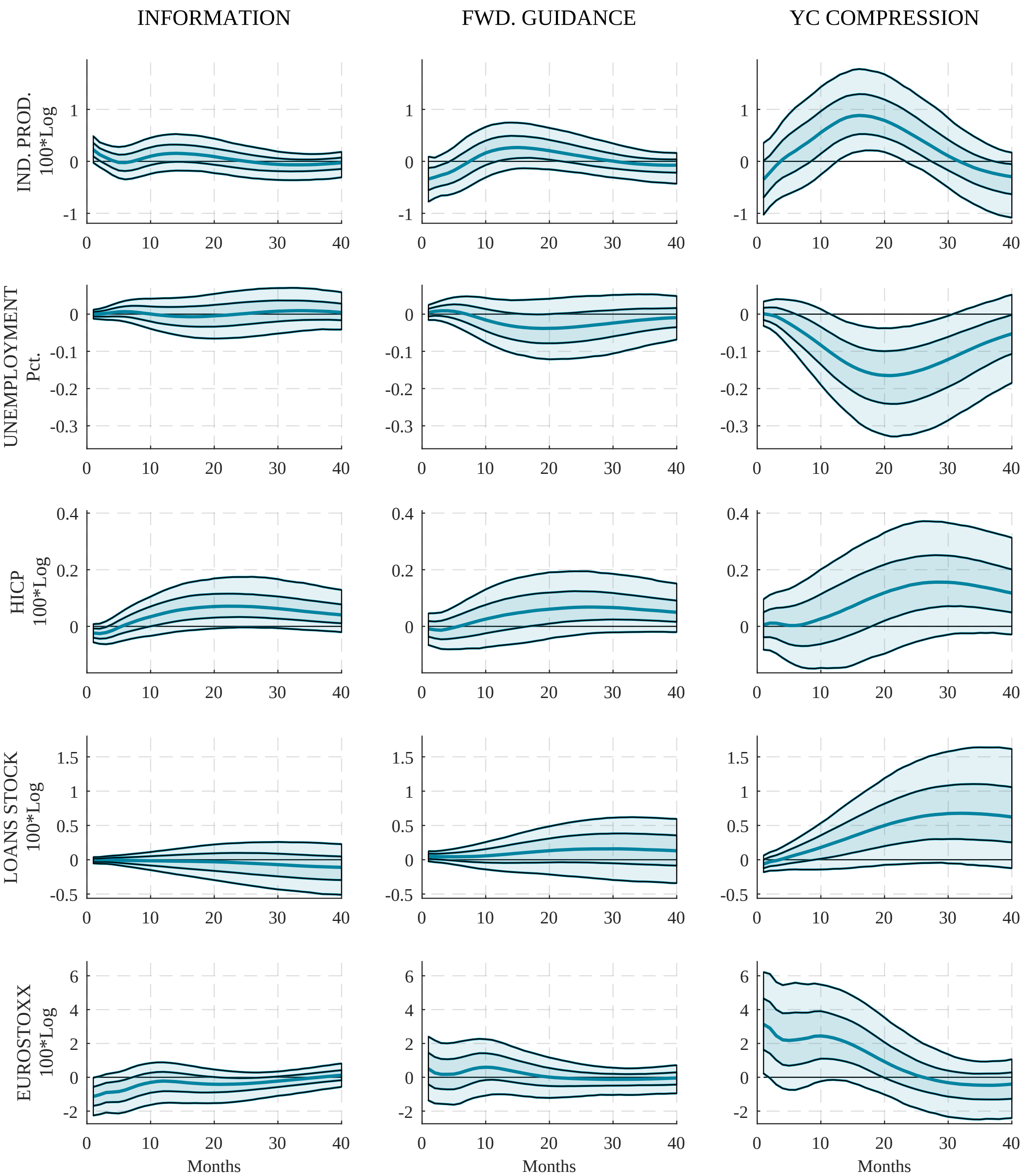
Figure 3: The Effects of Monetary Policy Shocks on Macro-economic Variables and Equities



Notes: Figure shows impulse responses to expansionary information, forward guidance, and yield curve compression surprises in the baseline VAR-X. The information and forward guidance surprises are normalised to lower the two-year German Bund yield by 10bp. The yield curve compression shock is normalised to reduce the yield curve (ten-year subtract two-year German Bund yields) by 10bp. Credible sets are at 68% and 95%.

