What does "below, but close to, two per cent" mean? Assessing the ECB's reaction function with real time data

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Abstract

Using unique real time quarterly macroeconomic projections of the Eurosystem/ECB staff, we estimate competing specifications of the monetary policy reaction function for the ECB in order to interpret the ECB's price stability objective. We provide evidence of two alternative interpretations: the ECB's policy responses to past inflation gaps are symmetric around a target of 1.6% to 1.7%, or the ECB is more concerned about inflation rates above 2% than rates below 2%, reflecting an asymmetric policy response to inflation. Out-of-sample predictions of the symmetric reaction function follow most closely the estimated shadow interest rates during the zero lower bound period.

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1 Introduction

In recent years, inflation has been persistently low in many economies. As a response, policy rates have been cut to very low levels, and new measures have been introduced to maintain an accommodative stance of monetary policy. The low inflation environment and recent discussion about monetary policy normalisation have raised the question of whether and how the current monetary policy framework should be reformed (see e.g. Williams (2017); Bernanke (2017); Bullard (2018); Honkapohja & Mitra (2018)). In the case of the ECB, another topic of discussion concerns the interpretation of its price stability objective.

The debate on the ECB's inflation target stems from the fact that the price stability objective is not precisely defined in the Treaty on the Functioning of the European Union. In 1998, the ECB's Governing Council defined price stability as '*a year-on-year increase in the Harmonised Index of Consumer Prices (HICP) for the euro area of below 2%*'. In 2003, the Governing Council clarified that '*in the pursuit of price stability it aims to maintain inflation rates below, but close to, 2% over the medium term*'. The price stability objective is thus not specified in terms of a point target or a point target with a tolerance band. Instead, it refers to a target range, of which the interpretation is not unambiguous[1]. Even if the ECB communication stresses the symmetry of the price stability objective, 'below, but close to 2%', the target has a strong feel of asymmetry.[2]

Not surprisingly, the ECB's inflation target has been interpreted in various ways. For example, Miles et al. (2017) point out that the ECB '*target itself is perceived as asymmetric*'. They also note that there '*is uncertainty about what 'close to, but below' means*'. Regarding the public, survey evidence indicates that the knowledge of households about the ECB's inflation target is 'far from perfect' (van der Cruijsen et al. (2015)). Different interpretations of the inflation target and/or vague monetary policy communication may increase inefficiency in monetary policymaking, give rise to risks of de-anchored inflation expectations and,

[1] Apel & Claussen (2017) classify three different categories for inflation targeting. A point target refers to a single number. If certain deviations from the point target are 'acceptable' for the central bank, it is complemented with a tolerance band. In the case of a target range, a targeted inflation interval is announced without any specific desirable level of inflation.

[2] According to the ECB strategy, '*by referring to 'inflation rates below, but close to, 2%' the definition makes clear that not only inflation above 2% but also deflation (i.e. price level declines) are inconsistent with price stability*'. For example, in March 2016 Mario Draghi, President of the European Central Bank, stated: '*The key point is that the Governing Council is symmetric in the definition of the objective of price stability over the medium term.*' (https://www.ecb.europa.eu/press/pressconf/2016/html/is160310.en.html). See also the speech of President Draghi in June 2016: https://www.ecb.europa.eu/press/key/date/2016/html/sp160602.en.html.

hence, jeopardize the effective transmission of monetary policy.

In this paper, we are specifically interested in assessing the ECB's own interpretation of the price stability objective. As is typical in this literature, we attempt to characterize the ECB's policy strategy in terms of a simple policy reaction function. We estimate a large number of competing specifications of the monetary policy reaction function for the Governing Council and focus on three key features of policy making. First, we pay attention to possible backward looking features in monetary policy making. Following Neuenkirch & Tillmann (2014), we allow for the possibility that the ECB reacts to past inflation gaps, determined by the deviations of realized inflation from the target. Second, we attempt to quantify the gist of the expression 'below, but close to 2%' by estimating specifications where a point inflation target varies between 1.6% and 2.0%. Third, we allow for the possibility that policy responses to positive and negative deviations of past inflation from the targeted level are different, i.e. the reaction function is asymmetric.

A novel feature of our analysis is that we use a unique real time dataset including the Eurosystem/ECB staff quarterly macroeconomic projections of inflation and real GDP growth in 1999 - 2016. Consequently, we are able to estimate the reaction function with a subset of the very same information the Governing Council has available when it decides on the monetary policy stance.[3] As emphasized by Woodford (2007), an important feature of "optimal" monetary policy is that it should respond to the projected future path of the economy and not only to current conditions. Macroeconomic projections are an important communication tool for central banks targeting inflation. They make the commitment to the inflation target verifiable by the public and can sharpen the public's understanding of how the central bank responds to foreseen economic developments. Publication of macroeconomic forecasts can also directly steer inflation expectations.

Our sample period, 1999Q4–2016Q4, covers the relatively stable pre-crisis years as well as the recent turbulent years characterised by the financial crisis, the sovereign debt crisis and low inflation. Using sub-sample analysis and recursive estimations, we analyse the stability of estimated parameters of the ECB's reaction function over time. In addition to the targeted rate of inflation, we conduct a robustness analysis with respect to the time span of forward-looking and backward-looking variables in the reaction function and with

[3] To our knowledge, earlier reaction function estimations using the ECB's projections have been based on annual information. However, Fischer et al. (2009) examine euro area monetary analysis in 1999–2006 using quarterly information.

respect to long-run natural real interest rates. We assess the performance of estimated reaction functions by comparing their in-sample predictions against the EONIA interest rate, which is the dependent variable in our estimations. In the analysis of the most recent period when standard interest rate policy has approached its effective lower bound, we evaluate the performance of our estimated functions by comparing their out-of-sample predictions against shadow interest rates estimated by Kortela (2016) and by Wu & Xia (2016).

Two alternative interpretations of the ECB's definition of price stability stand out from the estimations: the ECB's policy responses to past inflation gaps are symmetric around a target of 1.6% to 1.7%, or the ECB is more concerned about inflation rates above 2% than rates below 2%, reflecting an asymmetric policy response to inflation. Out-of-sample predictions of the reaction function based on the first interpretation follow most closely the estimated shadow interest rates during the zero lower bound period.

In earlier studies, euro area monetary policy has also been widely examined using alternative specifications of the classical Taylor rule (Taylor 1993).[4] Monetary policy analysis has often been based on real-time information. As a proxy for real-time information, the European Survey of Professional Forecasters (ECB SPF) (e.g. Gerlach & Lewis (2014)) and Consensus Forecast (e.g. Gorter et al. (2008)) have been used. Some authors have also used the ECB's macroeconomic projections (e.g. Belke & Klose (2011); Bletzinger & Wieland (2017)). As the ECB projections are published only for full calendar years, a quarterly variation in the projections has not been taken into account in reaction function estimations so far. Closest to our study is a recent article by Bletzinger & Wieland (2017), who also estimate a forecast-based reaction function for the euro area in order to assess the targeted level of inflation and ECB policy during the zero lower bound period. Their analysis is based on the ECB's SPF survey and ECB projections for full calendar years. The main difference from our approach is that they do not take into account the impact of past inflation deviations from the target, and their cyclical variable is defined as a difference between output growth and the European Commission's estimate of potential output growth.[5]

The paper is organised as follows. The Eurosystem/ECB staff projections are described in section 2, and alternative specifications of the monetary policy reaction function and estimation results are presented in

[4] See e.g. Clarida et al. (1998).

[5] Earlier studies of possible asymmetries in ECB monetary policy include Aguiar & Martins (2008), Surico (2003, 2007) and Ikeda (2010).

section 3. In section 4, we discuss in-sample predictions of different reaction functions. Using out-of-sample predictions, we also assess whether the recent non-standard monetary policy measures can be interpreted as a continuation of conventional monetary policy. Concluding remarks are provided in section 5.

2 Data analysis

2.1 Data description

Our dataset includes the real time Eurosystem/ECB staff projections made in 1999Q4 - 2016Q4 for the euro area year-on-year HICP inflation rate and year-on-year real GDP growth rate. These projections are publicly available as annual data for full calendar years, but our analyses are based on confidential quarterly information.[6]

For both the inflation rate and real GDP growth rate our data include real time estimates of previous-quarter values, current-quarter values (nowcast estimates) and real time projections until the end of each forecast horizon. The projections in our data cover the current and next two calendar years. The "final" data, i.e. revised data, for our purposes, are the latest available vintages published by Eurostat in the spring of 2017. The euro area GDP data are seasonally and working day adjusted. Our data take compositional changes in the euro area into account over time. Data vintages also reflect Eurostat's methodological changes and regular benchmark revisions made since 1999.

