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Banking in the Negative: A Vector Error Correction Analysis of Bank-Specific Lending and Deposit Rates

Alessandra Agati[1], Michael Sigmund[2]

Abstract

We analyze the impact of negative reference rates on the interest behavior of more than 500 Austrian banks from 2009Q1 to 2021Q4. Using panel vector error correction analysis with the Engle-Granger procedure in two steps, we establish a cointegration vector that links bank-specific lending rates, deposit rates, the 3-month Euribor, and the ECB Deposit Facility Rate. We propose two hypotheses to evaluate the effects of negative 3-month Euribor on this vector. Firstly, we explore how an Austrian Supreme Court decision enforcing a zero-lower bound on household deposits could decrease the lending-deposit rate spread. Secondly, we examine the emergence of two "true prices" for loans and deposits due to the negative 3-month Euribor. This is linked to an Austrian Supreme Court decision mandating the transmission of negative reference rates to bank-specific lending rates, potentially affecting cointegration with the 3-month Euribor. Our findings show a significant spread reduction after the introduction of negative reference rates, primarily driven by changes in the cointegration relationship between bank-specific lending rates and the 3-month Euribor. Additionally, by including the ECB Deposit Facility in our cointegration model, we capture the direct impact of the Targeted Long-term Refinancing Operations on the lending rate.

Keywords: Interest rate setting; panel cointegration; negative interest rate environment

JEL: C33, G21, E58, E43

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Non-Technical Summary

This study examines the impact of negative reference rates on the interest-setting behavior of banks. The interest rate setting behavior of banks is the most important determinant of net interest income and therefore the net interest margin, which is a major part of a bank's return on assets.

In response to a rising risk of deflation, the ECB adjusted the Deposit Facility Rate to 0% in 2012. Despite this, Euro Area inflation continuously decreased between 2012 and mid-2014, which incentivized the ECB to explore new monetary policy tools, among which setting the ECB Deposit Facility Rate (DFR) at −0.1% in June 2014. As expressed by the ECB, the idea behind this step was two-fold. First, the ECB aimed to reverse the expected future trajectory of short-term interest rates by pushing beyond the zero lower bound. Second, they wanted to encourage banks to provide more credit to the economy. However, any new monetary policy measure is rarely without controversy and may have side effects.

Despite the consensus that the benefits of negative interest rate policy for the economy as a whole have been greater than their costs, there have been conflicting opinions in the literature on how negative reference rates influence banks' behavior. On the one hand side, Rogoff (2017); Lilley and Rogoff (2019), Altavilla et al. (2022) argue that banks' interest rate setting, the net interest margin, and the ROA of banks do not change, i.e., bank-specific lending and deposit rates are just shifted down, even below zero, resulting in negative deposit rates. The other strand of literature argues that too low and even negative reference rates cut banks' interest rate margins, depressing their net worth and curtailing their credit supply (Brunnermeier and Koby, 2018). Both theories can be supported by theoretical models.

However, the first strand of literature might have overlooked legal and economic reasons why interest rates might not shiftily enter negative territory. While the interest rates on many assets (e.g., loans) follow the decreasing reference rate (e.g., 3-month Euribor), some deposit rates are floored at zero and cannot follow this rate. Competition among banks, the risk of bank runs, or the willingness of some households to search for alternative saving methods (e.g., cash into safes) might be economic arguments why deposit rates are floored at zero. Furthermore, in Austria, a high court decision rules out negative deposit rates for households.

We follow the standard literature (Cottarelli and Kourelis, 1994; Weth, 2002; Kok and Werner, 2006; Gambacorta, 2008) and model interest rate setting behavior of banks in an error vector correction model based on the two-step procedure proposed by Engle and Granger (1987). In the first step, to understand the potential changes in the interest-setting behavior of banks, we utilize a unique data set of over 500 banks observed on a quarterly basis since 2009. Our strategy is to theoretically motivate, test, and estimate a four-variable cointegration relationship between bank-specific lending rates, bank-specific deposit rates, the 3-month Euribor, and the ECB Deposit Facility. Next, we show which parts of the cointegration vector have changed under a negative 3-month Euribor. In the second step, we integrate the cointegrating vector into a vector error correction model to find other determinants of changes in bank-specific lending and deposit rates.

Our findings indicate a significant spread reduction after the introduction of negative reference rates, driven by changes in the cointegrating relationship between the bank-specific lending rate and the 3-month Euribor. In addition, we find a sluggish response to the bank-specific deposit rate growth after a shock to the 3-month Euribor. The bank-specific deposit rate is only adjusted towards equilibrium after 2 to 3 quarters. This adjustment is driven by lagged changes in the lending rate.

1. Introduction

Following the 2007-2008 global financial crisis and subsequent economic turmoil, the euro area began to face initial signs of deflationary pressure. Despite inflation rates in the euro area being near or above the 2% target set by the European Central Bank (ECB) from 2000 to 2007, proactive measures were taken to counter potential deflationary risks. In 2012, the ECB reduced the ECB Deposit Facility Rate (DFR) to 0%. However, inflation in the euro area consistently declined from 2012 to mid-2014, which led the ECB to further reduce the Deposit Facility Rate to −0.1% in June 2014. As highlighted by the ECB, this decision served a dual purpose. Firstly, the ECB aimed to influence the expected future path of short-term interest rates by surpassing the zero lower bound. Secondly, they sought to incentivize banks to extend more credit to the real economy.

Despite the consensus that the benefits of negative interest rate policy for the economy as a whole have been greater than their costs, there have been conflicting opinions in the literature on how negative reference rates influence banks' behavior. On the one hand, Rogoff (2017); Lilley and Rogoff (2019) and Altavilla et al. (2022) argue that negative policy rates should function as usual, without significant alteration in the passing through of bank-specific interest rates. However, it has been regarded as relevant to continue exploring this alternative monetary policy tool, particularly with respect to potential changes in the interest-setting behavior of banks. Negative interest rates have been implemented as a monetary policy tool by only a few major central banks, including the ECB (from June 2014 to July 2022), as well as the central banks of Denmark (from June 2012 to July 2022), Japan (since January 2016), Sweden (from February 2015 to May 2022), and Switzerland (from December 2014 to August 2022). Furthermore, smaller central banks, such as those of Hungary, the Czech Republic, and Israel, have also experimented with negative interest rates on a smaller scale.

On a macroeconomic scale, Czudaj (2020) shows that the adoption of negative policy rates results in a notable decline in expectations for 3-month money market interest rates and 10-year government bond yields. Furthermore, Rostagno et al. (2019) provide empirical support for the notion that negative interest rates contribute to reducing sovereign bond yields. Furthermore, Czudaj (2020) offers evidence for a substantial positive effect of negative interest rates on GDP growth and inflation expectations. Furthermore, Demiralp et al. (2021) illustrate a favorable impact on the growth of non-financial corporate loans attributable to negative interest rates.

However, when looking for possible drawbacks of the policy, from the outset, lowering the profitability of banks was identified as a potential adverse effect of negative policy rates. The simple idea was first explained in Kerbl and

Sigmund (2016): while the returns on many assets (e.g., loans) follow the decreasing reference rate (e.g., 3-month Euribor), many deposit rates are floored at zero and cannot follow the negative policy rate. This suggests that if the reference policy rate drops below zero, these deposit rates cannot be further decreased and will remain fixed at zero. These dynamics lead to reduced net interest margins for banks, particularly pronounced when the lending rate is legally or contractually bound to track the reference rate. This is in line with the theoretical predictions of Eggertsson et al. (2023) that banks relying on deposit financing were less likely to reduce their lending rates in response to policy rate cuts once the deposit rate had reached its lower bound.

The imposition of a zero floor on certain deposit rates can be attributed to two primary motivations. Firstly, in countries such as Austria and Belgium, legal judgments have prohibited the imposition of negative deposit rates to household saving accounts. Secondly, banks may have concerns that (small) depositors might choose to withdraw their funds and opt to hold cash or cash equivalents instead, or they could decide to switch to a competing institution capable of offering positive deposit rates.

More recently, empirical evidence on the adverse effects on banks' profitability in the context of negative policy rates has become more pronounced (Borio and Hofmann, 2017; Claessens et al., 2018; Molyneux et al., 2019; Freriks and Kakes, 2021; Raunig and Sigmund, 2022). These negative effects on bank profitability are particularly notable in their net interest income.

Consequently, the first question we ask is the following. Do negative policy interest rates influence monetary policy transmission at the bank level? Is it possible to incorporate negative interest rates into existing theories regarding banks' interest-setting behavior and deduce empirically testable hypotheses regarding their impact on bank-specific deposit and lending rates and ultimately, on the net interest margin? If so, what have been the consequences of negative interest rates on the interest rate setting behavior of banks?