Figure 4: The Effects of Monetary Policy Shocks on Financial Variables

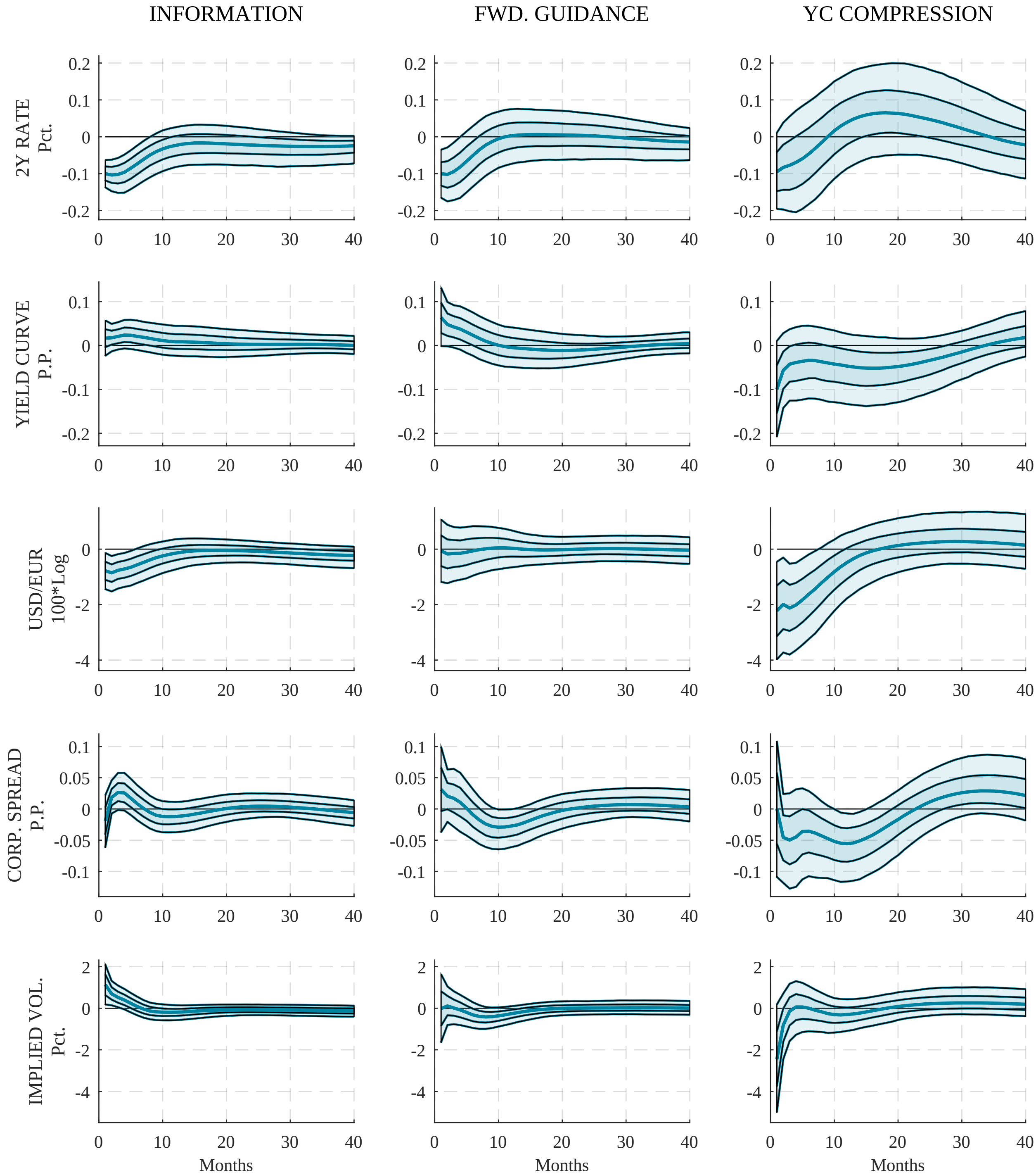


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