Figure 1 illustrates the inflation projections. It shows two separate medians of the inflation projections based on whether the latest observed inflation rate during each projection exercise has been above or below 1.9%. More precisely, we have organized the projection data in figure 1 in the following way: the label "F0" on the horizontal axis refers to the median value of nowcast estimates from all the projection vintages and the labels "F1" - "F11" refer to the median values of the corresponding inflation projections for 1 - 11 quarters ahead. In addition to the medians, figure 1 also presents the highest and lowest inflation projections for different forecast horizons.

[6] See the ECB (2016) and Alessi et al. (2014) for a detailed description of the Eurosystem/ECB staff projections exercises.

Figure 1 shows that the medians of projections made at times when the recent observed inflation rate is high (i.e. higher than 1.9%) converge to 1.70 - 1.80% after six quarters. At the same time, however, the medians of projections starting from lower inflation conditions (i.e. 1.9% or lower) converge to slightly lower rates around 1.60 - 1.75%. Lower medians converge to their eventual rates in a rather linear fashion, while the evolution of the higher medians has a somewhat different shape: the median projections for five and six-quarters-ahead are slightly below the medians at the end of the forecast horizon, i.e. inflation is projected to temporarily undershoot when inflation has been initially above 1.9%.

It is also notable in figure 1 that regardless of the current level of inflation, after about six quarters the median inflation projections are already in the proximity of their levels at the end of the forecast horizon. When compared to the actual realized inflation, the projected inflation exhibits stronger and faster mean reversion.

It is important to note that the ECB inflation projections are conditioned on market expectations of the interest rate (since June 2006), and not on some "optimal state contingent path of the interest rates". Therefore, the projected inflation does not reflect the ECB's desired path of inflation *per se*. However, one can plausibly argue that the projected inflation rates at the end of the forecast horizon give the public a good guideline for inflation, which the ECB considers consistent with its mandate. Projected values of the economic variables, including inflation, at the end of the forecast horizon are largely determined by the models' long run equilibrium, i.e. values to which they are expected to converge in the absence of new shocks hitting the economy. This is important for the determination of inflation itself, since empirical literature largely agrees that the central bank forecasts have an impact on the private sector's inflation forecasts and expectations.[7]

As for the GDP, the GDP growth projections do not revert towards a single long-run value over the sample, but rather the projections seem to capture the slowdown of long-run growth rates over the sample period. While at the beginning of the sample the GDP growth projections converged to growth rates of around 3%, more recently the projections have converged to below 2% growth. This decline in the projected long run growth rate is consistent with the trend-like decline in the real interest rates (see figure A1.2).

[7] See e.g. Fujiwara (2005), Hubert (2015) and Lyziak & Paloviita (2018).

Our dataset also includes the EONIA interest rate measured at the end of each quarter, a shadow interest rate estimated by Kortela (2016)[8] and two proxies of the long-run natural real interest rate (see figures A1.1 and A1.2). An *ex-post* proxy for the natural real interest rate is constructed as the difference between a composite nominal yield of ten year euro area government bonds and real time nowcast estimates of current inflation, while an *ex-ante* proxy is calculated as the composite nominal bond yield minus the real time projection of the one-period-ahead inflation rate. The composite nominal yield is constructed by the ECB by aggregation using GDP weights. The shadow rate follows closely the EONIA rate until about mid-2014. Thereafter, the shadow rate starts falling strongly into a negative territory reflecting the quantitative easing of the ECB.

2.2 Relation between projections and actual data

Figure 2.1 shows how the actual inflation and projected inflation are correlated in our data set: the "F0" bar refers to the correlation coefficient between the actual inflation and nowcast estimates, and the bars "F1" - "F8" indicate how the actual inflation is correlated with the projections made 1 - 8 quarters earlier. The corresponding correlation coefficients between the projected and actual real GDP growth rates are summarized in figure 2.2. Figures 2.1 and 2.2 clearly show that inflation and output growth projections are highly correlated with the actuals at the short end of the forecast horizon.

Simple correlations reveal that it is very challenging for the Eurosystem/ECB staff to assess future price and output growth developments when considering medium to long term projection horizons. Comparison of forecast performances based on mean errors (ME) and root mean squared errors (RMSE) indicate that short term inflation projections are more accurate than short term real GDP projections.[9]

[8]A shadow rate is a summary measure of monetary policy stance, capturing unconventional as well as conventional policy measures. It indicates how much the central bank would have lowered the interest rates had the zero lower bound not been binding, i.e. it reflects monetary policy stance in very low or negative interest rates environments. Differences between alternative shadow rates for the euro area based on different methods are typically quite large. However, they all indicate that the ECB's monetary policy stance has recently been very accommodative. In Kortela (2016), shadow rate is based on the multifactor shadow rate term structure model (SRTSM) with a time varying lower bound.

[9]We have defined errors as the difference between projections and realisations. The MEs for one to four quarter ahead inflation projections (real GDP growth projections) are -0.02, -0.06. -0.11 and -0.13 (-0.11, 0.07, 0.29 and 0.51). The corresponding RMSE values for inflation are 0.37, 0.59, 0.78 and 0.95 and for real GDP growth 0.96, 1.33, 1.68 and 1.96.

A limited accuracy of inflation and GDP growth projections in the medium to long term is not specific to the ECB and the Eurosystem. Charemza & Ladley (2016) report that compared to CESifo World Economic Survey forecasts, the central banks' one-year ahead inflation forecasts are clearly biased towards the inflation target. Regarding two-year-ahead inflation forecasts, the bias is even stronger.[10]

3 Estimation of the ECB reaction function

In this section, we estimate a large number of competing specifications of the ECB's monetary policy reaction function for the period 1999Q4 - 2014Q2 (i.e. until the zero lower bound was reached). Our estimations are based on the general method of moments (GMM) with lags of regressors as instruments. Use of the GMM in this context is motivated by the potential simultaneity of the right hand side variables of the reaction function. It is conceivable that the forecasts for inflation and output growth are affected by current monetary policy. In addition, our reaction function includes a proxy for the neutral rate of interest, which is potentially also measured subject to error. To the extent that these errors are correlated with other regressors, OLS would give biased estimates.

While the reaction function we will estimate is not an outcome of explicit optimization based on a structural model and central bank's preferences, it is comparable to inflation forecast targeting procedure, advocated by Svensson & Woodford (2005), as a way to implement optimal state-contingent policy.[11]

In the estimation of the reaction function we need to make a choice as regards the cyclical variable. Following several authors[12], we use real GDP growth as a proxy for the euro area cyclical stance instead of the output gap. There is a number of motivations for this choice. First, the ECB's communication is based more on

[10] Charemza & Ladley (2016) analyze inflation forecasts made in 2000 – 2011 in ten inflation targeting central banks: Australia, Canada, Chile, Czech Republic, Korea, New Zealand, Mexico, Norway, Poland and Sweden. See also Sveriges Riksbank (2017) for the accuracy of Riksbank's inflation forecasts.

[11] The Eurosystem/ECB staff projections were at first based on a constant interest rate assumption, but in order to further improve the quality and internal consistency of macroeconomic projections, both short and long term interest rate assumptions have been based on market expectations since the June 2006 projection exercise. According to the ECB (2006), *"this change is of a purely technical nature"*, which "does not imply any change in the ECB's monetary policy strategy or in the role of projections within it". We therefore interpret this change as if the internal forecasting procedure of the ECB had changed, but we don't expect a change in the reaction function itself.