In the literature, the pass-through of monetary policy to bank rates is often analyzed by only testing and estimating a cointegration relationship between a bank's lending rate and a reference rate or between a bank's deposit rate and a reference rate. Using these cointegration results, the banks' interest-setting behavior is then analyzed in a vector error correction model (VECM).

De Graeve et al. (2007) study the long-term transmission of the market rate to different lending rates of Belgian banks. On average, the results show an incomplete pass-through characterized by substantial heterogeneity between rates and banks, justified by differences in market power. Cottarelli and Kourelis (1994); Gambacorta (2008) applied a similar analysis to the Italian sector. Gambacorta (2008) focuses in particular on identifying the bank-specific factors that influence banks' lending and deposit rate setting. Weth (2002), on top of applying a cointegration analysis to study pass-through heterogeneity, found evidence of structural differences between German banks influencing the rate adjustment speed after movement from the long-term equilibrium. Kok and Werner (2006) test for heterogeneity and size of the pass-through across euro area banks' rates. They estimate different pass-throughs for different portfolio and maturity structures. Sander and Kleimeier (2004) enhance the cointegration analysis by introducing the possibility of a change in the pass-through and allowing for asymmetric adjustment, caused by a shock, such as the introduction of the euro. Similarly, Marotta (2009) investigate the change in the cointegration parameters following the change in the monetary regime, testing for multiple unknown structural breaks.

Our contribution to the literature is the following. To our knowledge, we are the first to analyze the co-integration relationship between bank lending and deposit rates, and the 3-month Euribor while considering that banks aim to maximize both their interest rate spread and interest rate margin, as suggested by Klein (1971); Ho and Saunders (1981). Thus, we go a step further than the existing literature and also ask whether bank-specific interest rates are cointegrated and how this panel cointegration relationship might have changed under negative reference rates. Then, we use these results, also known as the first step in the Engle-Granger cointegration procedure, and integrate them into a panel VECM.

Drawing from the standard theoretical net interest margin model proposed by Monti (1972); Ho and Saunders (1981), we develop two testable hypotheses on how negative reference rates may affect the cointegration between bank-specific interest rates and the 3-month Euribor. First, an Austrian Supreme Court decision imposing a zero-lower bound on household and/or NFC deposits could potentially reduce the spread between lending and deposit rates.[3] Second, as postulated by Ho and Saunders (1981), there is typically a bank opinion on one true price for loans and deposits. However, negative reference rates could lead to the emergence of two true prices, one for loans and the other for deposits. This is the result of a recent decision by the Austrian Supreme Court, which mandates that negative reference rates must be passed on to bank-specific lending rates. This would point to a potential change in the cointegration relationship between bank-specific lending and deposit rates and the 3-month Euribor.[4]

[3] See court case decision 5 Ob 138/09v of the Supreme Court of Justice (October 13, 2009).

[4] Negative reference rates need to be passed on until the total rate reaches zero (Oberlandesgericht Innsbruck, 4 R 58/16k, July 14, 2016, AK vs. Hypo Tirol). See also court case decisions dealing with Swiss franc-denominated foreign currency loans where the reference rate, CHF Libor, had already moved into negative territory at the end of 2014: Landesgericht Feldkirch (5 Cg 18/15z, August 28, 2015, VKI vs. Raiffeisenbank am Bodensee), Handelsgericht Wien (57 Cg 10/15v, September 24, 2015, VKI vs. Uni Credit BA) and Landesgericht Eisenstadt (27 Cg 32/15x, November 15, 2015, VKI vs. HYPO-BANK Burgenland).

We establish a cointegration relationship between bank-specific lending, bank-specific deposit rates, and the 3-month Euribor. Our cointegration results show that the pass-through from bank-specific deposit rates and the 3-month Euribor to bank-specific lending rates is greater than one. We provide empirical evidence that the direction of the cointegration relationship is from the bank-specific deposit to the lending rate, whereas the 3-month Euribor influences both rates. Further, we show that the pass-through is relatively homogeneous across banks. Most importantly, the negative interest rate environment led to a significant increase in the co-integration vector between bank-specific lending and the 3-month Euribor, which is the mechanism behind the reduction of net interest income under negative reference rates, since the stronger cointegrating vector is multiplied by a negative 3-month Euribor. In the standard net interest margin model, this implies that a negative 3-month Euribor has caused two true prices for loans and deposits. By adding the ECB Deposit Facility into our cointegration model, we also capture the direct effect of the Targeted Long-term Refinancing Operations on the lending rate. In the VECM, we find that changes in the 3-month Euribor have a stronger and more immediate effect on the lending rate, which is reversed after a few quarters by a combination of the adjustment coefficients and the coefficients of the lagged dependent variables. Hence, banks profit from rising reference rates in the short run.

We continue as follows. In Section 2, we describe our data set. In Section 3, we discuss how changes in the legal framework could theoretically influence the interest-setting behavior of banks. In Section 4, we describe our empirical approach, including the panel unit root tests, the panel cointegration tests, and the first step and the second step of the Engle-Granger procedure. In Section 5, we describe our results, starting with the panel unit root and panel cointegration test results in Section 6. Then, we present the results of the cointegration relationship. In Section 7, we show the results for the panel VECM. Section 8 concludes.

2. Data

Our data set consists of a quarterly panel of all domestically operating banks in Austria. These data are unbalanced and reported at the unconsolidated level, such that data from (foreign) subsidiaries do not influence our results. The data are taken from the regulatory reporting system in Austria over the period 2009Q1–2021Q4. The dataset includes balance sheet data, income statement data, and regulatory capital data taken from the Common Reporting Framework (COREP). We include all banks holding a banking license during the specified period, excluding special-purpose banks and foreign bank affiliates. We further restrict the sample to banks that report a minimum of 25 quarters overall and 6 consecutive quarters to ensure the applicability of the panel unit root and panel cointegration tests in Section 5.

Moreover, to prevent reporting errors from distorting the empirical analysis, we follow Gunter et al. (2013); Sigmund et al. (2017) and apply a two-stage cleaning algorithm to the variables that are defined in percent or as ratios (e.g., lending and deposit rates). First, we remove outliers across banks for each time period. An observation is considered an outlier if it is too far from the median (more than four times the distance between the median and the 2.5% or 97.5% quantile). In the second stage, we remove outliers over time for each bank. Here, the threshold distance is defined as 12 times the distance between the median and the 10% or 90% quantile. Such parameters ensure that the number of removed observations remains limited, and the resulting distributions exhibit a reasonable shape when judged from a qualitative perspective. After this cleaning procedure, around 23,000 data points remain in the sample.

We download the 3-month Euribor and the ECB Deposit Rate Facility data from the ECB's Statistical Data Warehouse.

2.1. Lending and Deposit Rates

From the regulatory reporting system, we obtain data on the average loan and deposit volumes as well as interest income and interest expenses, excluding the interbank market volumes for each bank in each period. Following the common definition of the effective interest rate (EBA, 2016), we calculate the lending and deposit rates in the following way: For the lending rate, we divide interest income from loans by the average loan volume. For the deposit rate, we divide interest expenses for deposits by the average deposit volume. We denote these interest rates as non-bank deposit and non-bank lending rates.

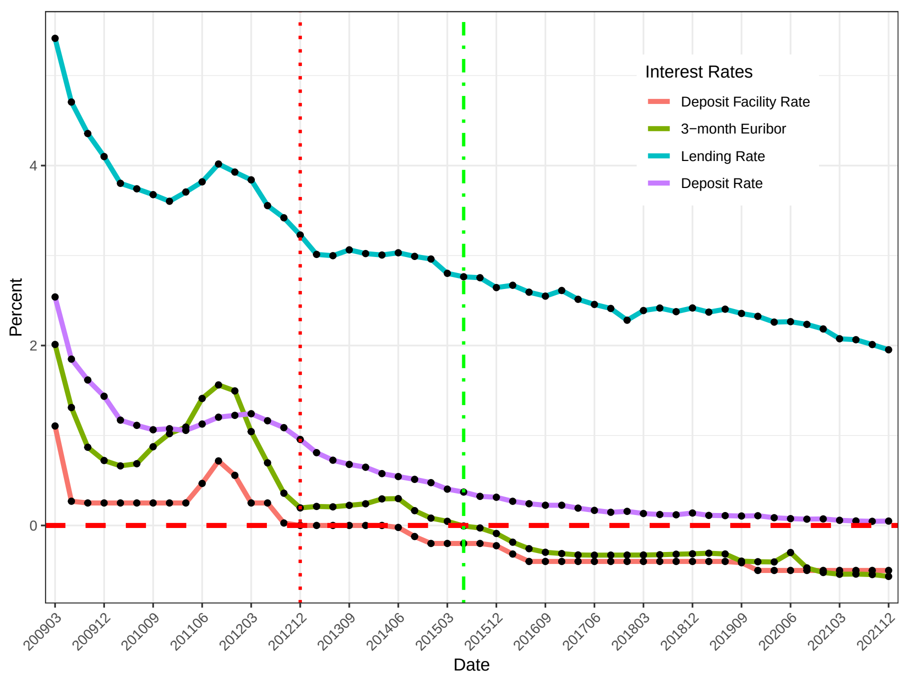
For the non-bank lending rate, we exclude interest income from cross-border loans and only consider euro-denominated loans to domestic customers. The main argument for excluding cross-border loans and foreign currency loans is the following. Banks may apply a different interest rate setting behavior and, in particular, follow different reference rates. Second, the non-bank deposit rate includes all interest expenses for non-bank deposits.