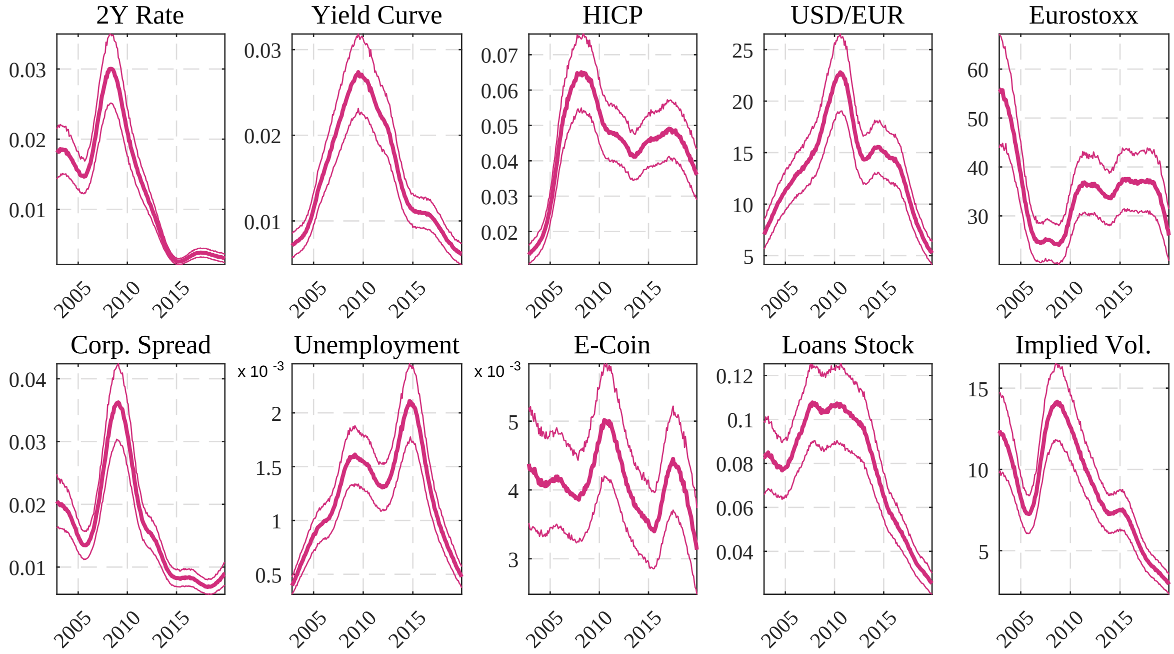
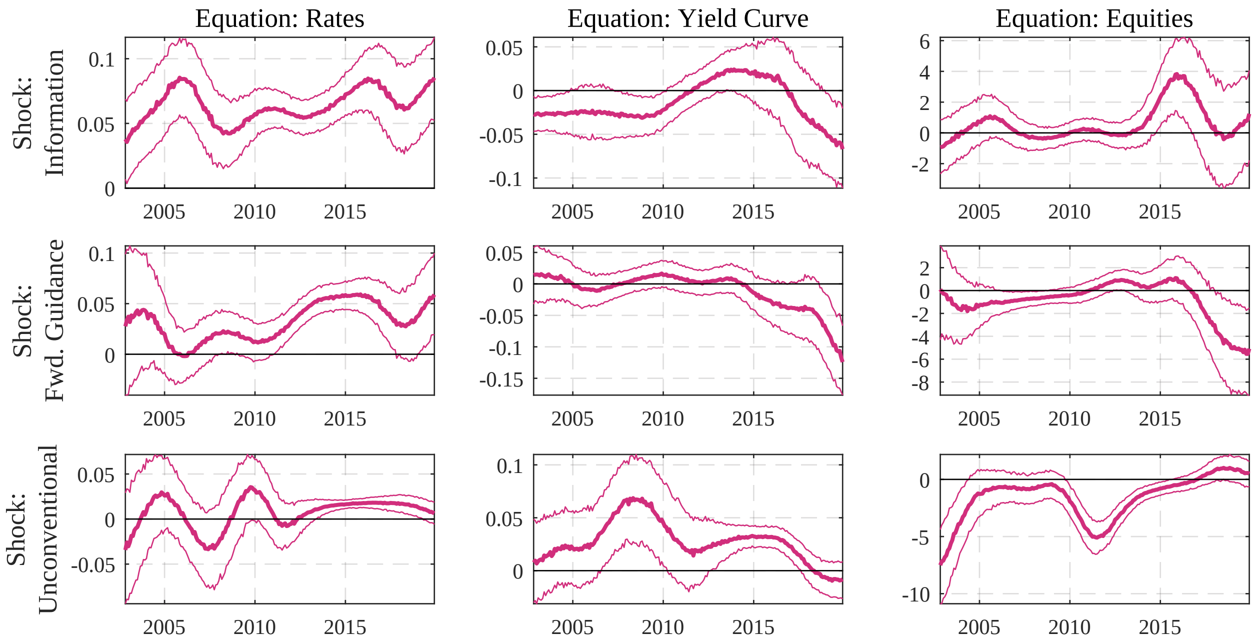
Figure 5: Time Varying Conditional Standard Deviation Parameters