[12] See for example Neuenkirch & Tillmann (2014), Gerlach & Lewis (2014), Gorter et al. (2008) and Sturm & de Haan (2011).

the current and future output growth than the output gap (see e.g. Gerlach, 2007). Second, the output gap estimates are very inaccurate, especially in real time (Orphanides & van Norden 2002, Orphanides 2008)[13]. For the euro area, the problem of reliable real time output gap estimates is even more severe, due to a relatively short sample and methodological issues that arise from calculating the real time output gap estimate for the euro area as a whole.[14] Finally, and reflecting at least partly the above mentioned issues, the estimates for potential output are only available from 2009Q2 at a quarterly frequency and from 2006 at an annual frequency in the ECB projection data.[15]

When estimating reaction functions, forecast horizons for forward-looking variables are typically assumed to be relatively short reflecting a poorer forecast accuracy over a longer period of time.[16] In section 3.1, we consider forward-lookingness of the ECB's policy responses without fixing forecasts horizons *a priori*. Instead, we compare competing linear specifications with varying forecast horizons and then, based on the following criteria, choose the most reasonable projection horizons. The estimated coefficients for forward-looking variables must imply that the interest rate reacts sufficiently strongly to projected inflation and output in order to stabilize the economy, consistent with the Taylor principle. Furthermore, following Taylor (1993) and the ECB's mandate for maintaining price stability, the estimated parameter for projected inflation should be larger than the one for projected real GDP growth. We also assess parameter stability as well as the relevance of real interest rate variable in the reaction function by running estimations in which we extend the pre-crisis sample (1999Q4 - 2008Q2) recursively a quarter by quarter until the whole sample 1999Q4 - 2014Q2 is reached.

After choosing our preferred forecast horizons for inflation and real GDP growth in the ECB's decision making, we assess whether the ECB conditions its policy decisions not only on the future economic outlook,

[13] It is also worth noting that in the ECB's New-Area-Wide Model (NAWM), the reaction function has been specified in terms of deviations of output growth from its long run empirical mean (Christoffel et al. 2008).

[14] See e.g. Marcellino & Musso (2011).

[15] The caveat of using expected output growth in the estimation of the reaction function is that we are not able to infer separately the inflation target and perceived trend output growth. Using data available for the whole sample, we have experimented with an alternative approach. We have estimated reaction functions including the estimates of real time output gap based on a difference between the real GDP growth nowcast (or one-quarter ahead real GDP growth projection) and eight-quarter-ahead real GDP growth. The underlying assumption is that the medium run growth forecast is a good proxy for the perceived euro area growth potential. The results from these estimations were largely consistent with the findings in the next section (available upon request).

[16] For example, when estimating reaction functions for the ECB, both Neuenkirch & Tillmann (2014) and Gerlach & Lewis (2014) consider a-year-ahead forecasts of inflation and output growth.

but also on past inflation rates. More specifically, we analyse the ECB's potential concerns about monetary policy credibility due to inaccuracy and systematic bias in forecasting. We follow Neuenkirch & Tillmann (2014) and augment our preferred linear specification with a nonlinear backward-looking inflation gap term, determined by average past deviations of inflation from the target.

Inclusion of the inflation gap term into the reaction function can be rationalized by the central bank's commitment to correct past errors: when inflation has been persistently above (below) the target, policy responses should aim at below (above) the target inflation rate in order to correct overshooting (undershooting). Therefore, the central bank should not allow persistent deviations of inflation from the target for too long before the policy is re-adjusted (see e.g. Woodford, 2007). Current low inflation regime emphasises the need to examine the ECB's possible responses to past inflation gaps, as persistent deviations of inflation from the target may lead to increasing risks of de-anchoring inflation expectations (see e.g. Ehrmann 2015, Lyziak & Paloviita 2017).

We estimate several competing nonlinear estimations by allowing the targeted inflation rate to vary from 1.6 to 2.0%. In order to assess the length of the time span over which the ECB's possibly reacts to past inflation gaps, we also consider alternative credibility loss terms based on average inflation rates in the $1-8$ previous quarters. First, we assume that the ECB's responses to past inflation gaps are symmetric (section 3.2), and then we allow for separate, possible asymmetric responses to positive and negative inflation gaps (section 3.3).

We compare and eventually choose our preferred symmetric and asymmetric nonlinear specifications by applying the same criteria as in the case of the linear model. Again, parameter stability is assessed by recursive estimations.[17]

[17] Due to a relatively short sample, recursive estimations are considered only for symmetric nonlinear models.

3.1 Linear reaction functions

First, we estimate the following linear reaction function:

$$i_t = c_1 * i_{t-1} + (1 - c_1) * (c_2 + c_3 * (\pi^f_{t+j|t} - \pi^*) + c_4 * \triangle y^f_{t+k|t} + D * r^n_t) \tag{1}$$

In equation (1), the EONIA rate i_t measures the monetary policy stance and the term i_{t-1} captures interest rate smoothing. The term $\pi^f_{t+j|t}$ refers to the ECB's projection of j-quarters-ahead HICP inflation and $\triangle y^f_{t+k|t}$ to the ECB's projection of k-quarters-ahead real GDP growth. Both the HICP inflation rate and real GDP growth rate are measured in year-on-year terms. In the original Taylor's (1993) formulation, the neutral real interest rate is set to a constant, equal to 2%. This implied together with a 2% inflation target that the equilibrium nominal rate would be 4%. There is compelling evidence that equilibrium real interest rates are variable and have been trending downwards both in the U.S. and in the euro area recently. While equilibrium real interest rate is difficult to estimate and it is subject to large uncertainty, there is no reason why a time varying equilibrium rate could not be incorporated into a policy rule.[18] Consequently, we append the reaction function with a proxy for the neutral real interest rate r^n_t, using both *ex-ante* and *ex-post* proxies; when the natural real rate enters (does not enter) into a reaction function, the dummy variable D is equal to one (zero).[19] In line with Clarida (2012) and Neuenkirch & Tillmann (2014), we use the long term real interest rate as a proxy for the equilibrium real rate.

We set the inflation target to a number close to 2%, more specifically $\pi^* = 1.9$.[20] While this choice of the target does not have an impact on the estimated slope coefficients, it together with the constant c_2 and the coefficient of output growth c_4 in the equation (1) defines time invariant potential output such that $\triangle y^* = (\pi^* - c_2)/c_4$.

[18] For discussion see e.g. Taylor (2018).

[19] Our specification of the interest rate rule, which includes a proxy for the natural rate of interest (i.e. when D=1 in equation 1) is akin also to Wicksell (1898), who argued that in order to maintain price stability, monetary policy should aim to track some measure of neutral rate determined purely by real factors (such as productivity of capital). King & Wolman (1999) and Woodford (2003) have shown that such a rule can result from optimizing central bank behavior in a standard New Keynesian model. In this formulation of the policy rule, when the equilibrium real rate rises, the central bank sets the interest rate higher so as to keep the output (growth) close to its equilibrium level (see also Curdia et al., 2015).

[20] In the NAWM model of the ECB, the operational definition of price stability is also set at 1.9% (Christoffel et al. 2008).

Table A2.1 summarizes the estimation results with and without the natural real interest rate proxies and varying projection horizons from zero (nowcast) to four quarters. The results seem to lend support to specifications with i) very short run (one quarter ahead) GDP growth projections; ii) somewhat longer term (one year ahead) inflation projections; and iii) reaction functions including a proxy for the natural rate of interest. To be more specific:

1. We obtain statistically significant coefficients for nowcast as well as one-quarter- or four-quarters-ahead inflation, if the forecast horizon for real GDP growth is very short, i.e. zero (nowcast) or one-quarter.

2. A specification with the four-quarters-ahead inflation and one-quarter-ahead real GDP growth (i.e. $\pi^f_{t+4|t}$ and $\triangle y^f_{t+1|t}$) produces satisfactory coefficient estimates with either of the two proxies of the natural real interest rate, as well as without a natural rate proxy.

3. Regarding parameter stability, we first estimate reaction functions with the four-quarters-ahead inflation ($\pi^f_{t+4|t}$) and one-quarter-ahead GDP ($\triangle y^f_{t+1|t}$) for the (pre-Lehman) period of 1999Q4 - 2008Q2, and then expand the sample one quarter at a time until 2014Q2. We obtain more stable coefficients for inflation and output growth with a natural interest rate proxy in the specification than without it. In addition, the specification using the *ex-ante* natural real interest rate seems to work even better than the *ex-post* natural real interest rate.[21]

Table 1 summarizes our preferred linear specification, which is based on a four-quarters-ahead inflation gap and one-quarter-ahead output growth. According to this specification, the ECB reacts to a projected inflation gap about three times stronger than to a projected cyclical stance measured by output growth. The interest rate smoothing is rather high as expected and the relatively large coefficient for the inflation gap implies that the Taylor principle clearly holds: the real *ex-ante* interest rate increases when inflation rises. Inclusion of time varying natural rate has only a small effect on the coefficient on output growth. The effect on the coefficient for expected inflation gap is somewhat larger, but this difference is partly mechanical, because we measure the real interest rate as a difference between a composite nominal yield of ten year euro

[21] The results are available upon request. Curdia et al. (2015) find out that using the Wicksellian efficient rate of return as the main indicator of real activity fits the U.S. data better than otherwise identical Taylor rules.

area government bonds and real time estimates of current or one period ahead inflation forecast. Overall, it seems reasonable that the ECB conditions its interest rate decisions on the short end of the forecast horizon due to increasing forecasting challenges in the medium and longer term.

