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The effects of conventional and unconventional monetary policy: identification through the yield curve

Tomi Kortela* and Jaakko Nelimarkka†

January 20, 2020

Abstract

Since the Great Recession, the main evolution in monetary policy has been its attempts to affect the medium and the long-term interest rates with instruments other than the policy rate. Consequently, measuring the stance of monetary policy by a single interest rate becomes problematic. This study explores the macroeconomic effects of conventional and unconventional policy measures in the euro area in a unified framework. We identify simultaneously three monetary policy shocks that influence different parts of the yield curve. These shocks reflect various aspects of actions and communications of the European Central Bank in conventional and unconventional monetary policy periods. According to the results, conventional interest rate policy, forward guidance and quantitative easing have asymmetric output and price responses.

JEL Codes: C32, C36, E43, E52, C54

Keywords: Unconventional monetary policy, structural VAR, zero lower bound, term structure of interest rates

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1 Introduction

The Great Recession and the subsequent European debt crisis required substantial monetary stimulus from central banks. In response to the deteriorating economic outlook, policy rates were first decreased to their zero or effective lower bounds. At the lower bound, central banks exercised unconventional monetary policy measures, including forward guidance on interest rates and quantitative easing (QE) through asset purchase programmes.

The increased number of monetary policy instruments has posed a challenge for the analysis of their macroeconomic effects, often conducted with vector autoregressive (VAR) models. First, monetary policy is usually examined in the context of one instrument, typically the policy rate.¹ At the effective lower bound, the short-run rate does not, however, describe the stance of monetary policy as stimulus is produced by unconventional measures.² Second, the unconventional monetary policy period is relatively short, starting broadly defined from the aftermath of the financial crisis in 2008 when the policy rates hit their effective lower bounds. Hence, only few observations exist to measure the effects of those policies, which leads to estimation uncertainty and to a lack of identification. Third, unconventional policies need to be observed through variables informative about those measures. What those variables are is, however, unclear, as no particular observables directly represent the unconventional policies.³

This paper estimates the macroeconomic effects of monetary policy through the term structure of interest rates. We introduce a structural VAR (SVAR) model with monetary policy shocks that affect different parts of the yield curve. These shocks, extracted from the non-systematic

¹In a standard monetary policy VAR – for example, [Christiano et al. \(1999\)](#) – the policy instrument is the short-run rate which can be controlled by the central bank. Similarly, in a standard medium-scale dynamic stochastic general equilibrium model such as [Woodford \(2003\)](#) or [Smets and Wouters \(2007\)](#) monetary policy is governed by the policy rate. A single instrument is also considered in more recent theoretical explorations, see, for example, [Gust et al. \(2017\)](#). In principle, forward guidance can be modelled in a standard framework. However, the implications of those models regarding their effects may be counterfactual ([Del Negro et al., 2015](#)).

²By using a shadow rate, the effects of monetary policy may be captured in the standard monetary VAR (see, [Wu and Xia, 2016](#)). However, the shadow rate estimates are sensitive across different specifications, see [Christensen and Rudebusch \(2016\)](#).

³For instance, it is unclear whether the size of the central bank balance sheet is a sufficient measure for unconventional monetary policy ([Elbourne and Ji, 2019](#); [Boeckx et al., 2019](#)). For a more detailed discussion and a survey on empirical methods to identify and estimate the effects of unconventional monetary policy, see [Rossi \(2019\)](#).

component of monetary policy, enable to measure the effects of various policy measures. The three shocks arise from the observation that the monetary policy announcements of the central bank lead to considerable shifts in the forward rates across maturities during both conventional and unconventional monetary policy regimes.

Our modelling strategy views monetary policy as operating on the whole yield curve, regardless of whether the zero lower bound binds. Hence, no distinction between the conventional and unconventional monetary policy eras is required. In general, the identified monetary policy shocks induce sudden changes in the short, medium and long-term interest rates. In the conventional monetary policy era, these shocks reflect policy surprises concerning the policy rate, its future path and term premia. Correspondingly, when unconventional monetary policy is conducted, the shocks are in connection with surprises about quantitative easing, forward guidance and short-term interest rate changes close the effective lower bound.

We introduce a novel, unified framework to evaluate the effects of various monetary policy instruments. As monetary policies are to a large extent observable on the yield curve, the latter functions as a sufficient statistic to measure their effects. The yield curve being informative about monetary policy over time, the introduction of unconventional measures implies no policy shifts in our model. Rather, the central bank influences the entire term structure of interest rates over time by policies that differ in how the interest rates change. The macroeconomic effects of a monetary policy ultimately hinge upon the shape of the yield curve shift, independent of what the underlying policy measure is.

In the study, we start with the evaluation of market reactions to the monetary policy announcements of the European Central Bank (ECB). Observed through the yield curve, we report considerably heterogeneous effects on the forward rates after the announcements of the ECB, both in the conventional and unconventional monetary policy eras. Specifically, the announcements induce different types of shifts of the yield curve, a single interest rate being insufficient to describe these surprises. Nevertheless, these market reactions may be fully captured by shifts of the yield curve. Despite the fact that the composition of monetary policy instruments has evolved over time, we argue that its dynamics observed on the yield curve remain similar.

Given the heterogeneity observed in the yield curve changes, we identify three shocks that trigger different shifts of the yield curve and stem from monetary policy. In the identification scheme of the SVAR model, we characterise the policy shocks by a combination of restrictions. First, sign restrictions on the shift of the yield curve determine the nature of the shocks with respect to interest rates. Second, using the proxy SVAR methodology ([Stock and Watson, 2012](#); [Mertens and Ravn, 2013](#); [Arias, Rubio-Ramírez, and Waggoner, 2018b](#)), we exploit variation in the shape of the yield curve around the scheduled monetary policy meetings to find the surprise component of monetary policy. Last, to reinforce our identification and to address potential pitfalls related to the proxy-based identification, we impose additional sign and zero restrictions.

With the model, we estimate the macroeconomic impact of different monetary policies in the euro area. The results indicate that the reactions of output and prices depend on the character of a policy. Which part of the yield curve is initially affected has consequences on the macroeconomic effects of monetary policies. While prices and output respond to conventional monetary policy in line with the empirical literature ([Ramey, 2016](#)), a policy affecting the long-term rates has limited inflationary effects. On the other hand, a monetary policy related to the expectations induces output and price reactions that differ in their timing, compared to the conventional interest rate changes. Potentially, the differences stem from the fact that transmission channels vary between policy instruments.

This paper contributes to several strands of literature. First, we provide evidence on the overall effects of monetary policy, examined in the empirical literature starting from [Christiano, Eichenbaum, and Evans \(1999\)](#).⁴ The stance of monetary policy is typically measured by a short-term interest rate, and the effects are identified by various techniques. In our framework, instead, monetary policy affects different parts of the yield curve. Methodologically, we closely rely on [Inoue and Rossi \(2018\)](#) who show that the VAR model can embed the yield curve. Whereas they study each yield curve shift separately event by event, we examine a set of independent policies through the orthogonal shocks. In particular, the yield curve functions as a parsimonious

⁴The vast literature on the effects of monetary policy is summarised, amongst others, in [Ramey \(2016\)](#). Recent contributions include [Romer and Romer \(2004\)](#); [Gürkaynak, Sack, and Swanson \(2005a\)](#); [Uhlig \(2005\)](#); [Gertler and Karadi \(2015\)](#); [Wu and Xia \(2016\)](#); [Nakamura and Steinsson \(2018\)](#).

approach to observe both conventional and unconventional monetary policies.

Second, this paper contributes to the large literature assessing the macroeconomic effects of unconventional monetary policies. The impact of quantitative easing and forward guidance has been examined, amongst others, by [Krishnamurthy and Vissing-Jorgensen \(2011\)](#), [Chen, Cúrdia, and Ferrero \(2012\)](#), [D’Amico, English, López-Salido, and Nelson \(2012\)](#), [Hamilton and Wu \(2012\)](#), [Del Negro, Giannoni, and Patterson \(2015\)](#) and [Swanson \(2017\)](#). We particularly evaluate the effects of unconventional measures implemented by the ECB, where the evidence is more scarce. To these studies belong, inter alia, [Andrade, Breckenfelder, Fiore, Karadi, and Tristani \(2016\)](#), [Hutchinson and Smets \(2017\)](#), [Koijen, Koulischer, Nguyen, and Yogo \(2017\)](#), [Mouabbi and Sacuh \(2019\)](#), [Cova, Pagano, and Pisani \(2019\)](#).⁵ Compared to the earlier evidence, we take conventional and unconventional policy measures simultaneously into consideration. We find that different policies have asymmetric effects on prices and on the real economy.

Finally, our framework is related to the view ([Gürkaynak, Sack, and Swanson, 2005a](#); [Kuttner, 2001](#); [Cochrane and Piazzesi, 2002](#); [Hanson and Stein, 2015](#); [Nakamura and Steinsson, 2018](#)) that both conventional and unconventional monetary policies affect longer-term interest rates, observed above all in the United States. [Brand, Buncic, and Turunen \(2010\)](#) and [Altavilla, Brugnolini, Gürkaynak, Motto, and Ragusa \(2019\)](#) confirm similar evidence from the euro area. As [Altavilla et al. \(2019\)](#), we use the yield curve factors to separate different types of central bank communication and actions. However, we explicitly identify different policies from the surprises to measure their macroeconomic effects.

The paper proceeds as follows. In Section 2, we evaluate the daily shifts of the yield curve after the monetary policy announcements. In Section 3, we present our methodology. The subsequent section quantifies the effects of the three monetary policy shocks on interest rates and the euro area economy. Finally, Section 5 concludes.

⁵For a survey on the effects of unconventional policies outside the U.S., see [Dell’Ariccia et al. \(2018\)](#).

2 Monetary policy surprises and yield curve

To measure the effects of monetary policy, it is necessary to find exogenous variation stemming from deviations of the central bank from its policy rule. To recover this non-systematic part, the literature usually exploits variation in the interest rates around the scheduled monetary policy announcements (see, e.g. [Kuttner, 2001](#); [Gürkaynak et al., 2005a,b, 2007](#)). That is, news about monetary policy leads to revisions of economic agents' expectations. Provided these surprises reflect exogenous variation and are adequately measured, they facilitate the identification of monetary policy shocks. In this section, we analyse monetary policy surprises over the term structure of interest rates in the euro area.