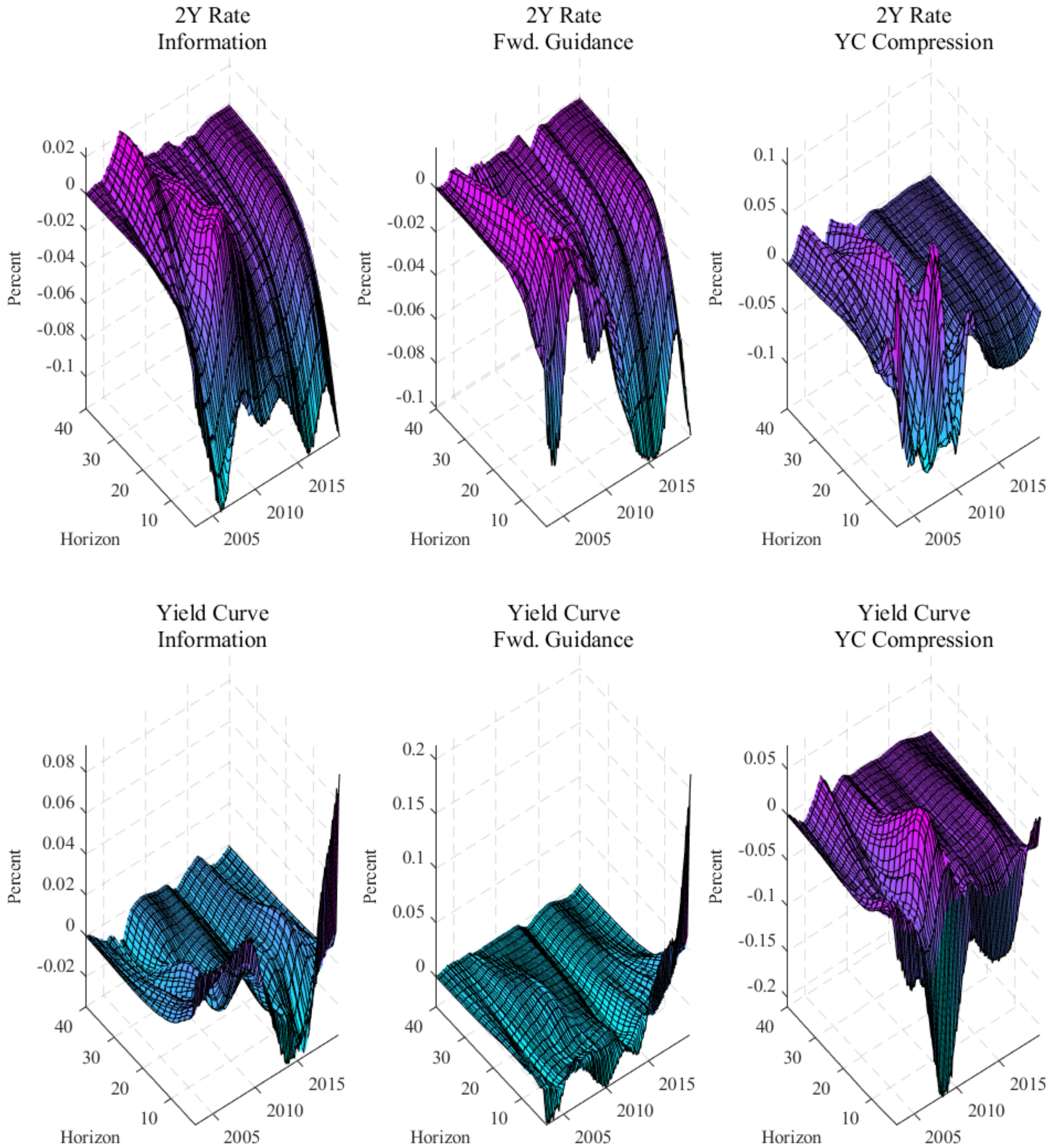
Notes: Figure shows estimated conditional standard deviations across time. Quasi-posterior credible sets are at 68%.