3.2 Symmetric responses to past inflation gaps

Next, we follow Neuenkirch & Tillmann (2014) and augment our preferred linear specification with a backward-looking "credibility loss term" CL_t[22]:

$$i_t = c_1 * i_{t-1} + (1 - c_1) * (c_2 + c_3 * (\pi^f_{t+4|t} - \pi^*) + c_4 * \triangle y^f_{t+1|t} + c_5 * CL_t + r^n_t) \quad (2)$$

where the CL_t term is specified as

$$CL_t = (\bar{\pi}_{t-1,t-q} - \pi^*)|\bar{\pi}_{t-1,t-q} - \pi^*|.$$

$\bar{\pi}_{t-1,t-q}$ refers to an average past inflation rate and q to the number of lags. The idea of including these terms into the reaction function is that the central bank may set the interest rate higher (lower) today if the past inflation gap is positive (negative) even if inflation is projected to be at the target in the near future.[23,24] As discussed above, concerns for past inflation gaps may reflect the central bank's desire and commitment to correct past errors. Note also that the credibility loss term weighs large average past deviations of inflation from the target (π^*) more than small ones.

[22] Neuenkirch & Tillmann (2014) analyze monetary policy in five inflation targeting economies: Australia, Canada, New Zealand, Sweden and the United Kingdom.

[23] Monetary policy credibility measures proposed by de Mendonca & de Guimarães e Souza (2009) is also based on past deviations of inflation from the target.

[24] Using quite similar an approach, Dovern & Kenny (2017) investigate the impacts of "too low for too long" on long term inflation expectations of professionals in the euro area. They define an inflation "performance gap" as the difference between recent long term inflation expectations and a moving average of past inflation rates.

Figure 3 presents the evolution of the ECB CL term for the inflation targets of 1.7% and 2.0% using seven lags over which the average past inflation ($\bar{\pi}_{t-1,t-7}$) is measured. Both measures indicate that in the mid-2000s, past inflation gaps were minor, while more pronounced past inflation gaps are measured around 2002, 2009, 2011 and 2013, and again after 2014 when the nominal interest rate hit the lower bound and inflation slowed down persistently. The relatively large inflation gaps especially in the post-crisis period may have had a significant impact on the monetary policy of the ECB.

When estimating equation (2), we allow for the length of the time span, i.e. the number of lags (q) over which the average past inflation is measured, to vary from 1 to 8 quarters. We also consider a number of different inflation targets π^*, at or below 2%; the lowest inflation target rate examined is chosen to be 1.6% in the light of figure 1. This exercise allows us to draw some inference concerning both the ECB's *de facto* inflation target and the ECB's concerns of past inflation gaps.

Estimation results are summarized in table A2.2. Based on our model evaluation criteria, longer credibility loss time spans, ranging up to 6 - 8 lags and lower inflation target rates (perhaps even as low as 1.6% or 1.7%) produce the most satisfactory and relatively robust coefficient estimates (estimated parameters seem to be relatively stable when the sample rolls recursively over the financial crisis towards 2014Q2[25]).

Our preferred nonlinear specification is reported in table 2. Compared to our preferred linear specification in table 1, we now obtain smaller coefficients for interest rate smoothing and projected inflation gap while the ECB seems to react relatively strongly to the past inflation gaps. The estimated output growth coefficient is roughly unchanged relative to the preferred linear specification.

In sum, we find that a concern for past errors seem to have played a role in the ECB's policy decisions. Quite intuitively, however, the ECB has responded only to persistent inflation gaps as indicated by the long lags of the credibility loss term.[26] Perhaps most importantly, our results suggest that the ECB's *de facto* inflation target has been considerably below 2%, perhaps even as low as 1.6 - 1.7%.[27]

[25]The results are available upon request.

[26]This is reasonable, since monetary policy is not expected to respond to temporary shocks to inflation such as large variations in energy prices.

[27]Bletzinger & Wieland (2017) consider a target range of 1.5%-2.0%, concluding that the ECB point inflation target is 1.7%.

3.3 Asymmetric responses to past inflation gaps

Next, we consider possible asymmetry in the ECB's policy making, i.e. we allow different responses to positive and negative past inflation gaps. We estimate the following specification:

$$i_t = c_1 * i_{t-1} + (1 - c_1) * (c_2 + c_3 * (\pi^f_{t+4|t} - \pi^*) + c_4 * \triangle y^f_{t+1|t} + c_5 * CL^+_t + c_6 * CL^-_t + r^n_t) \qquad (3)$$

where

$$CL^+_t = D^{CL}_t * CL_t$$

$$CL^-_t = (1 - D^{CL}_t) * CL_t.$$

In equation (3), the dummy variable D^{CL}_t is equal to one (zero) if $CL_t > 0$ ($CL_t < 0$). The coefficient c_5 captures monetary policy reactions to past positive and the coefficient c_6 to past negative inflation gaps. In order to measure the ECB's credibility concerns in a meaningful way, the parameters c_5 and c_6 must be positive, but their sizes may differ.

Again, we run several competing specifications in order to draw some inference concerning both the ECB's *de facto* inflation target and the ECB's concerns of past inflation gaps. In table A2.3, the credibility loss term is based on $1 - 8$ lags of actual inflation and the inflation target varies from 1.6 to 2.0%. Consistent with our results for symmetric reaction functions, table A2.3 indicates that the time span of the past inflation gap should be rather long, ranging from 6 to 8 quarters (the ECB reacts only to rather persistent inflation gaps). However, as our preferred specification in table 3 reveals, now the inflation target closer to 2% seems more appropriate and the ECB's policy is asymmetric: it responds more aggressively to positive than to negative inflation gaps (i.e. the parameter estimate for c_5 is significantly larger than for c_6).[28] Such asymmetric reaction to past inflation gaps implies that, over a long period of time, inflation will be below 2%, i.e. asymmetry itself lowers the *de facto* inflation target.

As for the estimated coefficient for inflation, this policy rule suggests that the ECB is considerably backward-looking, because the estimated coefficient for inflation forecast is rather small, three to four times smaller than in the previous estimations (see tables 1 and 2). At the same time, the point estimate for the output term is somewhat higher.

In order to assess whether asymmetric policy responses reflect the zero lower bound of interest rates, we have re-estimated the reaction function (3) using the shadow rate instead of the EONIA for the longer sample 1999Q1 - 2016Q4. The results are qualitatively unchanged.[29]

In summary, the ECB's definition of price stability seems to manifest itself in two alternative ways. Either the *de facto* target of the ECB is significantly below 2% and policy responses to past inflation gaps are symmetric, or the ECB's inflation target is close to 2% and it reacts more strongly to past positive than to past negative inflation gaps. The two policy rule specifications have also other interesting differences: in the case of the symmetric specification, the policy response to the projected inflation is clearly higher (three times higher) and to past inflation gaps substantially lower compared to the asymmetric specification. While in both cases a reaction to past inflation gaps implies that the ECB attempts to correct past inflation misses, this behavior is particularly strong under the asymmetric specification. Given that there is no substantial difference in the interest rate smoothing coefficient, the ECB appears to be more forward looking under the symmetric specification. As for now, there is no clear statistical criteria by which we could give preference to either of the two reaction function specifications.

[28] Note that a time invariant potential output can be calculated as $\Delta y^* = (\pi^* - c2)/c4$. According to the symmetric reaction function (asymmetric reaction function), the average projected potential output growth is 2.5% (2.3%). These numbers naturally deviate somewhat from the *ex-post* data, reflecting both real time uncertainty of future real GDP growth and end-point-problems. At the same time, the implied projected potential growth rates are in line with the Eurosystem/ECB staff real GDP growth projections. The projected growth rates at the end of each projection horizon are good proxies for the real time estimates of the projected potential output growth. As already discussed in section 2, the ECB's projections of real GDP growth converge to values between slightly below 2% and 3%.