2.1 Monetary policy and long-term rates

According to the standard macroeconomic theory, a conventional monetary policy shock induces a sudden change of the short-run rate. Through the expectations hypothesis, the shock propagates into the longer-term yields such that the magnitude of the effect decreases with maturity. However, a distinct feature found in the empirical literature concerns the variation in the middle and in the long end of the yield curve. The longer-term interest rates tend to change around monetary policy announcements by more than the expectations hypothesis implies.⁶ As shown by [Inoue and Rossi \(2018\)](#), surprises related to monetary policy statements significantly change all parts of the yield curve.

The movements of the long-term rates during the era of conventional monetary policy are typically interpreted as evidence that the central bank can influence term premia ([Hanson and Stein, 2015](#); [Abrahams, Adrian, Crump, Moench, and Yu, 2016](#)).⁷ Similarly, recent empirical studies

⁶See, [Gürkaynak et al. \(2005a\)](#), [Kuttner \(2001\)](#), [Cochrane and Piazzesi \(2002\)](#), [Hanson and Stein \(2015\)](#) and [Nakamura and Steinsson \(2018\)](#) for the US evidence. Correspondingly, for the euro area, see, [Altavilla et al. \(2019\)](#); [Brand et al. \(2010\)](#).

⁷This conclusion is also supported by the observation that changes in long-term yields are almost completely driven by changes in term premia when surveys are used to model the expected path of short-term interest rates ([Crump et al., 2018](#)). Moreover, in a number of term structure models the term premium is also the main driving factor of long-term yields, see for example, [Adrian et al. \(2013\)](#) and [Joslin et al. \(2014\)](#). On the contrary, [Nakamura and Steinsson \(2018\)](#) argue that changes in long-term rates after the monetary policy announcements are due to changes in the expected trajectory of the natural rate of interest.

by [Gertler and Karadi \(2015\)](#), [Gilchrist, Lopez-Salido, and Zakrajsek \(2015\)](#) and [Caldara and Herbst \(2019\)](#) suggest that changes in the term premium are an important part of monetary policy transmission. Monetary policy thus constantly affects the price of risk in the financial markets.⁸

It is also a well-established fact that unconventional monetary policy matters for the long-term rates, the short end of the yield curve being locked by the effective lower bound (see, e.g., [Krishnamurthy and Vissing-Jorgensen, 2011](#)). Monetary policy then influences the long-term yields, most notably, by forward guidance and quantitative easing. Whereas the former informs economic agents about the future path of the policy rate in the medium run – in the maturities from 2 to 5 years – the policies implementing quantitative easing reduce the long-term rates mainly by suppressing the term premium.

The ability of the central bank to affect the entire term structure has implications for the estimation of the effects of monetary policy. To describe monetary policy accurately enough and in a more thorough manner, it is necessary to control for the full spectrum of interest rates. Otherwise, important transmission channels and aspects of monetary policy may not adequately be captured.

2.2 Monetary policy surprises in the euro area

Next, we study in detail how surprise reactions to the announcements of the ECB have changed the interest rates. Following [Inoue and Rossi \(2018\)](#), we define a monetary policy surprise as a shift in the entire term structure of interest rates. In detail, let $f_{t,d}(\tau)$ be an instantaneous forward rate with maturity τ in years, $\tau \in [0, \infty)$, observed in month t on day d . The latter is

⁸The mechanisms behind this theory are based on the existence of yield-oriented investor ([Rajan, 2005](#)) or importance of demand and supply for the prices of assets due to preferred habitat investors ([Vayanos and Vila, 2009](#)). In addition, responses of heterogeneous investors to monetary policy announcements can cause the sensitivity of long-term rates to short-term rates, see [Brooks et al. \(2018\)](#). [Kliem and Meyer-Gohde \(2017\)](#) shows in a dynamic stochastic general equilibrium (DSGE) model that monetary policy may matter for the term premium by changing households precautionary saving motive.

related to the yield of a zero coupon bond with maturity τ , $y_t(\tau)$, through

$$y_t(\tau) = \frac{1}{\tau} \int_{i=0}^{\tau} f_t(i) di. \quad (1)$$

Accordingly, the standard term structure relationship between forward rates and yields applies. Given a scheduled monetary policy meeting of the Governing Council of the ECB in month t on day d^* , the monetary policy surprise $MPS_{t,d^*}(\tau)$ reads as

$$MPS_{t,d^*}(\tau) = f_{t,d^*}(\tau) - f_{t,d^*-1}(\tau). \quad (2)$$

Hence, the monetary policy surprise is a function of τ that is constructed using daily changes of forward rates across maturities.

By definition (2), the surprise is described in terms of instantaneous forward rates, derived from a dynamic term structure model. The use of these estimates allows to interpret the interest rate changes in the context of no arbitrage. Equally well, $MPS_{t,d^*}(\tau)$ could be described through yields, as also proceeded in [Inoue and Rossi \(2018\)](#). However, the use of forward rates facilitates the analysis, as the magnitudes by which different maturities are affected are more straightforward to compare.⁹ We derive the forward rates and the monetary policy surprises from daily euro area data on Overnight Index Swaps (OIS).¹⁰

In [Figure 1](#), we plot monetary policy surprises on selected scheduled monetary policy meeting days. Panel A shows the shifts of the forward rates from the period of conventional monetary policy, i.e., before entering the zero-lower-bound period. Clearly, these shifts cannot be fully

⁹To derive the instantaneous forward rate, we use the fit given by the arbitrage free dynamic Nelson-Siegel model by [Christensen et al. \(2011\)](#), more closely introduced in [Section 3.1](#). The difference between the actual value and the fit of the yield is small and implies no distortions. In particular, the conclusions of this section could also be made with forward rates directly implied by the yields. The latter are available from the approximation $f_{t,d}(m, n) \approx [my_t(m) - ny_t(n)] / (m - n)$, where $f_{t,d}(m, n)$ is the forward rate from period m and to n .

¹⁰The OIS rates give term structure for EONIA which is the overnight unsecured interbank rate in the Euro area. The EONIA rate follows closely the effective policy rate of the ECB. The OIS contracts are considered to be free of default risk and, hence, they are suitable for measuring the risk-free interest rate in the Euro area. The OIS rates can directly be interpreted as a zero-coupon spot rates. The OIS data span the time period from 6 January 2006 to 18 June 2018. To extend the time series to the launch of the European Monetary Union, we use the cross-country average of daily yields on government bonds of Germany and France for the preceding period, from January 1999 to January 2006.

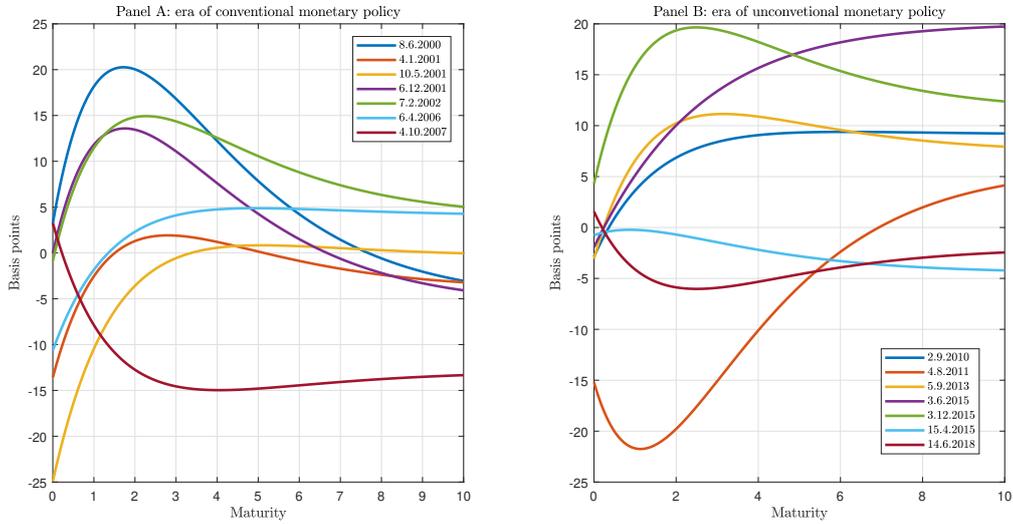


Figure 1: Daily change in the forward rates at the selected monetary policy meetings
The left panel shows selected monetary policy surprises defined by (2) during the monetary policy period, 1999–2008. The right panel depicts surprises from the unconventional monetary policy period starting from 2009. Maturity is given in years.

described by one short-term interest rate only. In a large number of surprises, the maximum effect occurs at maturities ranging from 1 to 3 years, such as around the meetings of 8 June 2000 and 6 December 2001. In addition, a monetary policy meeting may be followed by substantial changes in the 10-year forward rate, such as on 7 February 2002 and 4 January 2001. On the other hand, the market reactions of 4 January 2001 and 6 April 2006 resemble conventional policy surprises, where the magnitude of the forward rate changes is decreasing in maturity.

As in the era preceding the financial crisis, Panel B of Figure 1 shows that surprises are associated with heterogeneous shifts in the term structure after the introduction of unconventional monetary policies. In spite of new measures, the surprises are not necessarily related to changes in the longer-term yields only. Occasionally, such as on 4 August 2011 and 3 December 2015, short-term interest rates considerably changed. This is potentially a result of the so-called policy packages. In these packages, the ECB has combined both conventional and unconventional instruments to conduct monetary policy.¹¹ A surprise may thus consist of multiple components featuring both

¹¹For instance, in March 2016, the Governing Council of the ECB decided to lower the deposit facility rate by 10 basis points and to increase the monthly volume of net asset purchases by 20 billion euros.

conventional and unconventional elements.

At this stage, it is worth noting that we measure monetary policy surprises as reactions of the forward rates within a one-day window. Accordingly, we assume that all public information and expectations of the public about monetary policy are incorporated into the yields at the beginning of the day the monetary policy statement is scheduled. Moreover, the change in the rates on this day is assumed to be dominated by news concerning the ECB's monetary policy announcement. These may be strong assumptions that have been circumvented in the literature with the use of a tighter window, such as in [Nakamura and Steinsson \(2018\)](#) and [Altavilla et al. \(2019\)](#). In contrast, [Hanson and Stein \(2015\)](#) show that a 2-day window and a 60-minute windows give similar results about the movements of the interest rates.

In fact, the use of a longer than intra-day window has several advantages. First, it is not always clear that the market can incorporate all the information to market prices within minutes after the announcement. [Altavilla et al. \(2019\)](#) also report that the intra-day tick data may produce large measurement errors. Second, as shown in [Appendix A](#), the differences between our estimates of the monetary policy surprises and intra-day data of [Altavilla et al. \(2019\)](#) are relatively small. Third, daily data allow us to estimate a dynamic factor model on the term structure of interest rates and identify the underlying yield curve factors more accurately.