Figure 6: Time Varying Impact Matrix Parameters



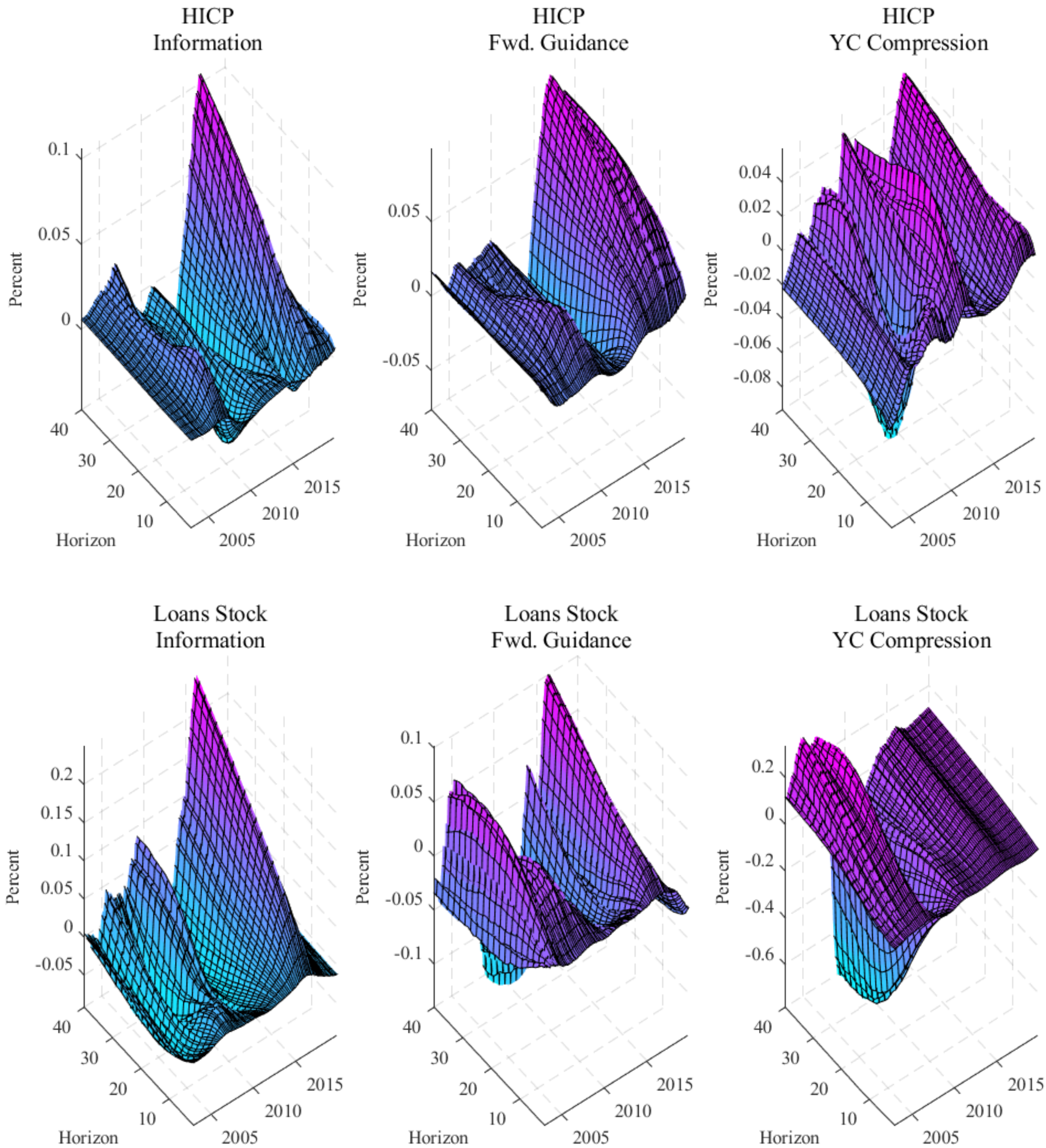
Notes: Figure shows estimated impact parameters across time. Quasi-posterior credible sets are at 68%.

Figure 7: Time Varying Impulse Response Functions:
Interest Rates and the Yield Curve