[29] Estimation results are available upon request.

4 Predictive performance of different reaction functions

4.1 In-sample predictions

The performance of our preferred reaction functions from tables 1 to 3 can be assessed by comparing their in-sample predictions to the EONIA interest rate. Figure 4 indicates that the asymmetric reaction function deviates at times significantly from the EONIA rate and from predictions of the two other functions, especially at the beginning of the sample, when the euro area inflation was quite often above 2%. During 2005 - 2007, however, the asymmetric reaction function tracks relatively well the EONIA rate. In mid-2008 it misses the increase in the EONIA rate, and from there on it stays most of the time above the EONIA and also above predictions of the two other reaction functions. Both the symmetric and linear reaction function would have implied a stronger interest rate hike prior to the financial crisis, but in general more lax policy after 2009.

The linear reaction function, which only responds to the expected future path of the economy and not at all to past inflation gaps, generates the lowest interest rate path (i.e. the most accommodative monetary policy stance) at the end of the sample. This reflects relatively strong responses to the projected slowdown of inflation during this period. The symmetric nonlinear reaction function with a low *de facto* target inflation generates a similar path, but yields somewhat a less accommodative policy stance, because it puts weight on a past positive inflation gap (see figure 3) and the impact of the projected slowdown of inflation is smaller. Excluding the end of the sample, the linear and symmetric nonlinear reaction functions give rather similar predictions for the interest rate path until about 2012. According to these specifications, the zero lower bound would have been reached in 2009, i.e. much earlier than it was actually reached. Instead, according to the asymmetric nonlinear reaction function the zero lower bound would not have been reached at all.

4.2 Out-of-sample predictions and comparison to shadow rates

How do the estimated reaction functions describe the monetary policy stance under unconventional monetary policy measures when the interest rate has hit the zero lower bound? In other words, are unconventional and conventional measures determined by the same basic principles, so that unconventional measures can be thought of as a continuation of conventional monetary policy when the zero lower bound is reached? Assuming that one of our preferred policy rule specifications provides a reasonable description of the ECB monetary policy until 2014, the same policy strategy should have been applied also afterwards for this policy to be time-consistent.

In July 2013, the ECB started using forward guidance to inform markets and the public on its future intentions with regard to key policy rates, and in January 2015 the ECB launched an expanded asset purchase programme (APP) to address risks of too low inflation for a prolonged period. Also other unconventional monetary policy measures were adopted in 2015 and 2016 in order to maintain an accommodative stance of monetary policy.[30]

To analyze the recent euro area monetary policy stance, we use our preferred reaction functions (estimated for the period 1999Q4 - 2014Q2) to produce out-of-sample forecasts for the period 2014Q3 - 2016Q4. In this exercise, predictions are based on real time projected inflation and real GDP growth and a proxy for the natural real rate of interest. In figure 5.1, the implied interest rates are compared with the shadow rate estimated by Kortela (2016). He argues that the euro area shadow rate has gradually decreased to about -3%, while a temporary increase was experienced in 2015. The interest rate implied by our linear rule remains negative and stable around -1% throughout the whole zero lower bound period; it is roughly one percentage point below the EONIA rate but considerably higher than the shadow rate for most of the period.

The nonlinear reaction functions taking into account of a credibility loss imply falling interest rates over the period 2014Q3 - 2016Q4. The symmetric nonlinear reaction function with a low *de facto* inflation target of 1.7% seems to track the shadow rate considerably better than the asymmetric nonlinear reaction function with an inflation target of 2%. This suggests, tentatively, that the ECB's definition of price stability is best characterized by an inflation target that is markedly below 2%, but the ECB is symmetric in its reactions to

[30]Since mid-2014, in order to provide financing to euro area credit institutions, two series of targeted longer-term refinancing operations (TLTROs) have been introduced: the first series of eight operations (LTRO-I) was announced in June 2014, and a second series of four operations (LTRO-II) in March 2016. In September 2014, the ECB made announcements of the third covered bond purchase programme (CBPP3), an asset-backed securities purchase programme (ABSPP) and a further deposit facility rate cut. APP purchases were started in March 2015 and they were re-calibrated in December 2015, March 2016 and December 2016.

past inflation gaps. If we consider the symmetric reaction function based on a lower inflation target of 1.6%, which is also a plausible target rate according to our estimation results shown in table A2.2, the implied predictions are even closer to the shadow rate (figure 5.2).

Finally, as a robustness check, we compare the same out-of-sample predictions to another shadow interest rate estimated by Wu & Xia (2016).[31] As shown in appendix 3, their shadow rate is steadily decreasing to about -5% in 2016. Compared to Kortela's (2016), their analysis indicates even more accommodative a monetary policy stance in the euro area in recent years. The main technical difference between Kortela (2016) and Wu & Xia (2016) is that Kortela (2016) allows for a time-varying lower bound for the euro area, reflecting the expected path of the deposit facility rate. The Wu & Xia (2016) methodology is based on a constant lower bound assumption. Nevertheless, also in the Wu & Xia (2016) case, the symmetric reaction functions with a low *de facto* inflation target (1.6 or 1.7%) seem to characterize the most accurately the conducted policy in the euro area.

5 Conclusions

In this paper, we have estimated the ECB's reaction function using real time projections from the Eurosystem/ECB staff macroeconomic projection exercises. Our unique quarterly dataset has enabled us to assess realistically the impacts of real time uncertainty on the ECB Governing Council's decision-making. We have estimated a large number of competing specifications with varying degrees of backward and forward lookingness of explanatory variables, asymmetry and different levels of the *de facto* inflation target. We have also considered two different proxies for the euro area shadow rate when assessing the relevance of out-of-sample predictions of our preferred specifications. By making recursive estimations, we have also considered the stability of the estimated parameters.

We have found two alternative interpretations of the ECB's definition of price stability. In the first one, the *de facto* inflation target of the ECB is well below 2%, perhaps even as low as 1.6–1.7%, and policy responses

[31] The shadow interest rate constructed by Wu & Xia (2016) is based on an analytical representation for bond prices in a SRTSM model (https://www.quandl.com/data/SHADOWS/EUROPE-European-Central-Bank-Shadow-Rate).

to past inflation gaps are symmetric. This finding is also consistent with the fact that the Eurosystem/ECB staff medium term inflation projections have had a tendency to converge on values well below 2%. In the second interpretation, the ECB is more concerned over inflation rates above 2% than rates below 2%, which reflects asymmetry in policy responses to inflation. While both of these reaction functions yield a good in-sample fit with respect to the EONIA rate, the out-of-sample predictions of the reaction function based on the first interpretation of price stability track more closely the estimated shadow rate during the zero lower bound period.

Our results suggest that, in general, the ECB's policy reaction function follows the basic optimality principles, in the sense that the ECB Governing Council responds relatively strongly to the expected future course of the economy and also aims at correcting past persistent deviations of inflation from the target. This is consistent with the recent ECB communication, according to which the launch of asset purchase programmes can be justified as a response to a too-prolonged period of low inflation.[32] At the same time, however, the asymmetric response to inflation and/or low *de facto* inflation target indicated by our findings may hamper the ECB's ability to achieve price stability. There are a number of reasons for this.

Firstly, when approaching the inflation target from below, the central bank may need to tolerate inflation rates above the target. Overshooting the target for a limited time may help the central bank to achieve its price stability objective faster and more efficiently when interest rates are at the zero lower bound. Under credible monetary policy, overshooting the target raises inflation expectations and lowers the *ex-ante* real interest rate. This boosts consumption and investment and therefore reduces economic slack.

Secondly, for a given equilibrium real interest rate, anchoring of inflation expectations to a relatively low level also leads to low nominal rates over the business cycle. This reduces the scope to absorb shocks in economic downturns and increases the likelihood of hitting the zero lower bound. Also Miles et al. (2017) have recently stressed that in the current low inflation environment, overshooting the target is necessary and the targeted rate of inflation should not be too low.[33]

[32] See http://www.ecb.europa.eu/press/key/date/2018/html/ecb.sp180314_1.en.html.