To conclude, surprises to the monetary policy announcements are associated with shifts of the whole yield curve. The shape of a shift also varies from one announcement to another. Studying the surprises with a single interest rate – regardless of its maturity – is thus insufficient to cover all the aspects of monetary policy communication. This insufficiency applies to both conventional and unconventional monetary policy. With the yield curve, instead, monetary policy can be studied in a broader framework, where different types of shifts are easily observable. Rather than changing a single interest rate only, we interpret a monetary policy surprise as a sudden shift in the entire term structure, in line with [Inoue and Rossi \(2018\)](#). As these shifts stem from the surprise actions of the central bank, they may be used to identify the macroeconomic effects of monetary policies that differ in how they affect the yield curve.

2.3 Similarity between conventional and unconventional monetary policy

The above evidence suggests that both conventional and unconventional monetary policy have significant effects on the entire term structure of interest rates. Hence, the end of the conventional monetary policy period did not necessarily lead to a regime shift, where the central bank started to affect all parts of the yield curve. Rather, observed through the yield curve, surprises concerning monetary policy are remarkably similar over time. This implies that monetary policy may be viewed as a continuum, the central bank affecting – directly or indirectly – a set of interest rates.

Before the Great Recession, the central bank used policy rates as their main instrument, but monetary policy also indirectly affected the medium and the long-term rates. Expectations regarding the future path of the policy rate have been a key part of monetary policy communication for a long time (see [Woodford, 2005](#), for general discussion and [Gürkaynak et al., 2005a](#), for an empirical exploration). Moreover, referring to the discussion in Sections 2.1 and 2.2, changes of term premia due to monetary policy were by-products of conventional actions of the central bank. After the short-term rates hit their lower bounds, new policies such as quantitative easing and forward guidance were introduced in order to affect the medium- and long-run rates directly. Essentially, forward guidance and quantitative easing make the expectations management and influencing the long-term rates direct policy instruments.

To illustrate the issue on the yield curve, let us find policy surprises that are similar in terms of their effects on the forward rates, despite originating from different monetary policy periods. We proceed by searching for a surprise in the conventional monetary policy period a match among surprises that occur after the effective lower bound started to bind.¹² The left and right panels of Figure 2 plot a sample of matched pairs for surprises where the strongest effects are on the medium-term and long-term maturities, respectively. The solid lines depict the surprises from the conventional monetary policy period. The dash-dotted line of the same colour represents the matched surprise from the unconventional policy era.

Importantly, the surprises plotted in Figure 2 suggest that we are able to find remarkably similar reactions to monetary policy from both periods. For instance, the reactions to the monetary

¹²A closest match is defined as the minimum of the sum of squared deviations across maturities.

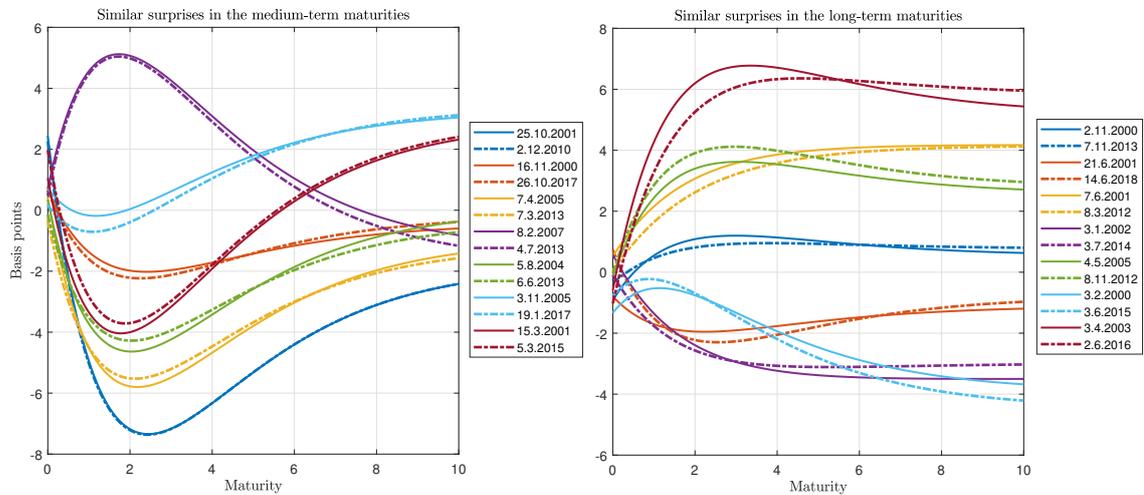


Figure 2: A sample of similar monetary policy surprises from the eras of conventional and unconventional monetary policy.

Solid lines represent the former and dash-dotted lines represent the latter. The color of the lines are the same for the matched pairs. Maturity is given in years.

policy announcement on 8 February 2007 and 4 July 2013, plotted in purple lines in the left panel, closely resembled each other. This similarity arises although the former shift is a response to a conventional monetary policy decision, whereas the Governing Council introduced forward guidance in the latter meeting. Correspondingly, the dark red lines in the right panel suggest that the shifts occurred on 3 April 2003 and 2 June 2016 closely coincided and caused the medium-term rates to hike. The surprises do not significantly differ from each other despite the fact that, in the former meeting, the ECB did not adjust its key interest rates in response to the escalated conflict in Iraq and, on the latter date, the ECB changed parameters of its asset purchase programme.

The evidence of Figure 2 about the similarity of yield curve responses suggests that the entire term structure of interest rates has continuously reacted to the central bank actions and communication. This observation allows to interpret that monetary policy affects the yield curve and through it the whole economy in a time-invariant manner. In particular, a distinction between different monetary policy periods becomes unnecessary as soon as the yield curve is included to the analysis. This implication is also supported by the results of [Debortoli, Gali, and Gambetti \(2018\)](#) and [Wu and Xia \(2016\)](#). According to their results, they find no significant change

in the responses of economic variables to surprise monetary policy although the Federal Funds rate attained its zero lower bound. Instead, there exists perfect substitutability between the conventional and the unconventional monetary policy

3 Identification and estimation of monetary policy shocks

As the previous section suggests, monetary policy affects the entire term structure of interest rates, both during the conventional and the unconventional monetary policy periods. This section presents a framework to examine monetary policy that operates on the whole yield curve. First, variation in the interest rates and surprises in monetary policy are condensed into factors that change the term structure of interest rates differently. Second, we jointly model the yield curve and other macroeconomic data in the structural VAR model such that the impact of different monetary policies on the economy can be estimated.

3.1 Yield curve factors and monetary policy surprises

For analysing movements of the interest rates and tracking relevant dynamics, it is useful to model the yield curve in terms of factors. To estimate these factors, we use the arbitrage-free dynamic Nelson-Siegel model by [Christensen, Diebold, and Rudebusch \(2011\)](#). This workhorse yield curve model can be seen as a special case of the canonical Gaussian dynamic term structure model by [Joslin, Singleton, and Zhu \(2012\)](#). Specifically, the factors of the Nelson-Siegel model can be interpreted in a meaningful manner for the identification of monetary policy shocks. In the following, we briefly describe the yield curve model. Details are found in [Appendix B](#).

Following [Nelson and Siegel \(1987\)](#) and [Christensen et al. \(2011\)](#), a forward rate in month t on day d with maturity τ in years, $f_{t,d}(\tau)$, follows

$$f_{t,d}(\tau) = l_{t,d} + s_{t,d}e^{-\lambda\tau} + c_{t,d}\lambda\tau e^{-\lambda\tau} - a(\tau) \quad \forall t, d \quad (3)$$

where $l_{t,d}$, $s_{t,d}$ and $c_{t,d}$ are the factors with loadings 1, $e^{-\lambda\tau}$ and $\lambda\tau e^{-\lambda\tau}$, respectively. λ is a

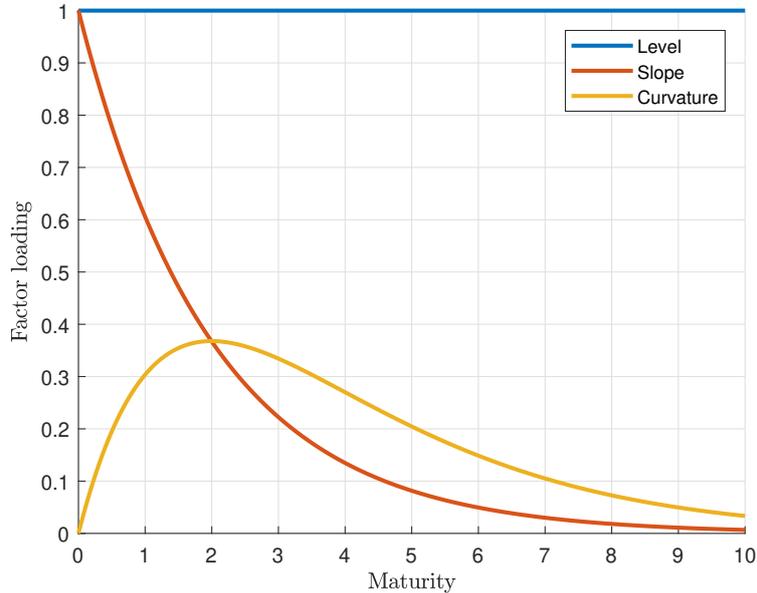


Figure 3: Loadings for the level ($l_{t,d}$), slope ($s_{t,d}$) and curvature ($c_{t,d}$) factors with $\lambda = 0.503$.

parameter estimated from data, and $a(\tau)$ is a time-invariant adjustment term that ensures the fit of the model to be arbitrage free.

The factors influence different parts of the yield curve, which can be seen from the loadings drawn in Figure 3. First, $l_{t,d}$ controls the level of the yield curve. This level factor has an equal impact on all maturities. Second, $s_{t,d}$ determines the slope of the yield curve: the shorter the maturity, the larger its impact. Conversely, the slope factor has negligible effect on the long-term interest rates. Third, $c_{t,d}$ is a curvature factor that moves the medium-term interest rates the most, while leaving the both ends of the yield curve intact.