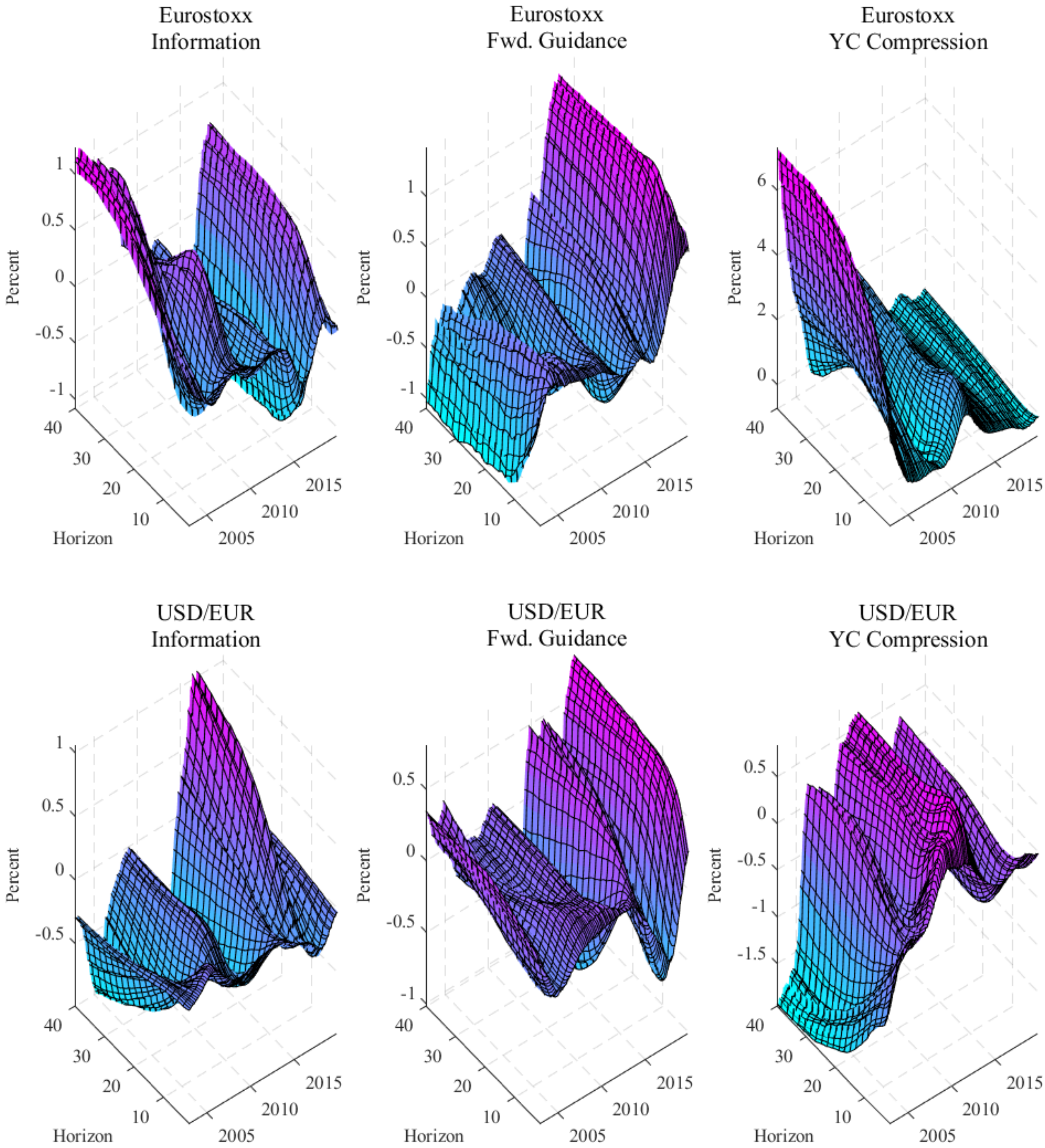
Notes: Figure shows (quasi) posterior median impulse responses to expansionary information, forward guidance, and yield curve compression surprises in the TVP-VAR-X. The information and forward guidance surprises are normalised to lower the two-year German Bund yield by 10bp in January 2015. The yield curve compression shock is normalised to reduce the yield curve (ten-year subtract two-year German Bund yields) by 10bp in January 2015.