We are able to use the average interest rates on the outstanding volume of loans and deposits. Hence, our results show the "average" long-run transmission of the reference rates to the bank-specific interest rates. Some studies use interest rate data for new businesses. However, such data only capture a small fraction of the total volumes outstanding after the period. A significant portion of the existing loan contracts is renegotiated. Therefore, we argue that focusing on new businesses only captures a small portion of the effects of a change in reference rates. Further, modeling only lending rates for new businesses does not fit in the (second step of the) cointegration analysis.

In our panel VECM we can model the short run and the long run dynamics. This means that we model the interest rate setting behavior from one equilibrium to the next equilibrium, e.g., after a policy rate change. This interest rate setting behavior is characterized by short run dynamics (VECM part) that are "error corrected" by the long run equilibrium cointegration relationship. If we were to model new business only, then the economic interpretation of our results would change dramatically. The long run cointegration relationship would then be a short run interest rate setting behavior, and there would be no second part of the model that captures the long run dynamics.

Following Gambacorta (2008), we use the 3-month Euribor as the main reference rate. In some specifications, we include the ECB Deposit Facility Rate as an alternative.

Figure 1: Average Bank-specific Interest Rates and Reference Rates



Source: OeNB. Own calculations. ECB's Statistical Data Warehouse.
The figure shows the development of the average bank-specific deposit and lending rates, as well as the 3-month Euribor and the ECB Deposit Facility Rate. The dotted vertical line indicates when the ECB Deposit Facility Rate was set to 0%. The dot-dashed vertical line indicates when the 3-month Euribor crossed 0%.

2.2. *Bank-specific Explanatory Variables*

Heterogeneity across banks is known to influence the long-run pass-through equilibrium between rates, and the short-term adjustment dynamics (Kashyap et al., 1997; Gambacorta, 2008). To incorporate banks' heterogeneity into the cointegration analysis, we include many well-established bank-specific variables, taking advantage of the quality of the available bank-level data. Following Gambacorta (2008), these bank-specific variables aim to cover the interest rate channel, the credit risk channel, the bank lending channel, the bank capital channel, and the loan and deposit demand. We discuss the importance of including these bank-specific explanatory variables in Section 4.3.

Table 1: Summary statistics of included variables 2009-2021

Variable Name	Min.	1st Qu.	Median	Mean	3rd Qu.	Max	Data.Cov
Interest Rates							
Domestic non-bank lending rate	0.00	2.33	2.85	3.04	3.60	15.38	99.07
Non-bank deposit rate	-3.96	0.14	0.48	0.67	1.06	7.95	99.41
Δ LR	-2.66	-0.52	-0.18	-0.32	-0.01	2.31	97.07
Δ DR	-1.47	-0.26	-0.09	-0.19	-0.02	1.31	93.68
Bank Specific variables							
Log Total Assets	8.33	11.30	12.10	12.31	12.94	18.79	100.00
Share non-bank deposit	-0.00	0.73	0.80	0.76	0.84	1.00	98.66
Share sight deposits	0.00	20.59	28.38	35.10	43.00	100.00	99.04
Share CB deposits	0.00	0.00	0.00	0.25	0.00	79.18	100.00
Tier 1 ratio	4.65	12.17	15.95	16.98	20.89	48.04	96.59
Liquidity Ratio	0.00	2.16	6.70	9.13	13.47	53.02	98.62
LLP ratio	0.00	0.00	0.03	0.03	0.05	0.19	99.39
Net non-interest income ratio	-0.04	0.00	0.00	0.00	0.00	0.13	98.81
Reference rates							
3-month Euribor	-0.33	-0.19	0.22	0.41	0.87	2.01	100.00
ECB Deposit Facility Rate	-0.40	-0.32	0.00	0.02	0.25	1.11	100.00
Δ 3-month Euribor	-4.11	-0.62	-0.16	-0.54	0.01	0.73	100.00
Structural variables							
Inflation Rate	-0.38	0.43	1.35	1.27	2.02	2.94	100.00
Nominal GDP growth	-4.04	1.99	3.06	2.68	3.69	6.26	100.00

Sources: OeNB. ECB's statistical data warehouse.
The table shows the minimum (Min.), first quantile (1^{st} Qu.), the median (Median), mean (Mean), third quantile (3^{rd} Qu.), maximum (Max) and data coverage (Data Cov.)
The domestic non-bank lending rate refers to the effective interest rates (EBA, 2016) for the non-bank domestic loan portfolio of a bank. The non-bank deposit rate refers to the effective interest rate for all non-bank deposits.
Δ LR, the change in the domestic non-bank lending rate is defined as follows: $\Delta LR = LR_{i,t} - LR_{i,t-1}$. Δ DR, the change in the non-bank deposit rate is defined as follows: $\Delta DR = DR_{i,t} - DR_{i,t-1}$.
Log Total Assets is defined as the logarithm of total assets.
Share non-bank deposits is defined as non-bank deposits divided by total assets.
Share sight deposits is defined as the ratio of sight deposits over the sum of sight and term deposits.
Share CB deposits is defined as the share of central bank deposits divided by total assets.
Tier 1 ratio refers to the Tier 1 capital ratio, which is defined as Tier 1 capital divided by risk-weighted assets.
The LLP ratio refers to the loan loss provision ratio. The net non-interest income ratio is the sum of all non-interest income divided by total assets.
Δ 3-month Euribor is defined as: Δ3-month Euribor = 3-month Euribor$_t$ − 3-month Euribor$_{t-1}$.
Inflation rate refers to the year-on-year growth rate of the harmonized index of consumer prices. Nominal GDP growth refers to the year-on-year nominal GDP growth.

3. Legal and Theoretical Considerations

In this section, we highlight two important aspects that might influence the cointegration of lending and deposit rates in a negative interest rate environment. First, we discuss legal decisions concerning negative deposit rates for households and how negative reference rates have to pass on in floating-rate loan contracts. Second, we introduce negative reference rates in the bank optimization model of Klein (1971); Ho and Saunders (1981).

3.1. Legal Framework

Two important legal decisions by the Supreme Court of Justice in Austria could influence the cointegration of lending and deposit rates. First, based on the decision 5 Ob 138/09v of the Supreme Court of Justice in 2009, banks are not allowed to charge negative interest rates on savings accounts for households.[5] This court decision does not apply to savings accounts for companies and to checking accounts for all types of customers. Second, more recently, negative reference rates need to be passed on until the total lending rate reaches zero (Oberlandesgericht Innsbruck, 4 R 58/16k, July 14, 2016).

This second decision implies the following for the lending rate setting behavior in a typical floating rate loan contract in Austria, which has the following form:

$$LR_{i,t} = \max_{b_i} \{\text{3-month Euribor}_t + b_i, 0\}, \tag{1}$$

.

where $LR_{i,t}$ refers to the lending rate at time t. The 3-month Euribor$_t$ is the 3-month Euribor at time t, but could also be replaced by a different reference rate, and b_i is the bank-specific markup. A typical mark-up lies between 1-3 percentage points, mainly depending on the type of loan and the creditworthiness of the customer (Pichler and Jankowitsch, 2016).

Before the second court decision, banks tried to implement the following interest rate setting:

[5]See https://www.ris.bka.gv.at/Dokument.wxe?Abfrage=Justiz&Dokumentnummer=JJT_20091013_OGH0002_0050OB00138_09V0000_000&Suchworte=RS0037730 for more details.

$$LR^*_{i,t} = \max_{b_i} \{\text{3-month Euribor}_t, 0\} + b_i. \tag{2}$$

Clearly, the interest rate setting in Eq. (2) would have been more favorable for banks, since $LR^*_{i,t} \geq LR_{i,t}$.