Using the yield curve model, we may decompose the monetary policy surprises, MPS_t in equation (2) on a scheduled monetary policy meeting day d^* in month t , into the three factors:

$$MPS_{t,d^*}(\tau) = f_{t,d^*}(\tau) - f_{t,d^*-1}(\tau) = \Delta l_{t,d^*} + \Delta s_{t,d^*} e^{-\lambda\tau} + \Delta c_{t,d^*} \lambda\tau e^{-\lambda\tau}, \quad (4)$$

where $\Delta l_{t,d^*} = l_{t,d^*} - l_{t,d^*-1}$, $\Delta s_{t,d^*} = s_{t,d^*} - s_{t,d^*-1}$ and $\Delta c_{t,d^*} = c_{t,d^*} - c_{t,d^*-1}$. This decomposition is illustrated in Figure 4, where monetary policy surprises from three dates are drawn using

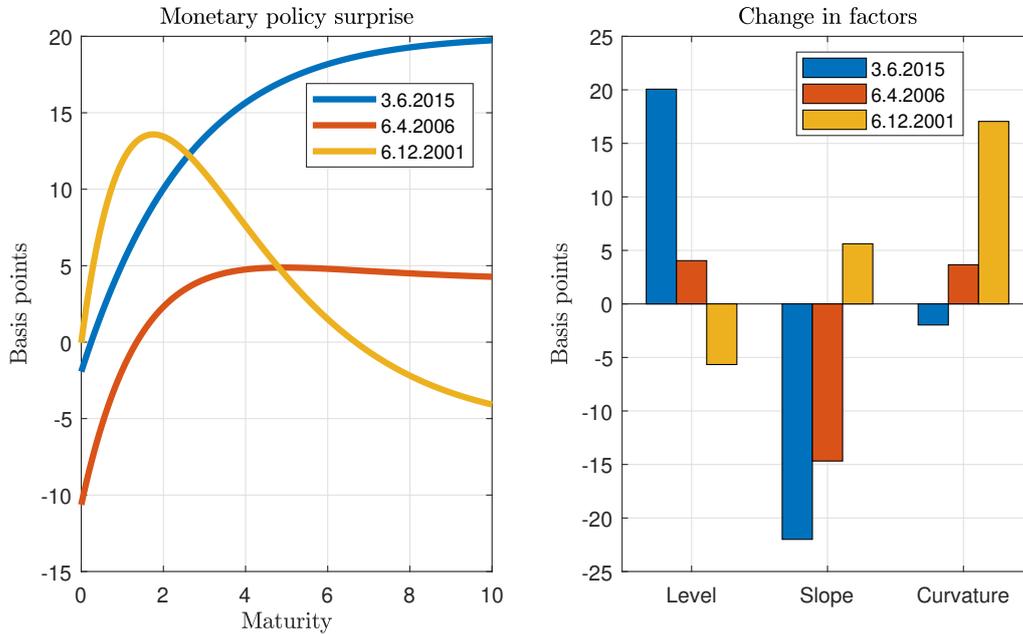


Figure 4: Three representative monetary policy surprises measured by the forward rates and factors.

equation (4). In the left panel, the surprises are plotted as shifts in the forward rates. In the right panel, the shifts are plotted in terms of the factors. As can be seen, a scheduled monetary policy meeting of 3 June 2015 was followed by an increase of long-term rates with no simultaneous change in the short end of the curve. Viewing through the factors, depicted in the right panel, and equation (4), a long-term interest rate hike triggered a rise of the level factor. Since the short-run rate did not move and $f_t(0) = s_{t,d} + l_{t,d}$, the increase in the level factor was compensated by a decrease of the slope factor with the same magnitude.

On the other hand, the announcement on 6 April 2006 caused short-term forward rates to decline by 10 basis points. Contemporaneously, the long-run forward rates did not change such that the shift was monotonic in maturity τ . Because of the monotonicity, the level and curvature factors reacted only marginally. The third plotted surprise, from 6 December 2001, induced medium-term forward rates to jump by 15 basis points. As neither short nor long-term forward rates moved, the change must be due to the curvature factor that imposes the highest loading on the medium-term maturities.

3.2 Monetary policy shocks on the yield curve

The examples of surprises plotted in Figure 4 and the respective behaviour of the factors suggest that it is possible to distinguish three different shocks from a yield curve shift. These shocks have an impact on different parts of the yield curve. Similarly, [Altavilla et al. \(2019\)](#) have used factor representation to decompose monetary policy surprises. Specifically, with the characterisation described below, the central bank may affect the short, middle and long end, depending on whether communication and actions concern the policy rate, expectations or the term premium.

First, let us introduce a shock that affects solely the long-term forward rates. According to the loadings in Figure 3, the level and slope factors then move to opposite directions. The most prominent example of policies reflected in this shock is quantitative easing. However, the evidence and discussion of the previous section indicate that monetary policy has affected the long-term rates well before the introduction of unconventional measures.

Second, the central bank may naturally surprise the public in the short end of the yield curve, corresponding to a classical monetary policy shock ([Christiano et al., 1999](#)). The shock leads to an unanticipated short-run interest rate change with magnitude decreasing as maturity increases. The shock incorporates into the longer-term yields consistently with what a standard macroeconomic model implies, i.e. according to the expectations hypothesis. Specifically, these types of reactions are generated by changes in the slope factor that determines the short-term interest rate fluctuations.

Third, the surprise reactions of the medium-term forward rates to monetary policy are caused by the curvature factor changes. We interpret these changes as stemming from the shock on expectations about the future monetary policy. In particular, the shock influences neither the short nor the long end of the yield curve. The former remains intact as the revealed information concerns the future path of the policy rate. The long-term rates do not change, since the shock does not affect term premia or the price of risk per se but the expected path of the short-run interest rate in the medium horizon. Notably, the shock reflects monetary policy communication such as forward guidance. As discussed in Section 2.1, the existence of this class of surprises

is not restricted to the explicit forward guidance only but the central bank has constantly used expectations management.

With this characterisation, we are able to distinguish three shocks that have a natural interpretation in how they affect the term structure of interest rates. Moreover, the shocks are closely connected to the three factors of the yield curve model such that their daily variation around the monetary policy announcements can be exploited in the analysis.

3.3 Monetary SVAR model

So far, reactions of the forward rates to the monetary policy announcements have been studied in a reduced form. That is, different shifts of the yield curve, i.e. changes in the factors, may be mutually correlated. Hence, adjusting one factor may trigger a shift in the other such that their effects cannot separately be measured. This implies that shifts of the yield curve as studied in the previous section cannot either be individually examined.

This subsection presents a structural vector autoregressive model by which the aforementioned shocks can be orthogonalised. With the model, it is possible to measure the macroeconomic effects of monetary policies that operate on different parts of the yield curve. Specifically, we use a VAR model that combines the yield curve factors with macroeconomic variables on a monthly frequency. The effects of three types of monetary policies can then be derived from the impulse responses of the model to the mutually orthogonal shocks.

Let x_t contain l monthly macroeconomic variables of interest and include the average monthly yield curve factors, level l_t , slope s_t and c_t , to a (3×1) vector $\beta_t = (l_t, s_t, c_t)'$.¹³ Equation (3) implies that the average forward rate with maturity τ in month t reads as

$$f_t(\tau; \beta_t) = l_t + s_t e^{-\lambda\tau} + c_t \lambda \tau e^{-\lambda\tau} - a(\tau). \quad (5)$$

¹³ l_t , s_t and c_t are computed as monthly averages from $l_{t,d}$, $s_{t,d}$ and $c_{t,d}$.

Assume – ignoring constant terms – that these variables evolve according to a VAR process

$$y_t = \sum_{i=1}^p A_i y_{t-i} + u_t \quad (6)$$

where $y_t = (x'_t, \beta'_t)'$ is an n -dimensional vector, $n = l+3$, that collects the macroeconomic variables and the monthly average yield curve factors in β_t . Furthermore, $(n \times n)$ matrices $\{A_i\}_{i=1}^p$ contain the autoregressive coefficients and $u_t \sim N(0, \Sigma)$ is an error term of dimension $(n \times 1)$, where Σ is a positive definite $(n \times n)$ covariance matrix.

Accordingly, we model the joint dynamics of macroeconomic variables and term structure similar to [Bianchi, Mumtaz, and Surico \(2009\)](#) and [Inoue and Rossi \(2018\)](#), the full spectrum of interest rates being contained in the model. Due to the VAR structure, the yield curve factors and the macroeconomic variables are in a constant dynamic interaction. That is, the term structure is allowed to be influenced by the macroeconomic aggregates. Correspondingly, the dynamics of macroeconomic variables are determined by a rich amount of information contained in the factors.¹⁴

Let us now identify the three monetary policy shocks discussed in the previous subsection. We isolate these shocks from the forecast error by exploiting variation of the yield curve factors around the scheduled monetary policy meetings, coupled with additional identifying restrictions. Following the SVAR literature, let the structural shocks in ε_t , $\varepsilon_t \sim N(0, I)$ be found from the reduced-form error u_t as

$$u_t = B\varepsilon_t, \quad (7)$$

where $BB' = \Sigma$ and B is an impact matrix identified with restrictions discussed below. To recover these shocks, we exploit a combination of sign, magnitude and proxy-based restrictions to find the correct impact matrix $B = PQ$ with $PP' = \Sigma$ and $QQ' = I$.¹⁵ These restrictions

¹⁴The findings of [Bauer and Hamilton \(2018\)](#) suggest that the yield curve factors efficiently extract information that goes beyond the dynamics of interest rates in a way that the dynamics cannot be explained by other variables. Hence, the inclusion of the yield curve to the VAR model improves its information content similar to the FAVAR models.

¹⁵Technically, to find B , let Q be an $(n \times n)$ orthonormal matrix such that $QQ' = I$. Furthermore, decompose Σ by Cholesky decomposition such that $\Sigma = PP' = PQQ'P'$, where P is a lower-triangular matrix. As $\Sigma = BB'$, B is found through rotation matrix Q as $B = PQ$.

control the sign of the initial responses, the shape of the yield curve shifts and the correlation of the respective shock with a proxy variable. Moreover, we use additional restrictions typically used for the identification of monetary policy shocks.

3.3.1 Sign restrictions on the yield curve

With sign restrictions on the forward rate responses, we aim to distinguish the shocks by how they affect the yield curve. In particular, following [Inoue and Rossi \(2018\)](#), we interpret the shocks as functional, i.e. the identified shocks induce shifts in the function (5). This first set of restrictions determine the effects of the shocks to align with those described in subsection 3.2.