[33] In the United States, too, the level and symmetry of the targeted rate of inflation has been discussed recently. See for example speeches by Charles Evans:
https://www.chicagofed.org/publications/speeches/2017/11-15-2017-low-inflation-and-symmetry-of-two-percent-

Finally, Taylor (2018) discusses at length the benefits of rule-based monetary policy, but he also notes that different opinions within a monetary policy-making body (the FOMC, in the case of the Federal Reserve System) may make it difficult to agree on a specific policy rule. Decision-making and communication are potentially even more challenging if members of the monetary policy-making body have different views on the inflation target itself.

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https://www.chicagofed.org/publications/speeches/2017/09-25-17-puzzle-low-inflation-implications-monetary-policy.

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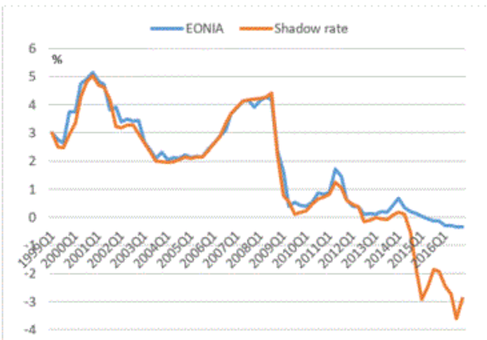
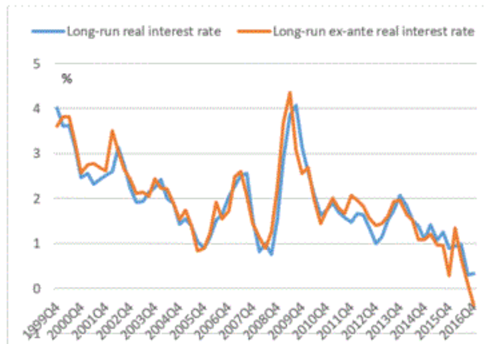
Appendix 1: EONIA, shadow rate and proxies of the long-run natural real interest rate

Figure A1.1. EONIA and the shadow rate at the end of each quarter



Sources: Thomson Reuters (EONIA) and Kortela (2016) (the shadow rate).

Figure A1.2. Proxies of the long-run natural real interest rate



Note: The long-run real interest rate equals to the difference of a euro area composite nominal yield of ten year government bonds and the real time nowcast of inflation rate. The *ex-ante* real interest rate equals to the difference of the composite yield and the real time one-period-ahead expected inflation rate.

Sources: ECB and authors' own calculations.

Appendix 2: Summary of estimations

Table A2.1. Coefficients of inflation and GDP growth in reaction function (1), with different projection horizons for inflation (rows) and output growth (columns)

a) Linear policy reaction function without a natural rate of interest

	$\Delta y^f_{t\|t}$		$\Delta y^f_{t+1\|t}$		$\Delta y^f_{t+2\|t}$		$\Delta y^f_{t+3\|t}$		$\Delta y^f_{t+4\|t}$	
$\pi^f_{t\|t}$	-0.50	1.30*	0.88*	1.46*	0.02	3.76*	0.00	2.89*	0.06	3.08*
$\pi^f_{t+1\|t}$	0.87*	1.06*	1.05*	1.21*	0.37	3.36*	0.11	2.84*	0.63	2.98*
$\pi^f_{t+2\|t}$	0.86	1.14*	0.76	3.19*	0.28	3.55*	0.08	2.86*	0.33	3.07*
$\pi^f_{t+3\|t}$	0.36	1.28*	0.00	3.94*	-0.47	4.07*	-0.11	2.94*	0.05	3.07*
$\pi^f_{t+4\|t}$	**2.34***	**0.94***	**2.97***	**1.84***	1.85	2.69*	0.75	2.59*	1.26	2.75*

b) Linear reaction function with r_t^{10yr} as a proxy for the natural rate of interest

	$\Delta y^f_{t\|t}$		$\Delta y^f_{t+1\|t}$		$\Delta y^f_{t+2\|t}$		$\Delta y^f_{t+3\|t}$		$\Delta y^f_{t+4\|t}$	
$\pi^f_{t\|t}$	-12.99	8.01	1.78*	5.39	0.04	4.95*	0.65	3.05*	0.50	2.79*
$\pi^f_{t+1\|t}$	**2.22***	**0.76***	2.31	6.23	0.20	4.82*	0.77	3.34*	0.66	2.63*
$\pi^f_{t+2\|t}$	**3.72***	**0.85***	2.76	5.60	0.78	4.37*	1.22	3.15*	1.00	2.63*
$\pi^f_{t+3\|t}$	2.26	0.62	3.69	5.47	0.25	4.82*	1.31	2.89*	1.40	2.55*
$\pi^f_{t+4\|t}$	**4.51***	**0.73***	**4.82***	**1.19***	**4.51***	**1.48***	**4.46***	**1.20***	**4.48***	**1.09***

c) Linear reaction function with $\tilde{r}_t^{10yr}$ as a proxy for the natural rate of interest

	$\Delta y^f_{t\|t}$		$\Delta y^f_{t+1\|t}$		$\Delta y^f_{t+2\|t}$		$\Delta y^f_{t+3\|t}$		$\Delta y^f_{t+4\|t}$	
$\pi^f_{t\|t}$	-4.32	3.35	1.16	7.49	0.13	4.41*	0.28	2.98*	1.72*	3.56*
$\pi^f_{t+1\|t}$	0.21	1.26	1.61	7.72	0.36	4.29*	0.52*	2.72*	1.05*	2.97*
$\pi^f_{t+2\|t}$	0.49	1.51	1.41	7.88	0.35	4.26	0.62	2.71	3.14*	5.12
$\pi^f_{t+3\|t}$	-4.34	2.91	-5.92	27.86	-0.59	4.96	0.40	2.91	3.68	6.67
$\pi^f_{t+4\|t}$	3.84*	0.84	**4.45***	**1.48***	**3.19***	**2.32***	**3.21***	**1.72***	3.12*	1.95

Note:

1. In each cell the first entry is the coefficient of inflation c_3, while the second entry is the coefficient of real GDP growth c_4.
2. Coefficient estimates which are statistically significant, at least at the 5% level, are marked by *.
3. Bolded numbers mark model variants, where i) both coefficients c_3 and c_4 are statistically significant, ii) the coefficient of inflation is greater than one, and iii) the coefficient of inflation is greater than the coefficient of real GDP growth.
4. We have added a grey background color to the combinations of inflation and output projection horizons ($\pi^f_{t+4|t}$, $\triangle y^f_{t+1|t}$) which satisfy the criteria i) - iii) in all the reaction functions (a, b and c), with and without a natural rate proxy.

Table A2.2. Symmetric monetary policy responses to a credibility loss in reaction function (2)

a) Reaction functions that include the long real interest rate r_t^{10yr} as a proxy for the natural rate

	target 1.6	target 1.7	target 1.8	target 1.9	target 2.0
$\overline{\pi}_{t-1,t-1}$	-0.61	-0.65	-0.68	-0.70	-0.61
$\overline{\pi}_{t-1,t-2}$	-0.49	-0.40	-0.20	-0.14	-0.13
$\overline{\pi}_{t-1,t-3}$	-0.11	-0.10	-0.11	-0.13	-0.17
$\overline{\pi}_{t-1,t-4}$	0.11	0.11	0.10	0.08	0.02
$\overline{\pi}_{t-1,t-5}$	0.94*	0.70*	0.58*	0.50*	0.44*
$\overline{\pi}_{t-1,t-6}$	1.21*	1.02*	0.82*	0.64*	0.09
$\overline{\pi}_{t-1,t-7}$	**1.50***	**0.94***	0.24	0.19	0.53
$\overline{\pi}_{t-1,t-8}$	**2.90***	0.77	0.42	0.39	0.53

b) Reaction functions that include the ex-ante long real interest rate $\tilde{r}_t^{10yr}$ as a proxy for the natural rate

	target 1.6	target 1.7	target 1.8	target 1.9	target 2.0
$\overline{\pi}_{t-1,t-1}$	-0.53	-0.44	-0.07	-0.02	0.01
$\overline{\pi}_{t-1,t-2}$	0.20	0.16	0.13	0.11	0.09
$\overline{\pi}_{t-1,t-3}$	0.06	0.06	0.06	0.06	0.05
$\overline{\pi}_{t-1,t-4}$	-0.43	-0.10	0.02	0.05	0.06
$\overline{\pi}_{t-1,t-5}$	-0.44	-0.44	-0.24	-0.01	0.08
$\overline{\pi}_{t-1,t-6}$	0.29	0.29	0.31	0.31	0.29
$\overline{\pi}_{t-1,t-7}$	**1.42***	**1.07***	0.76	0.62	0.58
$\overline{\pi}_{t-1,t-8}$	3.20*	1.30	1.19	1.16	0.96

Note:

1. The table reports estimates of the coefficient c_5 for the credibility loss term CL_t, for different spans of past inflation (rows) and inflation targets (columns).
2. Coefficient estimates c_5 which are of the correct sign (positive) and statistically significant, at least at the 5% level, are marked by *.
3. We have bolded the model specifications where also the coefficients of inflation and GDP growth projections (c_3 and c_4, not shown in the table) are positive and statistically significant, and in addition $c_3 > c_4$.
4. We have added a grey background color to the combinations of past inflation spans and inflation targets which meet the conditions 2 and 3 in both types of reaction functions considered here (i.e. these combinations are bolded in both tables, a and b).