Therefore, Supreme Court decisions are likely to cause an asymmetry in the way negative reference rates are passed on to lending and deposit rates and could affect the net interest rate margin (Kerbl and Sigmund, 2016). In this context, we can analyze the impact of negative reference rates on banks' net interest margins by examining their asymmetric interest rate setting behavior within the framework of cointegration. By taking into account the cointegration setting, we can enhance our understanding of the impact of negative reference rates on banks' net interest margins. A reduction in the pass-through from the deposit to lending rates hints at a smaller spread between the two rates, hence a thinner net interest margin. Moreover, the spread between the lending and deposit rates could also be reduced by a change in the markup b_i.

3.2. Banks' Optimization under Negative Interest Rates

We start with the model of Klein (1971); Ho and Saunders (1981) which assumes that the bank is a passive dealer that waits for the arrival of loans and deposits. To influence the probability of these arrivals, banks set a lending rate and a deposit rate:

$$LR_{i,t} = p_t + b_i \;, \tag{3a}$$

$$DR_{i,t} = p_t - a_i \;, \tag{3b}$$

$$s_{i,t} = LR_{i,t} - DR_{i,t} = a_i + b_i \;. \tag{3c}$$

$LR_{i,t}$ refers to the lending rate and $DR_{i,t}$ refers to the deposit rate of bank i at period t. Ho and Saunders (1981) call p_t the "true rate" of a loan/deposit and b_i would be the mark-up of the bank's lending rate over the "true rate" and a_i would be the mark-down of the bank's deposit rate over the "true rate". A bank tries to maximize b_i and a_i. In total, $s_{i,t} = a_i + b_i$ is the interest rate spread of a bank.

If $a_i < 0$, (as in our data), a bank will still want to maximize $s_{i,t}$, by trying to set $DR_{i,t}$ as closely as possible to p_t, that is, $\max_{a_i,b_i}\{a_i + b_i\} = \max_{a_i}\{a_i\} + \max_{b_i}\{b_i\}$ by linearity. If $a_i < 0$, then $DR_{i,t} > p_t$ and $\max_{a_i}\{a_i\} = \max_{DR_{i,t}}\{p_t - DR_{i,t}\} = \min_{DR_{i,t}}\{DR_{i,t} - p_t\}$.

Ho and Saunders (1981) assume that the arrival rate of new loans depends negatively on b and the arrival rate of deposits depends negatively on a_i. Thus, a lower lending rate attracts more loans (L) and a higher deposit rate attracts more deposits (D).

Although not originally intended, we argue that p_t could be the market reference rate (e.g., the 3-month Euribor or the ECB Deposit Facility Rate). Ho and Saunders (1981) complete their model by assuming that there exists a market where a bank can close any funding gap ($L - D \neq 0$) at a price p_t. This could be the interbank market in the euro area.

Assuming a certain type of utility function, Ho and Saunders (1981) solve their model and derive the optimal spread $s_{i,t}$:

$$s_{i,t} = a_i + b_i = \frac{\alpha}{\beta} + \frac{1}{2}R\sigma_1^2 Q \,. \tag{4}$$

$\frac{\alpha}{\beta}$ is the ratio of the intercept (α) and the slope (β) of the symmetric deposit and loan arrival functions of the bank. R is the bank's coefficient of absolute risk aversion. Q is the size of bank transactions and σ_1^2 refers to the "instantaneous" variance of the interest rate on deposits and loans.

Introducing negative policy rates into this model is straightforward, as p_t could be set to a negative rate. Without legal or economic restrictions, this would not make much of a difference in this model. However, given the legal restriction in Austria described in Section 3.1 that banks cannot charge negative rates for household savings accounts, we must assume that $DR_{i,t} \geq 0$, which implies that a_i in Eq. (3b) is negative. Hence, the spread $s_{i,t} = a_i + b_i$ is reduced. In terms of the cointegration relationship between the lending rate and the deposit rate, this would imply that there would be no changes in the cointegration vector after the introduction of negative reference rates. However, the spread between the lending and deposit rates would be reduced. We refer to this as the "spread reduction hypothesis".

Furthermore, the second Supreme Court decision, imposing that p_t must be passed on even into negative territory, could decrease $LR_{i,t}$. One might argue that negative policy or reference rates in combination with Supreme Court decisions might change a bank's opinion on the "true prices" for loans and deposits. The true price for deposits ($p_{D,t}$) might be zero. The true price for loans ($p_{L,t}$) could even be negative, since the reference rates must be passed on to negative territories. The adjusted spread might then be $s^*_{i,t} = a_i + b_i + p_{L,t} - p_{D,t}$ with $p_{L,t} < 0$ and $p_{D,t} \approx 0$. In this case, also the cointegrating vector between the lending rate and the deposit rate would change after the introduction of negative reference rates. We call this hypothesis the "two true prices hypothesis".

If the "two true prices hypothesis" materialized, we would calculate the spread between $LR_{i,t}$ and $DR_{i,t}$ based on Eq. (3a) and Eq. (3b) as follows:

$$LR_{i,t} = p_{L,t} + a_i + b_i - p_{D,t} + DR_{i,t} \ . \tag{5}$$

If we further assume that $p_{L,t}$ is close to the 3-month Euribor, $p_{D,t}$ is close to 0 in a negative interest environment, and we add some stochastic in the form of an error term, then the resulting equation looks like the cointegration relationship in Eq. (8a).

In Section 6, when we analyze the cointegration relationship between the lending rate and the deposit rate in a negative interest rate environment, we test the "spread reduction hypothesis", the "two true prices hypothesis" and both hypotheses in different empirical specifications.

4. Empirical Approach

In this section, we provide a detailed description of our application of the two-step procedure for cointegration analysis proposed by Engle and Granger (1987) to examine the relationship between the bank-specific lending rate, the bank-specific deposit rate, and the 3-month Euribor. In Section 4.1, we discuss which panel unit root test we apply to our bank-specific interest rates. In Section 4.2, we test for cointegration between bank-specific lending and deposit rates, as well as the 3-month Euribor. Then, we discuss how to estimate the cointegration relationship(s). This constitutes the first step in the cointegration analysis of Engle and Granger (1987) adjusted for our panel data. In Section 4.3, we describe how we estimate the second step in the cointegration analysis, namely, the panel VECM.

4.1. Unit Root Tests for Lending and Deposit Rates

An important requirement to establish the existence of cointegration between two or more variables is to test their stationarity and determine their integration order (Engle and Granger, 1987). Cointegration can only exist when two or more variables share the same order of integration, higher or equal to one. Hence, stationarity tests must be performed on all endogenous variables of interest.

The presence of a unit root in the context of panel data can be tested via adjusted testing procedures, similar to the augmented Dickey-Fuller. Among the available panel unit root tests, we choose the covariate-augmented Dickey-Fuller test proposed by Costantini and Lupi (2013). Their panel extension is based on the test introduced by Hansen (1995) and is found to have good size properties and higher testing power when confronted with alternative unit root panel tests. For testing purposes, we use the R codes proposed by Lupi (2010).

4.2. Cointegration between Lending and Deposit Rates

We perform the panel cointegration tests proposed by Kao (1999); Westerlund (2006); Pedroni (2001). We present the results of the cointegration tests of Pedroni (2001) in Section 5.2 and the other tests in Appendix A.

Following the cointegration test, we estimate the long-term equilibrium relationship using the Engle-Granger residual-based procedure, adapted for panel data. We normalize the direction of the cointegration relationship based on the banks' interest-setting behavior discussed in Section 3.

Hence, we set the lending rate as the dependent variable and the deposit rate and the reference rate as the independent variables. According to the literature, banks' rates can be interpreted as indicators of their interest income and expenses. The deposit rate, which affects the expense side of the balance sheet, serves as a proxy for the marginal cost of funding facing Austrian banks (Bernhofer and van Treeck, 2013). Since in our data, lending and deposit rates are volume-weighted interest rates for all loans and deposit types excluding the interbank market, connecting them in a cointegration relationship measures the average pass-through at the bank level.

The study by De Bondt et al. (2005) offers compelling evidence supporting the significance of deposits as a marginal buffer for funding lending in Austrian banks. The evidence supports the theory for which deposits can be used, at least in part, to fund lending activities and as such are a valid explanatory variable for loans. This claim is strengthened by the average balance sheet structure of Austrian banks. Since 2009, non-bank deposits have averaged approximately 76% of total assets.