The shocks of the model affect the term structure of interest rate through the level, slope and curvature factors in β_t . Let ε_t^i be the i th shock in ε_t . On impact, a shock ε_t^i induces a shift of the forward rates:

$$\Delta f_t(\tau; \beta_t) = \frac{\partial f_t(\tau; \beta_t)}{\partial \varepsilon_t^i} = \frac{\partial l_t}{\partial \varepsilon_t^i} + e^{-\lambda\tau} \frac{\partial s_t}{\partial \varepsilon_t^i} + \lambda\tau e^{-\lambda\tau} \frac{\partial c_t}{\partial \varepsilon_t^i}. \quad (8)$$

The latter two factors determine the shape of the shift, which can be analyzed by the first derivative of (8):

$$\frac{\partial \Delta f_t(\tau; \beta_t)}{\partial \tau} = \frac{\partial}{\partial \tau} \left(\frac{\partial f_t(\tau; \beta_t)}{\partial \varepsilon_t^i} \right) = \lambda e^{-\lambda\tau} \left(-\frac{\partial s_t}{\partial \varepsilon_t^i} + (1 - \lambda\tau) \frac{\partial c_t}{\partial \varepsilon_t^i} \right). \quad (9)$$

Depending on the changes of the slope and curvature factors, the shift in the forward rates may be increasing, decreasing or non-monotonic in τ . The shocks can therefore be distinguished through sign restrictions on (9) that depend on maturity τ .

Next, we define a set of restrictions that characterise the shape of the shifts induced by the shocks characterised in Subsection 3.2. Let us denote by ε_t^l , ε_t^s and ε_t^c the monetary policy shocks on the long-term forward rates, on the policy rate and on the expectations related to future monetary policy, respectively. The shock on the long-term forward rates, ε_t^l , is generated by the following

sign restrictions on the yield curve

$$\Delta f_t(\tau; \beta_t) > 0 \quad \forall \tau \quad \text{and} \quad \frac{\partial \Delta f_t(\tau; \beta_t)}{\partial \tau} > 0 \quad \forall \tau.$$

By the first restriction, forward rates increase, and the second restriction ensures that the shift is increasing in maturity. The latter restriction also implies, by (9), that the slope factor responds negatively and the level factor positively on impact. The overall effect of the shock is thus the strongest in the long end of the yield curve.

Next, the effects of a conventional monetary policy shock, ε_t^s , on interest rates satisfy

$$\Delta f_t(\tau; \beta_t) > 0 \quad \forall \tau \quad \text{and} \quad \frac{\partial \Delta f_t(\tau; \beta_t)}{\partial \tau} < 0 \quad \forall \tau.$$

Again, the first restriction ensures that interest rate response is of the same sign across maturities. The second restriction determines, in turn, that the short-term interest rates reacts by more than the long-term rates.

Finally, to find the shock on the expectations, ε_t^c , we use the following set of restrictions:

$$\Delta f_t(\tau; \beta_t) > 0 \quad \forall \tau, \quad \frac{\partial \Delta f_t(\tau; \beta_t)}{\partial \tau} > 0 \quad \tau \in [0 \ 1.5] \quad \text{and} \quad \frac{\partial \Delta f_t(\tau; \beta_t)}{\partial \tau} < 0 \quad \tau \in [2.5 \ 10].$$

Apart from the first restriction that is the same as above, the two latter restrictions guarantee that neither the short- nor the long-term forward rates significantly react. The maximum impact is set on the medium-term maturities ranging from 1.5 to 2.5 years, in line with the loading of the curvature factor in Figure 3.

The sign restrictions above facilitate the distinction of the three monetary policy shocks by how the monthly yield curve shifts on impact. The shapes induced by these shocks on the yield curve are similar to the surprise reactions to conventional and unconventional monetary policies observed in the euro area, as reported above.

3.3.2 Proxy variables for the monetary policy shocks

Naturally, defining the shifts in the average monthly yield curve alone is insufficient for the recovery of non-systematic variation of monetary policy. To shrink the set of those shifts to reflect surprises stemming from monetary policy, we select an empirical proxy for each shock from the daily yield curve data. In particular, we interpret that a large part of monetary policy surprises occur on days the ECB makes monetary policy statements, which provides exogenous variation for the identification.

Daily changes in the yield curve factors provide information about the shape of the surprise shifts, as indicated by the loadings drawn in Figure 3. Conveniently, each of the monetary policy shocks are associated with one of the yield curve factors. The monetary policy shock on the long-term forward rates, ε_t^l , and the level factor l_t are closely connected as the latter is the only factor to affect the long end of the yield curve. To recover the level shifts due to monetary policy, a natural proxy for ε_t^l is $\Delta l_{t,d^*}$.

The conventional monetary policy shock ε_t^s induces surprises that relate to the shorter-run rates. On the yield curve, the short-run rate is equal to $l_t + s_t$. Moreover, a reaction to a monetary policy surprise reads as $MPS_{t,d^*}(0) = \Delta l_{t,d^*} + \Delta s_{t,d^*}$, which is a natural proxy for ε_t^s .¹⁶ Finally, the loadings of c_t suggest that curvature factor contributes the most to the medium-term rates. The shock on the expectations about the future monetary policy, ε_t^c , is thus assumed to vary with changes in the curvature factor $\Delta c_{t,d^*}$.

To implement the proxy-based identification, we impose the long-term, conventional and expectations-related monetary policy shocks to be positively correlated with the daily change in the three aforementioned factors on the meeting day of the same month. In detail, we restrict the minimum correlation between the shock and proxy to be 0.2, i.e. $\rho(\varepsilon_t^i, m_t^i) \geq 0.2$ for each i with $m_t^i \in \{\Delta l_{t,d^*}, \Delta(l_{t,d^*} + s_{t,d^*}), \Delta c_{t,d^*}\}$ and d^* the day of a monetary policy announcement in month t .

¹⁶It is noteworthy to mention that we do not use s_{t,d^*} as our proxy directly, since the slope factor moves in response to the long-term shock as well. The increase of the level factor is followed by no short-run interest rate change only if $s_{t,d^*} = -l_{t,d^*}$.

3.3.3 Additional identifying restrictions

As long as our proxy variables are valid, the above strategy would recover the monetary policy shocks. The daily changes we use may, however, be noisy measures of monetary policy shocks. We tackle two potential shortcomings related to the proxy-based identification with the following additional identification techniques.

First, the public often infers monetary policy actions from the speeches of the members of the Governing Council outside the regular meetings. As a result, the proxy variables capture only surprises that take place when regular statements are published. To reinforce the identification, we additionally use the recursiveness assumption (Christiano et al., 1999) by which monetary policy may adjust to the current conditions but prices and production react to monetary policy only with a lag. The sluggish adjustment of real economic activity and prices is likely to be present in the euro area since monetary policy is mainly transmitted via the banking sector. The recursiveness assumption thus provides an additional tool to distinguish monetary policy shocks from the remaining variation. As opposed to the classical recursive identification, however, we do not restrict the response of monetary policy to financial variables to zero.

The second potential pitfall concerns the information effect of the central bank. As argued by Campbell, Evans, Fisher, and Justiniano (2012) and Nakamura and Steinsson (2018), the Federal Reserve reveals information about the underlying economic fundamentals in its statements. Jarocinski and Karadi (2019) find similar evidence from the euro area. That is, the central bank possesses superior information relative to the public, originating from the fact that it employs hundreds of experts to process economic data. Under the information effect, the economic agents revise their expectations about the state of the economy in response to the monetary policy statement. The identification described in the previous section would incorrectly treat such events as monetary policy shocks. To extract such signals out of the recovered shocks and control for the information effect, we impose, similar to Jarocinski and Karadi (2019), a sign restriction on stock prices. On impact, a contractionary monetary policy shock leads to a fall in the stock prices.¹⁷

¹⁷The present empirical strategy does not rule out the existence of an information effect but leaves it non-identified.

	Range	Description	Monetary policy shock		
			ε_t^l	ε_t^s	ε_t^c
$\Delta \bar{f}_t(\tau; \beta_t)$	$\tau > 0$	Shift of the forward rates	+	+	+
$\frac{\partial \Delta \bar{f}_t(\tau; \beta_t)}{\partial \tau}$	$\tau < 1.5$	Slope of the shift of the forward rates in the short end	+	-	+
$\frac{\partial \Delta \bar{f}_t(\tau; \beta_t)}{\partial \tau}$	$\tau > 2.5$	Slope of the shift of the forward rates in the long end	+	-	-
sp_t	-	Impact effect of the stock price index	-	-	-
P_t	-	Impact effect of prices	0	0	0
Y_t	-	Impact effect of output	0	0	0
$\min(\rho(\varepsilon_{t,i}, m_{i,t}))$	-	Minimum correlation with the proxy	0.2	0.2	0.2
$m_{i,t}$	-	Daily change on the regular meeting day of the Governing Council	$\Delta l_{t,d^*}$	$\Delta(l_{t,d^*} + s_{t,d^*})$	$\Delta c_{t,d^*}$

Table 1: Summary of the SVAR identification

The identifying restrictions imposed on the long-term monetary policy shock ε_t^l , conventional monetary policy shock ε_t^c and the monetary policy shock on the expectations ε_t^s .

3.3.4 Summary and discussion

Table 1 summarises the identification of the monetary policy shocks. The first restriction imposes a uniform shift of the yield curve upwards. The restrictions on the second and third rows characterise the shape of the yield curve movements. As a consequence of the negative sign set on the stock price response (sp_t), a surprise increase of the forward rates leads to adverse effects on the financial market, ruling out the signalling effects of monetary policy. On the other hand, the recursiveness assumption imposes exclusion restrictions on the price level (P_t) and output (Y_t). Finally, the last two rows of the table concern the proxy-based identification scheme. These state that the shocks are positively correlated with the daily changes on the short, middle and long end of the yield curve around the scheduled meeting days of the Governing Council of the ECB.

Finally, it is worth discussing the differences of our approach to the existing identification techniques. First, our approach is a close variant of the proxy SVAR methodology (Stock and Watson, 2012; Mertens and Ravn, 2013).¹⁸ The latter technique is based on empirical measures that are correlated with the identified shocks but orthogonal to the remaining shocks of the system. Here,

¹⁸A survey of the literature is provided by Stock and Watson (2018).

instead, the identifying restrictions presume correlation but no orthogonality as the inference relies on additional prior information about the nature of the shocks. Moreover, our approach allows to handle the identification of multiple shocks in a flexible manner. In the proxy SVAR, the shocks would be distinguished by additional exclusion restrictions set on B . As we characterize the shocks with a set of sign restrictions, the proxy SVAR technique is inapplicable for our purpose. Instead, our set identification approach is similar to [Arias et al. \(2018a\)](#) and relaxes the need for imposing zero restrictions on B when more than one proxy is used to identify multiple shocks.