Figure 8: Time Varying Impulse Response Functions:
Inflation and the Loans



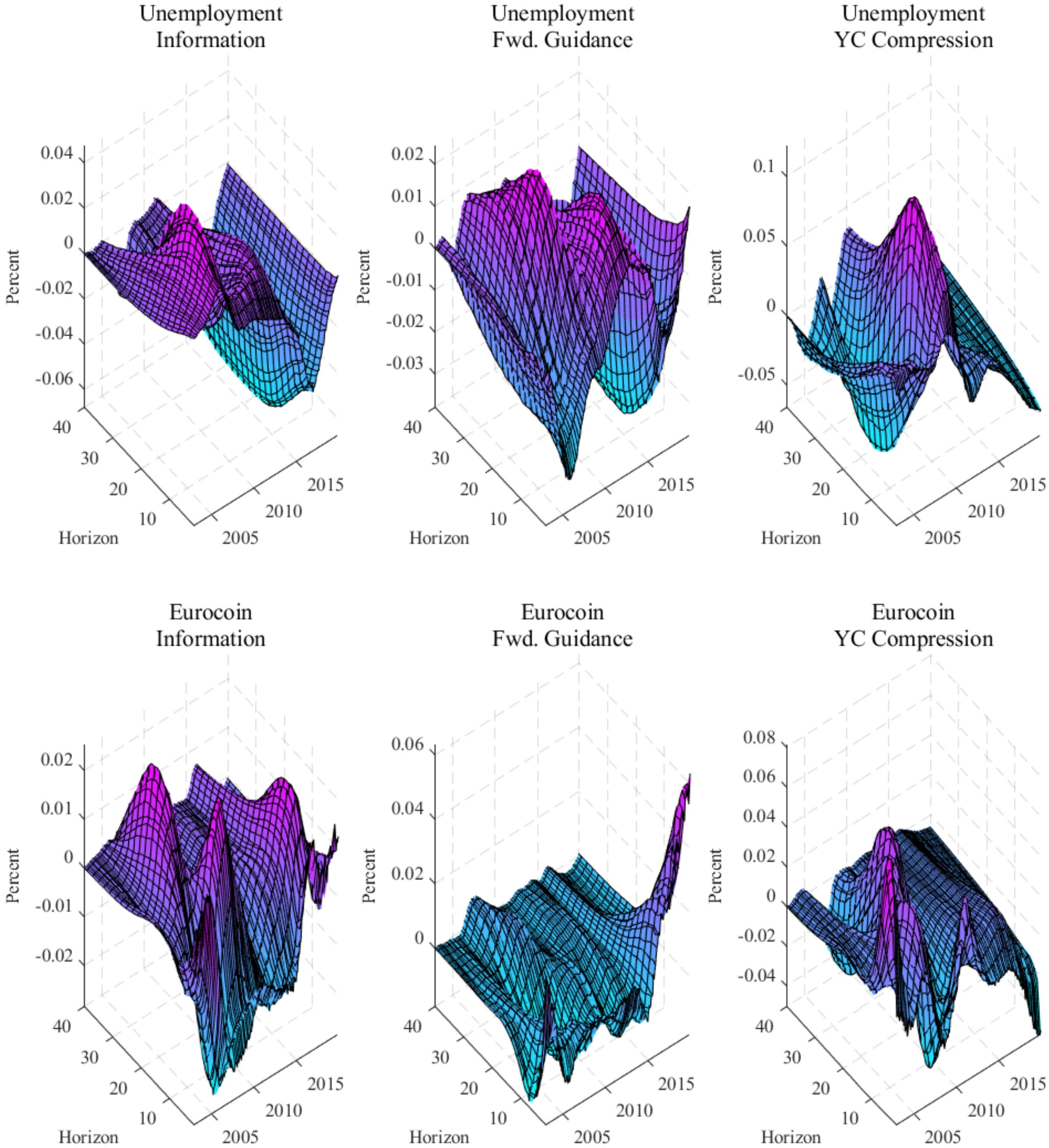
Notes: Figure shows (quasi) posterior median impulse responses to expansionary information, forward guidance, and yield curve compression surprises in the TVP-VAR-X. The IRFs are cumulative for both HICP and loans. The information and forward guidance surprises are normalised to lower the two-year German Bund yield by 10bp in January 2015. The yield curve compression shock is normalised to reduce the yield curve (ten-year subtract two-year German Bund yields) by 10bp in January 2015.

Figure 9: Time Varying Impulse Response Functions:
Equities and the Exchange Rate