From this perspective, the deposit rate serves as the basis for setting lending rates that adequately cover funding costs, risk, equity costs, and operating expenses. In other words, when funding costs – proxied by the deposit rate – rise, banks must raise lending rates (within competitive limits) to increase interest income sufficiently to offset the proportional cost increase and maintain a positive interest margin. Therefore, we estimate the following cointegration relationship:

$$LR_{i,t} = \mu_i + \beta_1 DR_{i,t} + \epsilon_{i,t} \ . \tag{6}$$

$LR_{i,t}$ refers to the lending rate of bank i at time t. $DR_{i,t}$ refers to the deposit rate of bank i at time t and μ_i is the fixed effect of bank i, which could be interpreted as the long-term equilibrium interest rate spread defined in Eq. (3c). β_1 is commonly known as the interest rate pass-through (Mark and Sul, 2003) or a long run multiplier (Kok and Werner, 2006).

The interpretation for the latter can be the following: a value of one indicates a 100% pass-through of changes in the deposit rate to the lending rate. A value below 1 suggests the presence of rigidities, as it implies that changes in deposit rates do not fully translate into corresponding adjustments in lending rates. A coefficient greater than 1 indicates a high degree of responsiveness of lending rates to changes in deposit rates, as even a slight change in deposit rates leads to a more than proportional adjustment in lending rates.

To account for the appearance of negative reference rates in the estimation of the cointegrating vector and test the two hypotheses derived in Section 3.2, we set up three additional cointegration models. In Eq. (7a), we introduce an interaction term that is the product of the dummy variable D^E and the deposit rate. The dummy variable D^E takes the value of 1 if the 3-month Euribor is negative and 0 otherwise. In this specification, we test the "two true prices" hypothesis. In Eq. (7b), we test the "spread reduction" hypothesis. In Eq. (7c), we test both hypotheses.

$$LR_{i,t} = \mu_i + \beta_1 \cdot DR_{i,t} + \gamma_1 \cdot D_t^E \cdot DR_{i,t} + \epsilon_{i,t} \ , \tag{7a}$$

$$LR_{i,t} = \mu_i + \beta_1 \cdot DR_{i,t} + \phi_1 \cdot D_t^E + \epsilon_{i,t} \ , \tag{7b}$$

$$LR_{i,t} = \mu_i + \beta_1 \cdot DR_{i,t} + \gamma_1 \cdot D_t^E \cdot DR_{i,t} + \phi_1 \cdot D_t^E + \epsilon_{i,t} \ . \tag{7c}$$

$LR_{i,t}$ refers to the lending rate. $DR_{i,t}$ refers to the deposit rate. μ_i is the fixed effect. D_t^E is a dummy variable, which takes the value of 1 when the 3-month Euribor is set below zero and 0 otherwise, and $\epsilon_{i,t}$ is the standard error term. Next, β_1 is the cointegrating vector. γ_1 measures the change in the cointegrating vector between the lending rate and the deposit rate under a negative 3-month Euribor. ϕ_1 measures the effect on the average spread between the lending rate and the deposit rate under a negative 3-month Euribor.

In the time series case, Stock (1987) shows that the OLS estimation of $\hat{\beta}_1$ is super consistent. However, Phillips and Hansen (1990) find that $\hat{\beta}_1$ might be biased in small samples. Therefore, originally for time series, Stock and Watson (1993) introduce the dynamic OLS estimator (DOLS). For panel data, Kao and Chiang (2001) suggest using the fixed effects DOLS estimator.[6] Consequently, we also estimate four fixed effects DOLS models in Appendix C

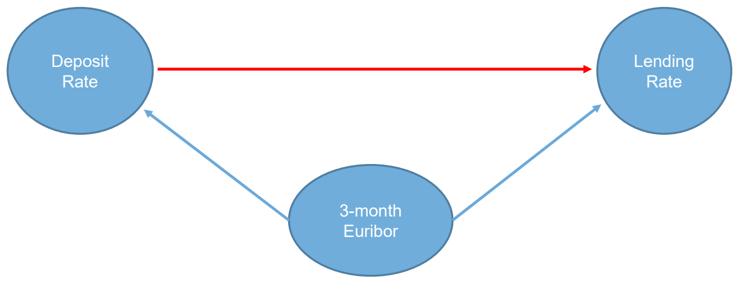
On the one hand, the literature suggests analyzing the cointegration between bank-specific rates and a reference rate. On the other hand, we suggest analyzing the cointegration between bank-specific lending and deposit rates in the above equations. In the next step, we combine both ideas in the following cointegration analysis.

To motivate our innovation, we follow Pearl (1995, 2009) and analyze the relationship between bank-specific lending rates, bank-specific lending rates, and the reference rate with a directed acyclic graph (DAG).[7] In Figure 2, we propose the following three-interest rate model. Each node represents a variable. The arrows connecting the nodes have a causal interpretation. The existing literature has already established the arrows from the 3-month Euribor to the deposit rate and from the 3-month Euribor to the lending rate (Gambacorta, 2008, among many others). We add, test, and estimate the arrow from the deposit rate to the lending rate to the literature.

[6] Wagner and Hlouskova (2009) provide a survey and comparison of alternative estimation methods which can be applied to cointegrated panels. In the restricted case of one cointegrating relationship, the fixed effects DOLS estimator shows the best performance compared to the fully modified OLS estimator suggested by Phillips and Moon (1999); Pedroni (2001).

[7] For an introduction to DAGs, see Cunningham (2021) and Huntington-Klein (2021).

Figure 2: Directed Acyclic Graph: Bank-specific Interest Rates and 3-month Euribor



This figure shows the directed acyclic graph of the bank-specific lending rate, the bank-specific deposit rate, and the 3-month Euribor. The directions of the arrows show the expected causal relationships between the variables.

To establish the causal effect of the bank-specific deposit rate and the bank-specific lending rate, we have to use *blocking* rules in the *backdoor criterion* stated by Pearl (2009).

A path between two random variables X and Y can be blocked by a set of conditioning variables Z as follows: (1) Along the path there is a chain ... $\rightarrow W \rightarrow$ ... or a fork ... $\leftarrow W \rightarrow$ ..., and W is in Z. (2) Along the path there is a collider ... $\rightarrow W \leftarrow$ ..., and neither W nor any of its descendants are in Z.

Backdoor criterion (Pearl et al., 2016): Given an ordered pair of variables (X, Y) in a DAG, a set of variables Z satisfies the backdoor criterion relative to (X, Y) if no variable in Z is a descendant of X, and Z blocks every path between X and Y that contains an arrow into X. The variables in Z are often called confounders.

Consequently, conditioning on a set Z that satisfies the backdoor criterion blocks all spurious paths between X and Y, creates no new spurious paths, and keeps the directed paths from X to Y open, thus identifying the causal effect of X on Y.

We now apply the backdoor criterion to the DAG in Figure 2. We have to block the path Lending Rate $\leftarrow$ 3-month Euribor $\rightarrow$ Deposit Rate to identify the total effect of the DR on the LR. Therefore, the only variable we include in

Z is the 3-month Euribor.[8] In the language of Pearl (2009), the 3-month Euribor is a confounder of bank-specific interest rates.

We are also interested in the total effect of the 3-month Euribor on the LR. Again, we apply the backdoor criterion. This time, we have to include no variable in Z. Since the DR can be seen as a mediator along the path 3-month Euribor → DR → LR, we can also estimate the direct effect of the 3-month Euribor on the LR by blocking the path through the DR.

Next, we explain why the arrows in Figure 2 do not point in opposite directions. It is safe to assume that the bank-specific deposit rate and the bank-specific lending rate of an Austrian bank do not cause the 3-month Euribor. Hence, there is no reverse causality.[9]

The arrow from the bank-specific deposit to the lending rate is debatable. There are different views on this relationship. We provide empirical evidence that there is no reverse causality with our DOLS results in Appendix C and also in Appendix B by applying more advanced causal graphs. De Bondt et al. (2005) find similar empirical evidence for DR → LR in Austria, comparing banks from many European countries.

Furthermore, the bank-specific deposit rate is a mediator for the 3-month Euribor, since it also connects the 3-month Euribor with the bank-specific lending rate via the bank-specific deposit rate. Such a mediator is useful since we can distinguish between total, direct, and indirect 3-month Euribor effects on the bank-specific lending rate (VanderWeele, 2015). We define the indirect 3-month Euribor effects as effects mediated by an adjustment of the bank-specific deposit rate. Since our models are linear, the total 3-month Euribor effect is the sum of the direct and indirect effects. The (net) indirect 3-month Euribor effect is, therefore, the difference between the total and the direct 3-month Euribor effect.