Second, following [Gürkaynak et al. \(2005a\)](#), [Barakchian and Crowe \(2013\)](#), [Gertler and Karadi \(2015\)](#), [Nakamura and Steinsson \(2018\)](#), [Jarocinski and Karadi \(2019\)](#), amongst others, we exploit variation stemming from the statements of the central bank. Usually, this high-frequency identification uses a 90-minute window before and after the release of a monetary policy statement. We use instead a less narrow daily window. The factors are also estimated from the dynamic Nelson-Siegel model with autoregressive structure. Consequently, using a shorter time window would be infeasible in practice. Furthermore, as discussed in Subsection 2.2 and in Appendix A, the surprises measured by a daily and more narrow window closely coincide. It is also worth emphasising that, by the agnostic nature of our identification approach, we are able to address the overall measurement problems with the comprehensive set of restrictions.

Last, the monetary policy shocks we identify are functional – following the approach put forth by [Inoue and Rossi \(2018\)](#) and [Inoue and Rossi \(2019\)](#) – as they induce the effects of monetary policy on the term structure of interest rates. Whereas [Inoue and Rossi \(2018\)](#) describe the monetary policy shocks as unique shifts in the yield curve, we orthogonalise the surprises into three components that reflect three policy instruments. As the identified shocks are now uncorrelated, we are able to investigate each shock separately as well as to construct policy scenarios that consist of their combination. Moreover, monetary policy remains time-invariant over time such that the use of multiple instruments implies no policy shift in our model.

Naturally, the analysis covers only those policies that appear as shifts on the yield curve. If unconventional monetary policy stimulates the economy in a manner that does not translate

to changes in the medium and long-term interest rates, the yield-curve-based approach may not capture these effects.¹⁹ However, we assume, consistent with the existing literature (see [Dell’Ariccia et al., 2018](#), for survey), that unconventional as well as conventional policies transmit through the term structure of interest rates.

4 The effects of monetary policies

This section derives the effects of monetary policies in the euro area from the monetary SVAR model. First, we discuss the data and estimation. Then, we document the effects of the three monetary policy shocks on the interest rates. Last, we report the overall impact of the shocks on the macroeconomy.

4.1 Data and estimation

We use the following monthly euro area data in the analysis. Our measure of prices is the Harmonised Index of Consumer Prices (HICP). The real economic activity is measured by an interpolated real gross domestic product (GDP). The series is interpolated to monthly frequency using the euro area industrial production index.²⁰ Both of these series are seasonally adjusted. As discussed above, we include the monthly averages of the yield curve factors to the VAR model, estimated from the dynamic arbitrage-free Nelson-Siegel model. We include two financial variables also used by [Jarocinski and Karadi \(2019\)](#) and [Miranda-Agrippino and Ricco \(2017\)](#) to control for the immediate reactions of the public. The stock price index is the monthly average of the Euro Stoxx 50, covering 50 blue chip stocks in 11 euro countries. Credit conditions are measured by the BBB corporate bond spread, a difference between the AAA and BBB-rated yields. The VAR model is estimated in log levels.

The Bayesian estimation of the model is standard and based on [Arias et al. \(2018a\)](#): the structural parameters are drawn independently from conjugate posterior distributions. The approach

¹⁹An example of this type of policy would be an increase of the excess reserves as one parameter of the QE.

²⁰As [Jarocinski and Karadi \(2019\)](#), we use the interpolated GDP to measure the economic activity more broadly. The interpolation is proceeded by the Chow-Lin method using the interpolation package of [Quilis \(2013\)](#).

handles the set identification resulting from the sign restrictions, and the credible sets can be constructed in a straightforward manner. Standard prior distributions are used for the analysis. The orthogonal matrix Q rotating the errors to satisfy the identifying restrictions follows a priori uniform distribution. The autoregressive parameters and the covariance of the error term are assumed to follow the normal-inverse-Wishart distribution a priori.²¹

By this conjugate distribution, the parameters of the model can be drawn as follows. First, the covariance matrix is drawn from the inverse-Wishart distribution. Conditional on this draw, the autoregressive parameters follow the normal distribution. Next, the rotation matrix Q is drawn from the uniform distribution. Given these parameters, the algorithm accepts the draw if the identifying restrictions set on B , on the yield curve shift and on the correlations with the proxies are satisfied.

4.2 The effects of monetary policy shocks on interest rates

Figure 5 plots the immediate effects of the long-term, conventional and expectations-related monetary policy shocks on the average monthly forward rates across maturities, derived from the reactions of the yield curve factors through equation (8). The size of the shocks is one standard deviation. The solid solid lines show the period-wise posterior medians. The dark and light grey shaded areas represent the 68 and 90-percentage credible sets, respectively. Maturities are reported in years.

In accordance with the sign restrictions on the shape of the yield curve shift, the shocks induce forward rates to move asymmetrically across maturities in the first month of propagation. In response to the shock ε_t^l , the long-term forward rates increase while the interest rates at the shorter maturities do not significantly change. In turn, the conventional monetary policy shock ε_t^s increases the interest rates consistently with the expectations hypothesis: the short end of the yield curve moves the strongest, whereas the impact fades as the maturity grows. Finally, the

²¹In detail, the reduced-form parameters, $\{A_i\}_{i=1}^p$ and Σ follow a priori the normal and inverse-Wishart distributions, respectively. We assume the Minnesota prior for these parameters with overall tightness 0.2 and decay parameter 1. The orthogonal matrix Q is block-diagonal with blocks (I_2, Q_2) , with elements of Q_2 following the uniform distributions $U(0, 1)$. The block-diagonality imposes the recursiveness assumption on prices and production.

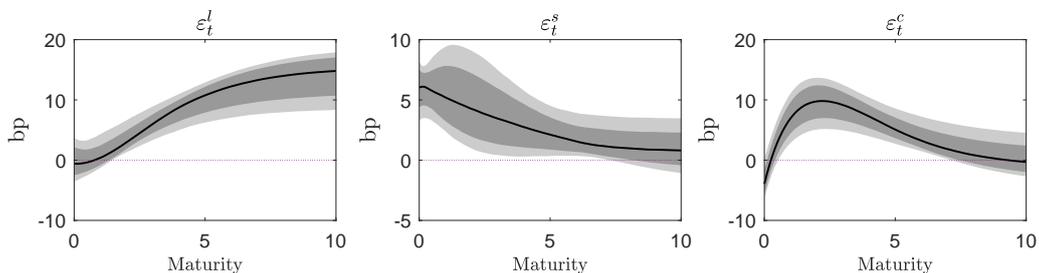


Figure 5: The shift of the forward curve in the first month following the identified shocks. The plots show the impact responses of the forward rates (in basis points) to a monetary policy shock on the long-term forward rate, ε_t^l , a conventional monetary policy shock, ε_t^s , and a shock on the expectations about future monetary policy, ε_t^c . The solid lines are the posterior medians and the dark and light shaded areas the 68 and 90 percentage credible sets, respectively.

shock on the expectations, ε_t^c , has the strongest effect on the maturities around two years, the short and long end of the curve staying approximately constant.

Whereas the sign restrictions applied to the propagation of the shocks in the first month of their arrival, no assumptions about the dynamic path caused by the shocks were imposed in the identification. Using the VAR model, we are able to derive the dynamic effects of the interest rates for all maturities from the impulse responses of the yield curve factors β_t and the standard term structure relationship, equations (5) and (1). Figure 6 depicts the impulse responses of the 3-month, 2-year and 10-year yields to the above shocks.

The interest rate responses of Figure 6 suggest that the shocks induce effects beyond the month when they arrive. First, according to the upper plots, the long-term monetary policy shock ε_t^l triggers a jump of the 10-year yield, the propagation continuing for the following two years. Contemporaneously, no significant dynamics at the shorter maturities occur. The shock is also persistent: the 10-year interest rate remains higher for the following two years.²² Evidently, these surprise changes are unlikely to reflect conventional interest rate policy. Rather, monetary policy has affected the term premium over time, and the shock captures surprises in this type of communication and actions.

Second, the conventional monetary policy shock ε_t^s is followed by an increase of the short-run

²²A particular concern would be that the identified shocks show no persistence such that their impact on the economy would be short-lived. For instance, Greenlaw et al. (2018) argue that the QE conducted in the US caused rather transitory effects on interest rates.

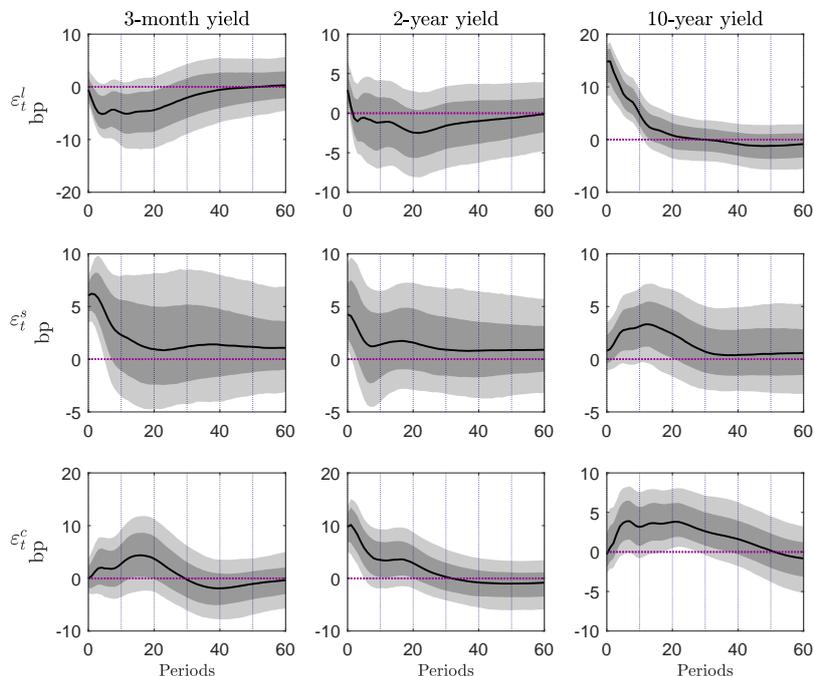


Figure 6: The impulse responses of the interest rates to the identified shock

The impulse responses of the yields (in basis points) derived from the yield curve factors to the monetary policy shock on the long-term rates (upper), to the conventional monetary policy shock (middle) and to the expectations regarding future monetary policy (lower). The solid lines are the posterior medians and the dark and light shaded areas the 68 and 90-percentage credible sets, respectively.

interest rate with muted shifts of the medium- and long-term yields. This transmission mechanism of the conventional monetary policy follows the expectation hypothesis that implies that the effect is decreasing in maturity. In particular, the shock induces classical, short-run-interest-rate-driven effects of monetary policy, as considered in the literature starting from [Christiano et al. \(1999\)](#). These short-run interest changes are unrelated to the changes in term premia.