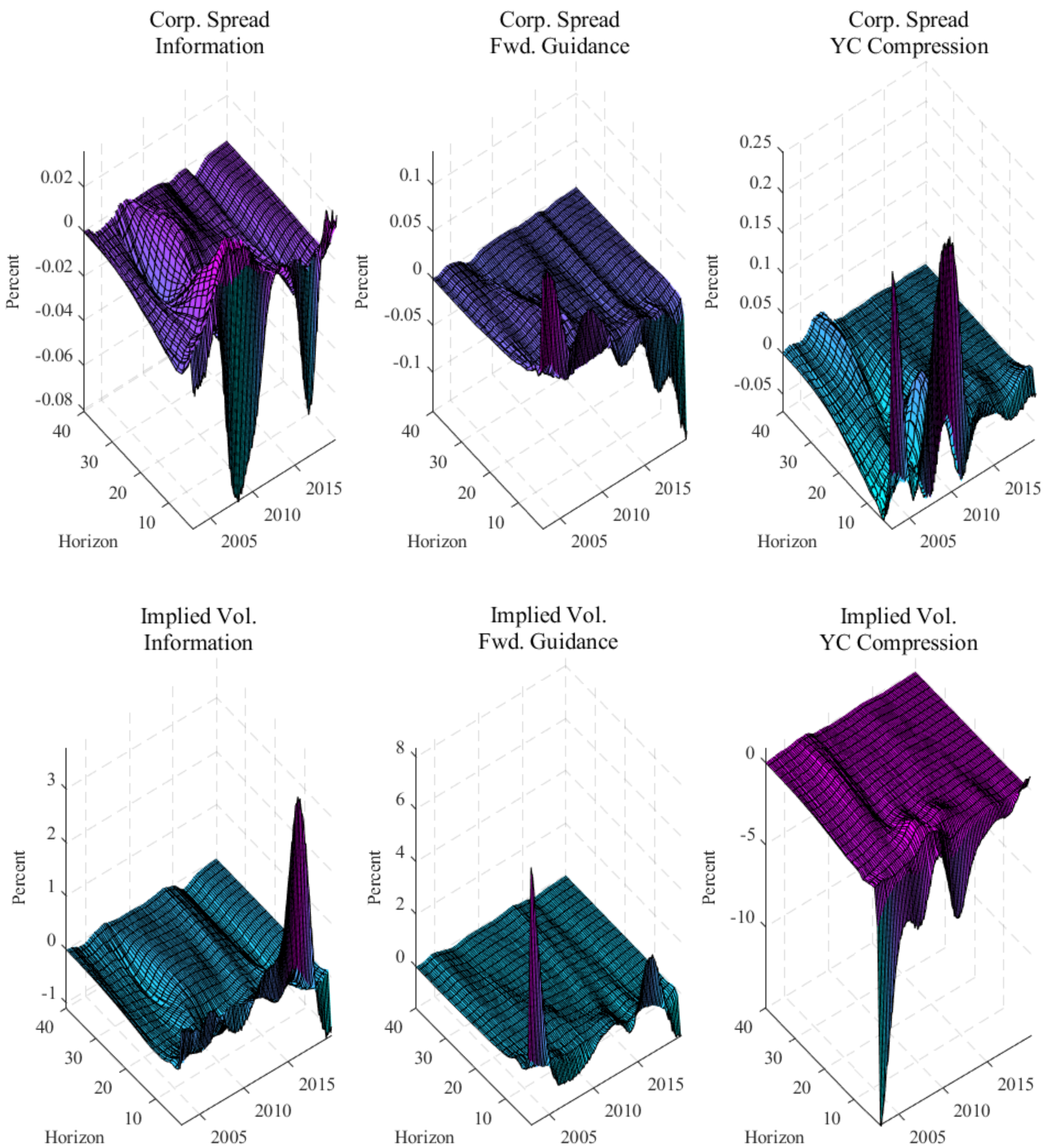
Notes: Figure shows (quasi) posterior median impulse responses to expansionary information, forward guidance, and yield curve compression surprises in the TVP-VAR-X. The IRFs are cumulative for both equities and USD/EUR. The information and forward guidance surprises are normalised to lower the two-year German Bund yield by 10bp in January 2015. The yield curve compression shock is normalised to reduce the yield curve (ten-year subtract two-year German Bund yields) by 10bp in January 2015.

Figure 10: Time Varying Impulse Response Functions:
Unemployment and E-coin



Notes: Figure shows (quasi) posterior median impulse responses to expansionary information, forward guidance, and yield curve compression surprises in the TVP-VAR-X. The information and forward guidance surprises are normalised to lower the two-year German Bund yield by 10bp in January 2015. The yield curve compression shock is normalised to reduce the yield curve (ten-year subtract two-year German Bund yields) by 10bp in January 2015.

Figure 11: Time Varying Impulse Response Functions:
Corporate Spreads and Implied Volatility



Notes: Figure shows (quasi) posterior median impulse responses to expansionary information, forward guidance, and yield curve compression surprises in the TVP-VAR-X. The information and forward guidance surprises are normalised to lower the two-year German Bund yield by 10bp in January 2015. The yield curve compression shock is normalised to reduce the yield curve (ten-year subtract two-year German Bund yields) by 10bp in January 2015.