Our identification strategy is non-parametric and for a given DAG, an arrow can be identified or not. Our identification strategy is also independent of the estimation framework. We decide to estimate the total effect of the DR on the LR by a linear fixed effects model. The following four specifications also identify the direct 3-month Euribor effect on the LR:

[8] In empirical economics, the concept of endogeneity bias is similar to confounding. In Eq. (6), a shock to the 3-month Euribor would be captured by $\epsilon_{i,t}$, which, most likely, is correlated with $LR_{i,t}$ and $DR_{i,t}$ causing an endogeneity bias.

[9] Also, around 70% of all Austrian loans to the private sector are contractually linked to the 3-month Euribor or a closely related reference rate. The same hold true for many deposit accounts.

$$LR_{i,t} = \mu_i + \beta_1 DR_{i,t} + \beta_2 E_t + \epsilon_{i,t} \ , \tag{8a}$$

$$LR_{i,t} = \mu_i + \beta_1 DR_{i,t} + \beta_2 E_t + \gamma_1 \cdot D_t^E \cdot DR_{i,t} + \gamma_2 \cdot D_t^E \cdot E_t + \epsilon_{i,t} \ , \tag{8b}$$

$$LR_{i,t} = \mu_i + \beta_1 DR_{i,t} + \beta_2 E_t + \phi_1 D_t^E + \epsilon_{i,t} \ , \tag{8c}$$

$$LR_{i,t} = \mu_i + \beta_1 DR_{i,t} + \beta_2 E_t + \gamma_1 \cdot D_t^E \cdot DR_{i,t} + \gamma_2 \cdot D_t^E \cdot E_t + \phi_1 D_t^E + \epsilon_{i,t} \ . \tag{8d}$$

$LR_{i,t}$ refers to the lending rate, $DR_{i,t}$ refers to the deposit rate, and E_t refers to the 3-month Euribor. μ_i is the fixed effect. D_t^E is a dummy variable, which takes the value of 1 when the 3-month Euribor is set below zero and 0 otherwise. Next, $\beta = (\beta_1, \beta_2)$ is the cointegrating vector and $\epsilon_{i,t}$ is the standard error term. γ_1 measures the change in the cointegration relationship between the lending rate and the deposit rate under a negative 3-month Euribor. γ_2 measures the change in the cointegration relationship between the lending rate and the 3-month Euribor under a negative 3-month Euribor. ϕ_1 measures the effect on the average spread between the lending rate and the deposit rate under the negative reference rate.

Again, we can test our two hypotheses with the above specifications. By conducting tests on the "two true prices" hypothesis presented in Eq. (8b) and Eq. (8d), we can precisely identify the entries of the cointegrating vector that undergo changes.[10]

Furthermore, we also estimate the total effect of the 3-month Euribor on the bank-specific lending rate, which implies leaving out $DR_{i,t}$ and all interaction terms with $DR_{i,t}$ in Eq. (8):

$$LR_{i,t} = \mu_i + \beta_1 E_t + \epsilon_{i,t} \ , \tag{9a}$$

$$LR_{i,t} = \mu_i + \beta_1 E_t + \gamma_1 \cdot D_t^E \cdot E_t + \epsilon_{i,t} \ , \tag{9b}$$

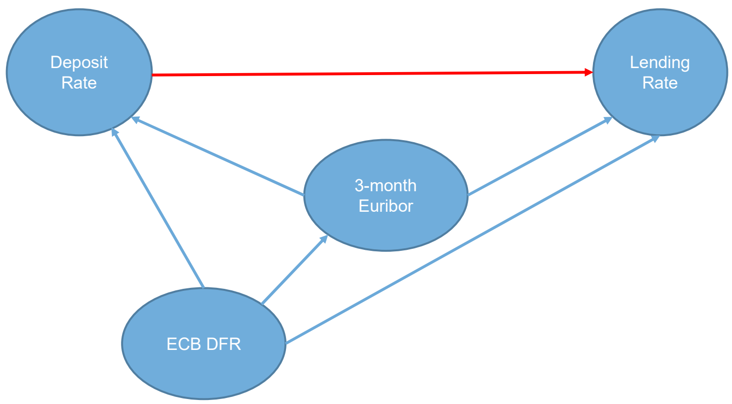
$$LR_{i,t} = \mu_i + \beta_1 E_t + \phi_1 D_t^E + \epsilon_{i,t} \ , \tag{9c}$$

$$LR_{i,t} = \mu_i + \beta_1 E_t + \gamma_1 \cdot D_t^E \cdot E_t + \phi_1 D_t^E + \epsilon_{i,t} \ . \tag{9d}$$

[10] It is important to note that we do not implement a "DOLS" version of Eq. (8), since in Appendix B we provide empirical evidence that there is no reverse causality from the bank-specific lending rate to the deposit rate.

In Figure 3, we extend the DAG in Figure 2 by including the ECB DFR and the 3-month Euribor. Although the DAG in Figure 3 is the more comprehensive model, we can justify using the DAG in Figure 2 if the "direct effect" of the ECB DFR on the deposit and lending rate is small. This would mean that the effects of the ECB DFR are mainly mediated through the 3-month Euribor (i.e., indirect effect). In Section 6.4, we will show that this is the case until the negative interest rate environment.

Figure 3: Directed Acyclic Graph: Bank-specific Interest Rates, ECB DFR 3-month Euribor



This figure shows the directed acyclic graph of the bank-specific lending rate (LR), the bank-specific deposit rate (DR), the 3-month Euribor, and the ECB DFR. The directions of the arrows show the expected causal relationships between the variables.

After applying the backdoor criterion, the direct effects of the ECB DFR, the 3-month Euribor, and the deposit rate on the bank-specific lending rate can be estimated as follows:

$$LR_{i,t} = \mu_i + \beta_1 DR_{i,t} + \beta_2 E_t + \beta_3 DFR_t + \epsilon_{i,t} \ , \tag{10a}$$

$$LR_{i,t} = \mu_i + \beta_1 DR_{i,t} + \beta_2 E_t + \beta_3 DFR_t + \gamma_1 D_t^E DR_{i,t} + \gamma_2 D_t^E E_t + \gamma_3 D_t^D DR_{i,t} + \gamma_4 D_t^D DFR_t + \epsilon_{i,t} \ , \tag{10b}$$

$$LR_{i,t} = \mu_i + \beta_1 DR_{i,t} + \beta_2 E_t + \beta_3 DFR_t + \phi_1 D_t^E + \phi_2 D_t^{DFR} + \epsilon_{i,t} \ , \tag{10c}$$

$$\begin{aligned} LR_{i,t} = {} & \mu_i + \beta_1 DR_{i,t} + \beta_2 E_t + \beta_3 DFR_t + \gamma_1 D_t^E DR_{i,t} + \gamma_2 D_t^E E_t + \gamma_3 D_t^D DR_{i,t} + \gamma_4 D_t^D DFR_t + \\ & \phi_1 D_t^E + \phi_2 D_t^{DFR} + \epsilon_{i,t} \ , \end{aligned} \tag{10d}$$

where D_t^{DFR} is a dummy variable that takes the value 1 if the ECB DFR is negative and 0 otherwise. All other variables are defined as in Eq. (8). To estimate the total 3-month Euribor effects on the lending rate, we drop all variables related to the deposit rate from Eq. (10) and estimate the now-familiar four models.

4.3. Panel Vector Error Correction Model

The panel vector autoregressive model (PVAR) was introduced by Holtz-Eakin et al. (1988). We employ an extension of this model to allow for p lags of m endogenous variables, k predetermined variables, and n strictly exogenous variables as described in Sigmund and Ferstl (2021).

$$\mathbf{y}_{i,t} = \zeta_i + \sum_{l=1}^{p} \mathbf{A}_l \mathbf{y}_{i,t-l} + \mathbf{B}\mathbf{x}_{i,t} + \mathbf{C}\mathbf{s}_{i,t} + \epsilon_{i,t} \ , \tag{11}$$

where $\mathbf{y}_{i,t} \in \mathbb{R}^m$ is a $m \times 1$ vector of endogenous variables for bank i^{th} cross-sectional unit in period t. Moreover, $\mathbf{y}_{i,t-l} \in \mathbb{R}^m$ is a $m \times 1$ vector of lagged endogenous variables. Next, $\mathbf{x}_{i,t} \in \mathbb{R}^k$ is a $k \times 1$ vector of predetermined variables that are potentially correlated with past errors. Moreover, $\mathbf{s}_{i,t} \in \mathbb{R}^n$ is an $n \times 1$ vector of strictly exogenous variables that neither depend on ϵ_t nor on ϵ_{t-s} for $s = 1, ..., T$. The disturbances $\epsilon_{i,t}$ are independently and identically distributed (i.i.d.) for all i and t with $\mathbb{E}[\epsilon_{\mathbf{i,t}}] = 0$ and $Var[\epsilon_{i,t}] = \Sigma_\epsilon$. Σ_ϵ is a positive semi-definite matrix.