Finally, the bottom row of Figure 6 shows the impulse responses to the shock on the expectations about future monetary policy, ε_t^c . The shock causes not only the 2-year yield to rise on impact but also a delayed increase of the short-run interest rate. In this respect, the shock is a news shock that materialises in the short-run interest rate with a lag. The shock thus informs economic agents about the future path of the policy rate. This type of behaviour relates to changes in the expectations about monetary policy, notably after the Great Recession in the form of forward

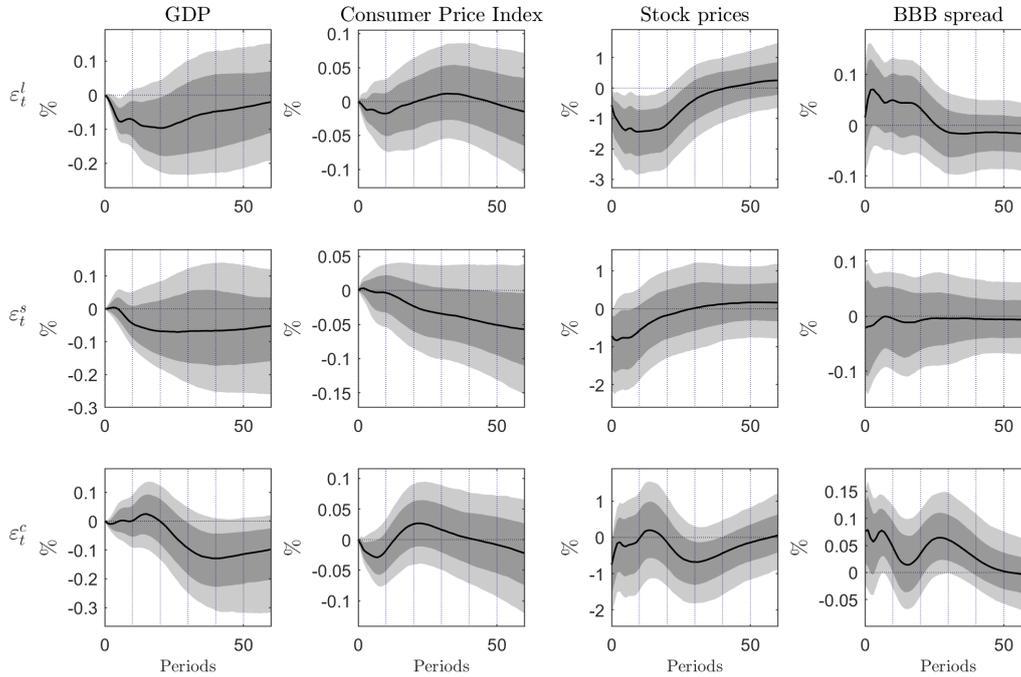


Figure 7: Impulse responses to the shock on the long-term rate (upper), on the short-run rate (middle) and on the expectations (lower). 68 and 90 percentage credible sets shown in the dark and light grey regions, respectively. Solid lines are the posterior periodwise medians.

guidance.

4.3 The effects of monetary policy shocks on the economy

Let us turn to the macroeconomic effects of the three shocks. The first row of Figure 7 depict the impulse responses of macroeconomic variables to the long-term monetary policy shock ε_{t^l} . The middle row of the figure, in turn, draws the responses to the conventional monetary policy shock. Finally, the lower plots of the figure show how the macroeconomic variables react to the shock on the expectations about the future monetary policy.

According to Figure 7, all shocks have negative impact on output measured by GDP. A 15-basis-point sudden increase of the long-run interest rate originating from the shock ε_{t^l} leads to a 0.1-percent fall of output during the following 20 months. Similarly but statistically insignificantly,

output declines in response to the conventional monetary policy shock. On the other hand, the shape of the GDP response to the shock on the expectations, ε_t^c , differs from the reactions to the other two shock. GDP reacts with a more delayed pattern to revisions about the path of short-run interest rate.

The price responses to the shocks are, instead, more asymmetric. All three contractionary monetary policy shocks cause a decline of the consumer price index. The decline is, however, more limited or statistically insignificant for the shocks on the long-term interest rate and expectations. In turn, the conventional monetary policy shock is followed by steadily declining prices with a pattern typically estimated in the literature (Christiano et al., 1999; Ramey, 2016).

As can be seen in Figure 7, the contractionary monetary policy shocks have adverse effects on the financial variables. The responses of stock prices are governed by the sign restrictions that ruled out the existence of signalling effects. The BBB spread moves in line with the view – discussed in see, Section 2.1 – that one transmission mechanism of monetary policy concerns the price of risk in the financial market. The credit conditions are tightened and the corporate bond spreads increased, as a consequence of higher longer-term yields induced by the shock ε_t^l . In contrast, the conventional monetary policy shock ε_t^s affects neither the term premium nor expectations but changes the risk free, short-run interest rate. The response of the BBB spread is consequently insignificant. These different transmission channels – stemming from the initial reactions of the forward rates – potentially explain why the GDP and price responses vary.

Our empirical approach extracts from the monetary policy surprises three components that constantly hit the economy, regardless of the short-run rate being at its effective lower bound. In Figure 8, we plot the estimated shocks in solid lines over time. In addition, the dashed lines depict the movements of the corresponding proxies, $\Delta l_{t,d^*}$, $\Delta(l_{t,d^*} + s_{t,d^*})$ and c_{t,d^*} , i.e., the daily changes in the yield curve measured on the monetary policy meeting day of the same month. Remarkably, the shocks on the long-term interest rates and expectations emerge already before the start of the unconventional monetary policy era. Similarly, conventional monetary policy shocks exist, although with somewhat more rare occurrence, during the zero-lower-bound period as well. The latter is consistent with the fact that the lower bound of the short-run interest rate is

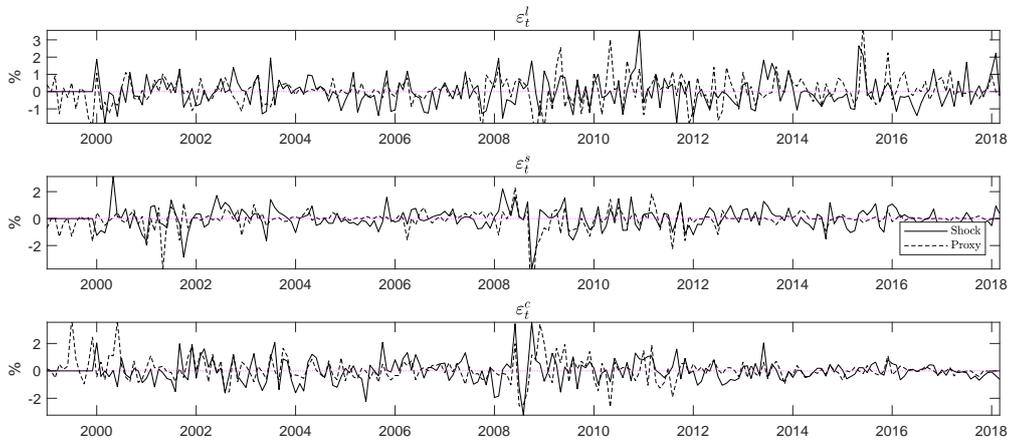


Figure 8: The shocks and their proxies over time

The long-term (upper), the conventional (middle) and the expectations (lower) shocks over time with their corresponding proxies. The solid lines depict the medians of the posterior estimates for the identified shocks. The proxy of the corresponding shock is shown in dashed lines.

not fixed: the ECB has lowered its policy rate during the unconventional monetary policy period as well. The time-invariance in the emergence of these shocks suggests that surprise changes in different parts of the yield curve – observed by the proxies – occur constantly over time.

To conclude, our results indicate that different policies of the central bank have asymmetric effects on output and prices. While conventional monetary policy is able to affect the price level and output in the longer run, a policy affecting the long-term rate has a limited effect on inflation. Hence, a policy such as quantitative easing that mainly affects the long-term rates can be expected to increase the real economic activity but less so the price level. In turn, by influencing the expectations, the central bank is able to increase both output and prices but with different timing than with a conventional policy. As a consequence of these reactions, a forward guidance policy affecting the expected path of the short run rate has price and output responses different from the ones attained by quantitative easing. In general, what the initial yield curve response is plays a role for the macroeconomic effects of the shocks.

5 Conclusion

This paper provided a framework to analyse the effects of monetary policies that affect different parts of the yield curve. The approach is based on the fact that monetary policy operates on the full spectrum of interest rates; the central bank controls the short end of the yield curve but influences the medium- and long-term rates as well. Hence, monetary policy is regarded as multidimensional. That is, the actions of the central bank lead to changes in the interest rates, expectations, credit conditions and term premium.

We estimated the effects of monetary policy with a structural VAR model that recovered three monetary policy shocks. These three shocks reflected monetary policy actions regarding the short-run interest rate, its future path and the term premium. We argued that the central bank has implicitly affected the whole yield curve when using both conventional and unconventional policies.

Assuming that the effects of monetary policy remain time-invariant when controlling for the whole yield curve, it is possible to evaluate conventional and unconventional actions of the central bank in a unified framework. We proceeded by including to the VAR model yield curve factors that reveal market information about the interest rates, expectations and the price of risk. Using a novel identification scheme that relies on sign and zero restrictions as well as on empirical proxies, the study provided a framework to derive the causal effects of three distinct monetary policies.

The framework presented in this paper has several advantages compared to the existing studies that either use a short-run interest rate only or restrict attention to the effects of unconventional policies. First, a distinction between the conventional and unconventional actions of the central bank becomes unnecessary, as the monetary policy may be viewed as a continuum over the term structure of interest rates. Second, with the use of the three distinct policy instruments, the effects of various monetary policies may be evaluated in a unified framework.

According to our results, different instruments used by the ECB asymmetrically affect the economy. Whereas the policy rate change has price and output responses similar to what earlier estimated the literature, the policies affecting the medium- and long-term rates have modest

effects on inflation. The transmission channels of different monetary policies are potentially distinct, which may explain the asymmetry.