Table A2.3. Asymmetric monetary policy responses to a credibility loss in reaction function (3)

a) Reaction functions that include the long real interest rate r_t^{10yr} as a proxy for the natural rate

	target 1.6		target 1.7		target 1.8		target 1.9		target 2.0	
$\bar{\pi}_{t-1,t-1}$	0.60	0.36*	0.61	0.26	0.62	0.15	0.63	0.03	-1.55	-0.35
$\bar{\pi}_{t-1,t-2}$	0.68	0.45	0.68	0.31	0.60	0.14	-1.24	-0.08	-1.42	-0.10
$\bar{\pi}_{t-1,t-3}$	-0.91	0.25	-1.00	0.15	-1.03	0.07	-0.47	-0.04	-0.29	-0.15
$\bar{\pi}_{t-1,t-4}$	-2.31	0.61*	-2.17	0.44*	-2.19	0.34	0.49	-0.01	0.02	0.00
$\bar{\pi}_{t-1,t-5}$	-3.17	1.09*	-3.83	0.82*	-4.37	0.62*	-4.80	0.48*	-5.32	0.39*
$\bar{\pi}_{t-1,t-6}$	2.61*	0.95	2.96*	0.97*	-0.51	0.83*	-1.06	0.68*	-1.97	0.57*
$\bar{\pi}_{t-1,t-7}$	2.89*	1.00	3.67*	0.77	**4.73***	**0.64**	**6.14***	**0.61**	**8.00***	**0.63***
$\bar{\pi}_{t-1,t-8}$	3.30*	-1.02	4.18*	-1.08	5.66*	-1.21	8.39*	-1.19	12.77*	-0.71

b) Reaction functions that include the *ex-ante* long real interest rate $\tilde{r}_t^{10yr}$ as a proxy for the natural rate

	target 1.6		target 1.7		target 1.8		target 1.9		target 2.0	
$\bar{\pi}_{t-1,t-1}$	0.43	0.51*	0.42	0.44*	0.41	0.37*	0.38	0.31*	0.34	0.24*
$\bar{\pi}_{t-1,t-2}$	0.65	0.54*	0.68	0.48*	0.71	0.41*	0.71	0.34	0.68	0.27
$\bar{\pi}_{t-1,t-3}$	-1.66	0.72*	-1.74	0.57*	-1.81	0.45*	2.75	0.24	-0.59	0.09
$\bar{\pi}_{t-1,t-4}$	-1.24	0.53*	-1.31	0.43*	-1.43	0.36*	-1.62	0.30*	-1.91	0.25*
$\bar{\pi}_{t-1,t-5}$	-1.86	0.96*	-2.08	0.76*	-2.35	0.61*	-2.74	0.50*	-3.34	0.42*
$\bar{\pi}_{t-1,t-6}$	0.74	0.26	0.37	0.40	-2.62	1.15*	-2.98	0.91*	-3.55	*0.74
$\bar{\pi}_{t-1,t-7}$	2.4*	0.64	3.06*	0.43	3.88*	0.31	4.92*	0.28	**6.21***	**0.31**
$\bar{\pi}_{t-1,t-8}$	3.65*	-8.67	4.57*	-4.26	5.83*	-1.85	7.46*	-0.77	9.69*	-0.14

Note:

1. The table reports estimates of monetary policy reactions to a positive past inflation gap (coefficient c_5, left entry in each cell) and a negative past inflation gap (coefficient c_6, right entry in each cell), for different spans of past inflation (rows) and different *de facto* inflation targets (columns).
2. Coefficient estimates which are of the correct sign (positive) and statistically significant, at least at the 5% level, are marked by *.
3. Bolded numbers mark model variants where i) both coefficients are of the correct sign (positive), ii) at least the reaction to a past positive inflation gap (c_5) is significantly different from zero, and iii) the policy reaction to past positive deviations from the inflation target is significantly stronger than the reaction to past negative deviations from the target (i.e. c_5 is significantly larger than c_6, at least at the 5% level).
4. We have added a grey background color to the combinations of past inflation span and inflation target ($\bar{\pi}_{t-1,t-7}$ and target 2.0), which satisfy the criteria i), ii) and iii) in both types of reaction functions considered here (i.e. in tables a and b).

Appendix 3: Shadow rate by Wu & Xia (2016) and predictions based on different reaction functions

Figure A3.1.

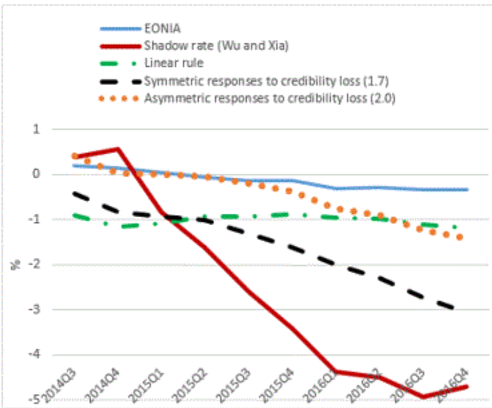
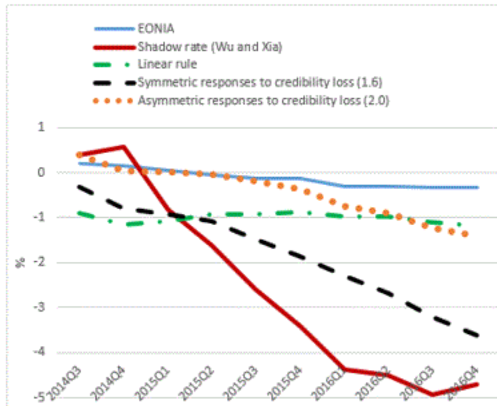


Figure A3.2.



Note: The symmetric responses to a credibility loss refer to a reaction function with a low *de facto* inflation target (1.6 or 1.7%). The asymmetric responses to a credibility loss refer to a reaction function with an inflation target of 2.0%.

Sources: ECB, authors' own calculations and Wu & Xia (2016) for the shadow rate.

Table 1. Baseline linear reaction function

$$i_t = c_1 * i_{t-1} + (1 - c_1) * (c_2 + c_3 * (\pi^f_{t+4|t} - 1.9) + c_4 * \triangle y^f_{t+1|t} + \tilde{r}^{10yr}_t)$$

	Coefficient	Std. Error	t-Statistic	Prob.
c_1	0.84	0.044	19.23	0.0000
c_2	-0.95	0.737	-1.29	0.2049
c_3	4.45	0.832	5.34	0.0000
c_4	1.48	0.507	2.92	0.0057
J-statistic	6.07			
Prob(J-statistic)	0.73			

Note: This table shows the GMM estimation results of our preferred linear reaction function of the ECB. The estimation sample is 1999Q4 - 2014Q2. See the main text for the definition of the variables and table A2.1 in appendix 2 for alternative competing linear specifications. The reported J-statistic is the Sargent-Hansen test for validity of the instruments.