For the second step in the cointegration procedure, which is based on our first-step cointegration specification in Eq. (6), we adjust Eq. (11) to our setting in the following way:

$$\begin{bmatrix} \Delta LR_{i,t} \\ \Delta DR_{i,t} \end{bmatrix} = \zeta_i + \Pi \begin{bmatrix} LR_{i,t-1} \\ DR_{i,t-1} \end{bmatrix} + \sum_{l=1}^{p} \Omega_l \begin{bmatrix} \Delta LR_{i,t-l} \\ \Delta DR_{i,t-l} \end{bmatrix} + CX_{i,t} + \epsilon_{i,t} \ . \tag{12}$$

The term $\Pi \begin{bmatrix} LR_{i,t-1} \\ DR_{i,t-1} \end{bmatrix}$ can be expressed in the error correction form based on the residuals from the first step in Eq. (6).[11]

$$\Pi \begin{bmatrix} LR_{i,t-1} \\ DR_{i,t-1} \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} \begin{bmatrix} LR_{1,i,t-1} & -\beta_1 DR_{2,i,t-1} - \mu_i \end{bmatrix} = \alpha EC_{i,t-1} \ . \tag{13}$$

The Π matrix is the product of the speed of adjustment coefficients (α_1, α_2) and long-run equilibrium coefficient β_1. Hence, the Π matrix can be interpreted as a relative adjustment measure, which indicates on average how banks' lending rates react to changes in deposit rates. Since the residuals in Eq. (13) are already lagged by one quarter, we treat the variables $EC_{i,t-1}$ as exogenous in the PVAR specification of Eq. (11).

The signs of the loading coefficients α_1 and α_2 are an important feature of a VECM when representing a cointegration model. Given that we are modeling the dynamics of interest rates around a long-run equilibrium, the signs of speed of adjustment coefficients (α_1, α_2) should act to bring the bank-specific interest rates back to their equilibrium levels. When the lending rate is "above" the equilibrium, the distance to the deposit rate is greater than in equilibrium, meaning the residuals are positive. We would expect a negative α_1 such that the lending rate decreases. The negative sign of its adjustment coefficients multiplied by the positive residuals ceteris paribus causes a negative $\Delta LR_{i,t}$, which reduces $LR_{i,t}$. On the contrary, when the lending rate falls below equilibrium, and the residuals are negative, the negative sign of the adjustment coefficients multiplied by the residuals suggests a positive $\Delta LR_{i,t}$ such that the distance between the two rates moves back to the long-run equilibrium.

The opposite reasoning holds for the deposit rate and its adjustment coefficients. Consider the same two scenarios, respectively, below and above equilibrium. Provided that we are inspecting only the deposit rate movements, when above equilibrium, with positive residuals, which means that the deposit rate is too small, the change in the

[11] If the residuals from Eq. (7a), Eq (7b), Eq (7c) or any of the DOLS specifications in Eq.(C.1) are used, then the error correction form has to be adjusted accordingly. If we use the three-variable cointegration specification from Eq. (8), then we need to include the $Euribor_t$ in Eq. (12) and adjust Eq. (13) accordingly.

deposit rate needs to be positive to reduce disequilibrium. Therefore, we would expect a positive coefficient of α_2. Similarly, when below equilibrium, causing negative residuals, the deposit rate would need to decrease further to increase the distance from the lending rate. Given the negative sign of the residuals, the "downward" movement of the deposit rate can be achieved if α_2 is positive.

Ω_l is a coefficient matrix for the l$^{\text{th}}$ lagged first differences of the lending rate and the deposit rate. We determine the optimal lag length p by the model selection procedure of Andrews and Lu (2001). Banks typically adjust their lending and deposit rates gradually over time. We expect positive autocorrelation for $\Delta LR_{i,t-l}$ in the ΔLR-equation and also positive autocorrelation for $\Delta DR_{i,t-l}$ in the ΔDR-equation. In this part, we deviate from Gambacorta (2008), since they interact bank-specific variables with the policy interest rates to account for bank-specific heterogeneity. However, since we utilize the bank-specific deposit rate, incorporating such interaction terms is not necessary, thereby avoiding the issue of overfitting. All lagged dependent variables ($\Delta LR_{i,t-l}$, $\Delta DR_{i,t-l}$ for $l = 1, ..., p$) are treated as lagged endogenous variables in the PVAR specification.

The off-diagonal elements (coefficients) of the matrix Ω_l, which are the coefficients of $\Delta DR_{i,t-l}$ in the ΔLR-equation and the coefficients of $\Delta LR_{i,t-l}$ in the ΔDR-equation, have to be seen in combination with the coefficients of the change in the 3-month Euribor and its lags. We expect negative coefficients since banks can only gradually adjust their lending and deposit rates, respectively, if there are shocks to these bank-specific rates.

Following Gambacorta (2008), it is important to include additional explanatory variables $X_{i,t}$ in the VECM model specifications. First, we address the "interest rate channel" by including the change in the 3-month Euribor and its lags. Following the empirical results of Borio and Hofmann (2017); Claessens et al. (2018); Raunig and Sigmund (2022), which provide evidence that the negative interest rate environment has had a negative influence on the return on assets of banks and the net interest margin, we also include a dummy variable that takes the value of 1 if the 3-month Euribor is negative and 0 otherwise.

We also include the logarithm of total assets as an indicator of banks' size. Bank size and balance sheet structure are regarded by the literature as a proxy of competition in the banking sector (Berlin and Mester, 1999; Cottarelli and Kourelis, 1994) and as a key determinant of banks' product pricing. Then, we add the liquidity ratio constructed as the sum of cash reserves and bonds over total assets. Higher levels of liquidity are expected to protect banks from shocks, translating to a slower adjustment speed (Kashyap et al., 2002).

Next, we include the loan loss provision ratio divided by total assets. The loan loss provision ratio serves as a measure of credit risk. As stated by Gambacorta (2008), the lending rate depends on the riskiness of the loan portfolio.

To control for the business model of a bank, we add the net non-interest income ratio. We then include the share of sight deposits that can be withdrawn on short notice and the share of central bank deposits to control for the funding structure of a bank. Finally, we include inflation and nominal GDP growth to account for the macroeconomic environment.

Moreover, Berlin and Mester (1999) state that banks that heavily depend on non-bank deposit funding adjust their deposit rates by less (and more slowly) than banks whose liabilities are more affected by market movements. Consequently, we include the lagged share of non-bank deposits in our VECM specifications. Since 2014, some banks have relied heavily on the long-term targeted refinancing operations offered by the ECB. To measure this influence on the growth rates of lending and deposit rates, we add the share of central bank deposits in total assets to our VECM specifications. We also include the share of sight deposits in our specifications. Sight deposits generally offer lower interest rates and can be withdrawn from a bank without notice or after a very short notice period.

Additionally, Gambacorta (2008) suggests measuring the influence of the "bank capital channel" by the Tier 1 capital ratio. To avoid any endogeneity issues, we lag these bank-specific variables by one quarter and include them as exogenous variables in the PVAR specification.

To capture loan and deposit demand, we include nominal GDP growth and inflation. We expect a positive coefficient of nominal GDP growth in the ΔLR-equation, since under better economic conditions, the number of projects becoming profitable in terms of expected net present value increases (Kashyap et al., 1993). On the other hand, in the ΔDR-equation Gambacorta (2008) argues that a higher level of income increases the demand for deposits and ceteris paribus, banks can set lower rates and attract the same volume of deposits. In theory, inflation should increase interest rates, especially the deposit rate, but high inflation might also result in an increase in policy rates which tend to reduce the demand for loans and hence reduce lending rates.

5. Panel Unit Root and Cointegration Tests

In this section, we present the first part of our empirical results. After establishing that the non-bank lending rate and the bank-specific deposit rate are integrated of order one, we run several cointegration tests. We test for a cointegration relationship between the bank-specific lending rate and the bank-specific deposit rate in Section 5.2.

We also test the cointegration relationships between the bank-specific interest rates and the ECB Deposit Facility Rate, as well as the 3-month Euribor. These cointegration test results are presented in Section 5.3. In Section 5.4, we conduct a comprehensive analysis to explore the possibility of a three-variable cointegration relationship between the bank-specific interest rates and the 3-month Euribor. In Section 5.5, we establish a four-variable cointegration relationship between the bank-specific interest rates, the 3-month Euribor, and the ECB DFR. In summary, all panel cointegration tests reject the null hypothesis of no cointegration against the alternative that all panels are cointegrated. Hence, we do not report cointegration tests that have the alternative hypothesis that some panels present cointegration.