Finally, it is noteworthy to mention that the study of monetary policy through the yield curve has several avenues for further research. Naturally, the methodology of the paper is readily available for the analysis of other economies. The model may be used to evaluate a range of different monetary policy actions given that their effects on the yield curve are known. The identification of the paper may also be enriched by additional high-frequency-based proxies that provide more information about the nature of the shocks. Finally, it is of interest to identify the economic mechanisms behind the different price and output responses across policies. We leave all these considerations for further research.

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A A comparison of monetary policy surprises measured with different window length

To measure the unexpected part of monetary policy, it is typical to assume that all public information about monetary policy is incorporated into financial variables before an announcement of the central bank. Consequently, changes in the market prices around the monetary policy announcements can be interpreted to reflect news about monetary policy. In Section 2, monetary policy surprises were measured using financial market data on daily frequency.

A potential source of uncertainty in our measure of monetary policy surprise concerns the window length of one day, which is longer than the intra day window used by [Gertler and Karadi \(2015\)](#), [Nakamura and Steinsson \(2018\)](#) and [Altavilla et al. \(2019\)](#). To examine the difference between the use of a one day and a shorter window, we compare our monetary policy surprises to the ones derived by [Altavilla et al. \(2019\)](#). The authors of the latter study develop a Euro Area Monetary Policy Event-Study Database (EA-MPD) which contains intra-day asset price changes – including Overnight Index Swaps (OIS) rates – around the policy decision announcement as well as around the press conference.²³ They use a 35-minute window around the release of the press release and around the press conference. The monetary policy event in this database, used here for comparison, is the change from the pre-press-release quote to the post-conference quote.

In Table A2, correlations and standard deviations of interest rates – or Overnight Index Swaps (OIS) rates – across maturities around the ECB’s scheduled monetary policy announcements are compared. The correlation between the two measures of monetary policy surprise is strong across maturities. In the middle of the yield curve, from 2 to 5 years, the correlation is the highest. The standard deviations of the two measures are relatively similar across maturities, although the estimates of the one-day-window measure obtaining are slightly higher.

Different data sources may explain differences in the two measures of monetary policy surprises. Our daily-based measure uses the average of the zero-coupons bonds of France and Germany for

²³The data are available in https://www.ecb.europa.eu/pub/pdf/annex/Dataset_EA-MPD.xlsx?afec88fe2e29c7abcdee5670b6d0f68.

Table A1: Comparison of monetary policy surprises measured by a daily window and EA-MPD across maturities

Maturity	1m	3m	6m	1Y	2Y	3Y	4Y	5Y	6Y	7Y	8Y	9Y	10Y
	Correlation												
	0.52	0.60	0.68	0.75	0.75	0.68	0.71	0.70	0.68	0.67	0.65	0.62	0.60
	Standard deviation, basis points												
EA-MDP	4	4	4	4	5	4	4	4	4	3	3	3	3
Daily	5	4	4	5	6	6	6	6	6	5	5	5	5

Table A2: Second moments of the two measures of monetary policy surprises

EA-MDP: the intra-day measure of [Altavilla et al. \(2019\)](#), Daily: changes in the forward rates on a daily frequency.

the period from January 1999 to January 2006, whereas [Altavilla et al. \(2019\)](#) use the government bond yields of Germany when OIS rates were not available. Moreover, in the long-end of the yield curve, a longer window potentially produces more volatile surprises because markets have more time to internalise the monetary policy announcement.

Differences between monetary policy surprises given by the EA-MDP database and our measure can also be illustrated by plotting the difference between two series. Figure [A1](#) shows the difference in selected maturities in a scatter plot. In the Figure each observation corresponds to a change around a scheduled monetary policy announcement of the ECB. In the short maturities, differences between the two series are typically smaller than a basis point. Larger differences shown in the left plot are mainly in the beginning of the the sample, due to different data sources, and during the financial crisis in years 2008–2010. In the medium and long maturities, a similar pattern occurs but with a smaller scale. In the latter, the difference between the surprises is usually at most 5 basis points.

In conclusion, Figure [A1](#) confirms that monetary surprises measured by a daily window are similar to those measured by a more narrow window. However, some differences exist and volatility is larger when a daily window is used. A wider window may, however, equally well capture all effects of monetary policy if it takes time for the financial market to internalise all information contained in the monetary policy statement.

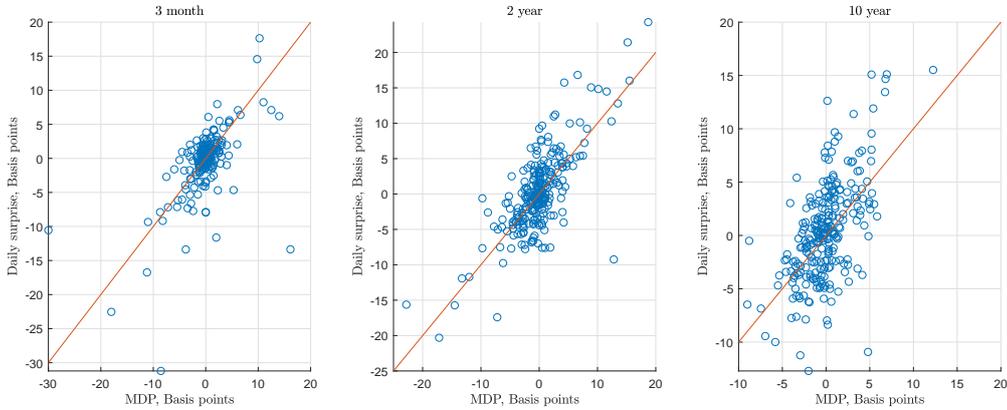


Figure A1: Difference in selected maturities between the two measures of monetary policy surprises

The values on x and y-axes correspond to the measure of [Altavilla et al. \(2019\)](#) and the daily-based measure, respectively. A 45-degree line has been plotted. Each observation corresponds to the reactions after the scheduled monetary policy announcement of the ECB.

B Arbitrage free dynamic Nelson-Siegel model

We use an arbitrage free dynamic Nelson-Siegel model to capture the term structure of interest rates. The model is based on [Nelson and Siegel \(1987\)](#), [Diebold and Li \(2006\)](#) and [Christensen et al. \(2011\)](#) and we develop the model in a continuous time by following the specification by [Krippner \(2015, Section 3\)](#).

The short-term interest rate r_t is affine in latent factors $x_t = [l_t \ s_t \ c_t]'$ in time t , that is,

$$r_t = a_0 + b_0' x_t \quad (\text{A1})$$

and we assume that $a_0 = 0$ and $b_0 = [1 \ 1 \ 0]'$. Therefore, $r_t = l_t + s_t$.

Under physical measure, \mathbb{P} , x_t evolves according to a correlated vector Ornstein-Uhlenbeck process:

$$dx_t = \kappa(\theta - x_t)dt + \Sigma dW_t, \quad dW_t \stackrel{iid}{\sim} \mathcal{N}(0, 1) \quad (\text{A2})$$

where κ is a matrix of mean-reversion parameters, θ is a vector of constants, Σ is assumed to be a lower triangular matrix that captures correlations between innovations which are given by

Wiener components dW_t .

It is assumed that there exists a risk-neutral probability measure \mathbb{Q} that prices all financial market assets. Hence, the expected returns for all assets under this measure are equal to the risk-adjusted short-term rate, i.e. there are no arbitrage opportunities. Under the risk-adjusted \mathbb{Q} measure, x_t also follows a correlated vector Ornstein-Uhlenbeck process:

$$dx_t = \tilde{\kappa}(\tilde{\theta} - x_t)dt + \Sigma d\tilde{W}_t, \quad d\tilde{W}_t \stackrel{iid}{\sim} \mathcal{N}(0, 1). \quad (\text{A3})$$

These assumptions imply that the stochastic discount factor is essentially-affine, as in [Duffee \(2002\)](#). However, under \mathbb{Q} measure mean and persistence parameters now differ from their \mathbb{P} measure counterparts. Without loss of generality, it can be assumed that $\tilde{\theta} = 0$ and

$$\tilde{\kappa} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \lambda & -\lambda \\ 0 & 0 & \lambda \end{bmatrix}.$$

Equations (A1), (A2), (A3) and the assumption of no-arbitrage define an identified term structure model.

The instantaneous forward rate, $f_t(\tau)$, (hereafter, forward rate) under the \mathbb{Q} measure is given by

$$f_t(\tau) = \tilde{\mathbb{E}}[r_t(\tau) | x_t] - a(\tau) \quad \text{where} \quad (\text{A4})$$

$$\tilde{\mathbb{E}}[r_t(\tau) | x_t] = l_t + s_t e^{-\lambda\tau} + c_t \lambda \tau e^{-\lambda\tau}. \quad (\text{A5})$$

Now, $\tilde{\mathbb{E}}[r_t(\tau) | x_t]$ is the expected path of the short-term rate under the \mathbb{Q} measure, and $a(\tau)$ captures the effects of Jensen's inequality, defined as follows:

$$a(\tau) = \int_0^\tau b'_0 e^{-\tilde{\kappa}(\tau-s)\Sigma} \left(\Sigma' \int_s^\tau e^{-\tilde{\kappa}'(u-s)} b_0 du \right) ds. \quad (\text{A6})$$

More details for deriving and calculating $a(\tau)$ can be found from [Christensen et al. \(2011\)](#) and [Krippner \(2015, p. 77-78\)](#). Finally, the interest rates, $R_t(\tau)$, are given by the standard term-

structure relationship:

$$R_t(\tau) = \frac{1}{\tau} \int_0^\tau f_t(v) dv. \tag{A7}$$

The model is estimated by using maximum likelihood and Kalman filter. The details of the estimation procedure are provided by [Krippner \(2015\)](#), and we only briefly summarize the procedure.²⁴ The estimation of the model is implemented in a state space form. The measurement equation is given by equation (A4) with the idiosyncratic measurement error term $\epsilon_t \stackrel{iid}{\sim} \mathcal{N}(0, \sigma_\epsilon^2)$, where ϵ_t is the vector of errors across maturities. The measurement error also serves as a residual of the model, or as a component of the interest rate which is not explained by the model. The transition equation under the \mathbb{P} measure is given by (A2), and Kalman filter is applied to the transition equation. Data used in the estimation are described in Section 2.2.

²⁴MATLAB programs used by [Krippner \(2015\)](#) are available at the homepage of [The Reserve Bank of New Zealand](#).

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