Table 2. Baseline reaction function with the symmetric response to a past inflation gap

$$i_t = c_1 * i_{t-1} + (1 - c_1) * (c_2 + c_3 * (\pi^f_{t+4|t} - 1.7) + c_4 * \triangle y^f_{t+1|t} + c_5 * CL_t + \tilde{r}^{10yr}_t)$$

where $CL_t = (\bar{\pi}_{t-1,t-7} - 1.7)|\bar{\pi}_{t-1,t-7} - 1.7|$

	Coefficient	Std. Error	t-Statistic	Prob.
c_1	0.77	0.051	15.30	0.0000
c_2	-1.51	0.396	-3.83	0.0004
c_3	3.61	0.798	4.53	0.0001
c_4	1.25	0.317	3.94	0.0013
c_5	1.07	0.417	2.56	0.0145
J-statistic	6.58			
Prob(J-statistic)	0.68			

Note: This table shows the GMM estimation results of our preferred reaction function of the ECB including symmetric reactions to past inflation gaps. The estimation sample is 1999Q4 - 2014Q2. See the main text for the definition of the variables and table A2.2 in appendix 2 for alternative specifications. The reported J-statistic is the Sargent-Hansen test for validity of the instruments.

Table 3. Baseline reaction function with the asymmetric response to a past inflation gap

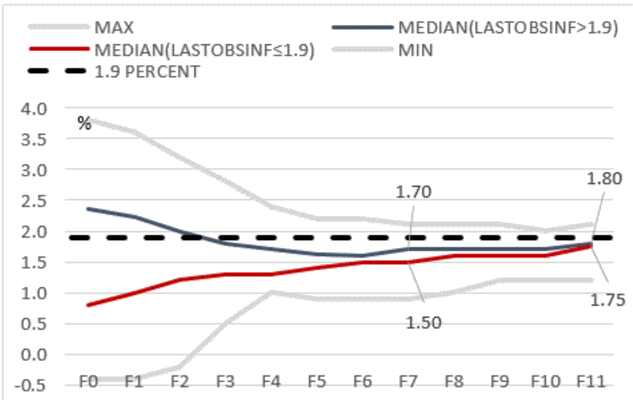
$$i_t = c_1 * i_{t-1} + (1 - c_1) * (c_2 + c_3 * (\pi^f_{t+4|t} - 2.0) + c_4 * \triangle y^f_{t+1|t} + c_5 * CL^+_t + c_6 * CL^-_t + r^n_t)$$

where $CL_t = (\bar{\pi}_{t-1,t-7} - 2.0)|\bar{\pi}_{t-1,t-7} - 2.0|$

	Coefficient	Std. Error	t-Statistic	Prob.
c_1	0.79	0.046	16.94	0.0000
c_2	-1.92	0.755	-2.54	0.0153
c_3	1.23	0.585	2.10	0.0424
c_4	1.69	0.379	4.47	0.0001
c_5	8.00	2.606	3.07	0.0039
c_6	0.63	0.312	2.01	0.0518
J-statistic	6.66	F-statistic ($H0$: $c_5 = c_6$)		6.84
Prob(J-statistic)	0.67	Prob(F-statistic)		0.013

Note: This table shows the GMM estimation results of our preferred asymmetric reaction function of the ECB. The estimation sample is 1999Q4 - 2014Q2. See the main text for the definition of the variables and table A2.3 in appendix 2 for alternative competing specifications. The reported J-statistic is the Sargent-Hansen test for validity of the instruments. The F-statistic is obtained from the test for asymmetry of the reaction function, by testing equality of the positive and negative credibility loss term coefficient estimates.

Figure 1. Median inflation projections conditioned on the latest observed inflation rate during each projection exercise



Note: On the horizontal axis, the label "F0" refers to real time current quarter nowcasts and the label "F1" to one-quarter-ahead projections, etc. The curves "MAX" and "MIN" refer to the highest and lowest inflation projections made in 1999Q4 - 2016Q4.

Sources: ECB and authors' own calculations.

Figure 2. Correlations

Figure 2.1. Between the actual and projected inflation rates

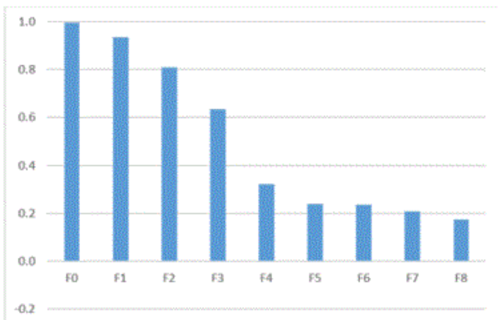
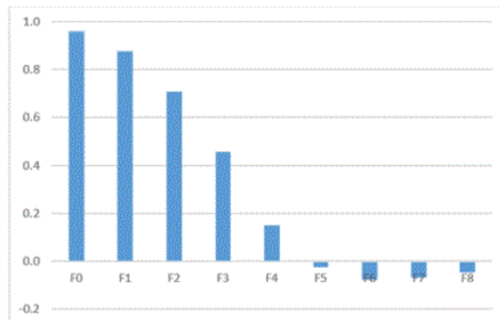
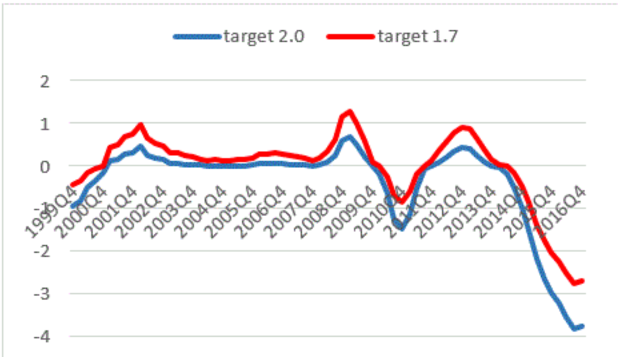


Figure 2.2. Between the actual and projected real GDP growth rates



Sources: ECB and authors' own calculations.

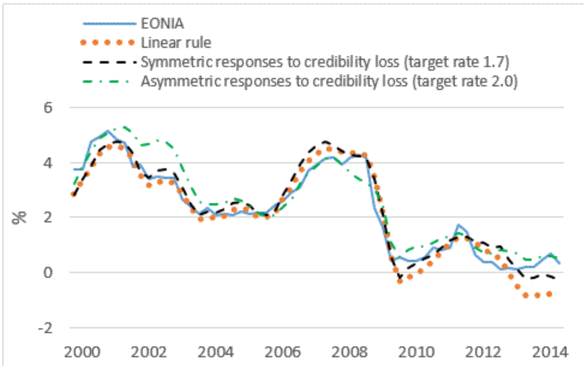
Figure 3. Values of the credibility loss term



Note: The horizon over which the average inflation is measured is seven quarters ($\bar{\pi}_{t-1,t-7}$). See the main text above for the definition of the credibility term.

Sources: ECB and authors' own calculations.

Figure 4. Dynamic in-sample predictions of different reaction functions



Note: The dynamic in-sample predictions are based on our preferred specifications of the ECB's reaction function reported in sections 3.1 - 3.3.

Sources: ECB, Thomson Reuters and authors' own calculations.

Figure 5. Shadow rate by Kortela (2016) and predictions based on different reaction functions

Figure 5.1.

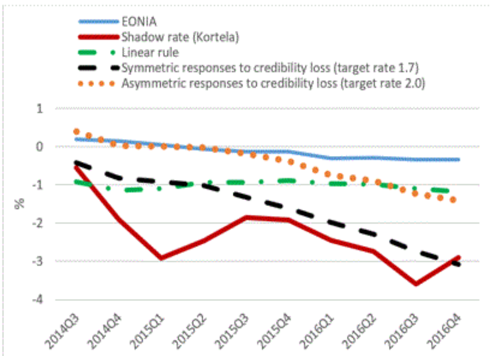
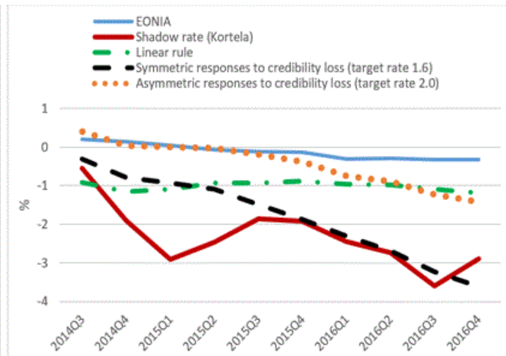


Figure 5.2.



Note: The symmetric responses to a credibility loss refer to a reaction function with a low de facto inflation target (1.7% or 1.6%). The asymmetric responses to a credibility loss refer to a reaction function with an inflation target of 2.0%.

Sources: ECB, authors' own calculations and Kortela (2016) for the shadow rate.