5.1. Panel Unit Root Tests

Before we test for cointegration between the non-bank deposit rate and the non-bank lending rate, we need to check if both rates are integrated of the same order. To find empirical evidence for the presence of a unit root in both bank-specific interest rates, we apply the covariate-augmented Dickey-Fuller test proposed by Costantini and Lupi (2013) with the R-package developed by Lupi (2010). This test allows for cross-correlation between individuals.

In Table 2, we report the test results. The null hypothesis of the test posits the existence of a unit root, in contrast to the alternative hypothesis, which asserts the absence of a unit root. For both interest rates, the resulting p-values are well above 10%. Hence, the tests do not reject the null hypothesis of a unit root in the non-bank lending and the bank-specific deposit rate.

Table 2: Panel Unit Root Tests

Panel C-ADF				
H_0:	Unit Root	Number of panels=	565	
H_a:	No Unit Root	Avg. number of periods=	38.45	
		t- statistic	p-value	max. lags
Non-bank deposit rate		0.73	0.77	4
Non-bank lending rate		0.43	0.67	4

Source: OeNB. Own calculations.
Panel extension of the covariate-augmented Dickey-Fuller test proposed by Costantini and Lupi (2013) on the base of Hansen (1995). We use the R package of Lupi (2010) to obtain the test results.
We test for a unit root in the non-bank lending rate and in the non-bank deposit rate.

5.2. *Cointegration Tests: Bank-specific Lending and Deposit Rates*

In this section, we test the cointegration relationship between the bank-specific lending and deposit rates with the Pedroni panel cointegration tests (Pedroni, 1999, 2004). All tests confirm the presence of cointegration.[12]

Table 3: Pedroni Panel Cointegration test: Bank-specific Lending and Deposit Rates.

Pedroni test for cointegration			
H_0:	No cointegration	Number of panels=	509
H_a:	All panels are cointegrated	Avg. number of periods=	44.686
Cointegrating vector:	Panel specific		
Panel means:	Included	Kernel:	Bartlett
Time trend:	Included	Lags:	0.00 (Newey-West)
AR parameter:	Panel specific	Augmented lags:	1
Cross-sectional means removed			
		Statistic	p-value
Modified Phillips-Perron t		−65.1019	0.0000
Phillips-Perron t		−81.9102	0.0000
Augmented Dickey-Fuller t		−73.3223	0.0000

Source: OeNB. Own calculations.
Test based on Pedroni (1999, 2004).
Software implementation via STATA comand xtcointtest pedroni.
Pedroni's test is characterized by the panel-specific cointegrating vector and AR parameter.
For each of the three test types applied, multiple specifications have been tested for robustness, all of which support the cointegration hypothesis. The current test includes a time trend and excludes cross-sectional means.

[12] Additional test results based on Kao (1999) and Westerlund (2005) are presented in Appendix A.

5.3. *Cointegration Tests: Bank-specific Interest Rates with Reference Rates*

We then test the cointegration between bank rates and reference rates. In the first part of Table 4, we test for cointegration between the lending rate and the 3-month Euribor. In the second part, we test for cointegration between the lending rate and the ECB Deposit Facility Rate. In Table 5, we repeat the cointegration tests but replace the lending rate with the deposit rate. As above, we only report results from Pedroni's cointegration test, which all confirm the presence of cointegration between each bank's rates and the reference rates.

Table 4: Pedroni Cointegration tests: Bank-specific Lending Rates and Reference Rates

1. Lending rate and 3-month Euribor			
H_0:	No cointegration	Number of panels=	509
H_a:	All panels are cointegrated	Avg. number of periods=	44.99
Cointegrating vector:	Panel specific		
Panel means:	Included	Kernel:	Bartlett
Time trend:	Included	Lags:	3.00 (Newey-West)
AR parameter:	Panel specific	Augmented lags:	1
Cross-sectional means removed			
		Statistic	p-value
Modified Phillips-Perron t		−50.0170	0.0000
Phillips-Perron t		−72.9308	0.0000
Augmented Dickey-Fuller t		−67.4798	0.0000
2. Lending rate and ECB Deposit Facility Rate			
H_0:	No cointegration	Number of panels=	509
H_a:	All panels are cointegrated	Avg. number of periods=	44.99
Cointegrating vector:	Panel specific		
Panel means:	Included	Kernel:	Bartlett
Time trend:	Included	Lags:	3.00 (Newey-West)
AR parameter:	Panel specific	Augmented lags:	1
Cross-sectional means removed			
		Statistic	p-value
Modified Phillips-Perron t		−50.0170	0.0000
Phillips-Perron t		−72.9308	0.0000
Augmented Dickey-Fuller t		−67.4798	0.0000

Data sources: OeNB. Own calculations.
The tests are based on Pedroni (1999, 2004). We apply the STATA comand "xtcointtest pedroni".
Pedroni's test is characterized by the panel-specific cointegrating vector and an AR parameter.
For each of the three test types applied, multiple specifications have been tested for robustness, all of which support the cointegration hypothesis. The current test includes a time trend and excludes cross-sectional means.

Table 5: Pedroni Cointegration tests: Bank-specific Deposit Rates and Reference Rates

1. Deposit rate and 3-month Euribor			
H_0:	No cointegration	Number of panels=	509
H_a:	All panels are cointegrated	Avg. number of periods=	44.695
Cointegrating vector:	Panel specific		
Panel means:	Included	Kernel:	Bartlett
Time trend:	Included	Lags:	3.00 (Newey-West)
AR parameter:	Panel specific	Augmented lags:	1
Cross-sectional means removed			
		Statistic	p-value
Modified Phillips-Perron t		−28.0769	0.0000
Phillips-Perron t		−49.5344	0.0000
Augmented Dickey-Fuller t		−15.9710	0.0000
2. Deposit rate and ECB Deposit Facility Rate			
H_0:	No cointegration	Number of panels=	509
H_a:	All panels are cointegrated	Avg. number of periods=	44.695
Cointegrating vector:	Panel specific		
Panel means:	Included	Kernel:	Bartlett
Time trend:	Included	Lags:	3.00 (Newey-West)
AR parameter:	Panel specific	Augmented lags:	1
Cross-sectional means removed			
		Statistic	p-value
Modified Phillips-Perron t		−13.4533	0.0000
Phillips-Perron t		−28.8531	0.0000
Augmented Dickey-Fuller t		−51.4717	0.0000

Data sources: OeNB. Own calculations.
Test based on Pedroni (1999, 2004).
Software implementation via STATA comand xtcointtest pedroni.
Pedroni's test is characterized by the panel-specific cointegrating vector and AR parameter.
For each of the three test types applied, multiple specifications have been tested for robustness, all of which support the cointegration hypothesis. The current test includes a time trend and excludes cross-sectional means.

5.4. Cointegration Tests: Bank-specific Interest Rates and 3-month Euribor

In Table 6, we establish a cointegration relationship between the bank-specific interest rates and the 3-month Euribor. From a mathematical standpoint, there can exist only one single cointegration relationship involving all three variables. Otherwise, we would be required to place zero restrictions on the matrix Π in Eq. (12) (Luetkepohl, 2006), which would preclude the existence of a cointegration relationship among these three variables.[13]

[13] A typical identifying restriction for three endogenous variables and two cointegrating vectors would be the following $\begin{pmatrix} 1 & 0 & \beta_1 \\ 0 & 1 & \beta_2 \end{pmatrix}$.

Table 6: Pedroni Three-variable Cointegration Test: Bank-specific Interest Rates, and 3-month Euribor

Pedroni test for cointegration			
H_0:	No cointegration	Number of panels=	509
H_a:	All panels are cointegrated	Avg. number of periods=	44.686
Cointegrating vector:	Panel specific		
Panel means:	Included	Kernel:	Bartlett
Time trend:	Included	Lags:	0.00 (Newey-West)
AR parameter:	Panel specific	Augmented lags:	1
Cross-sectional means removed			
		Statistic	p-value
Modified Phillips-Perron t		−33.3985	0.0000
Phillips-Perron t		−41.8611	0.0000
Augmented Dickey-Fuller t		−30.8766	0.0000

Source: OeNB. Own calculations.
Test based on Pedroni (1999, 2004).
Software implementation via STATA comand xtcointtest pedroni.
Pedroni's test is characterized by the panel-specific cointegrating vector and AR parameter.
For each of the three test types applied, multiple specifications have been tested for robustness, all of which support the cointegration hypothesis. The current test includes a time trend and excludes cross-sectional means.

5.5. Cointegration Tests: Bank-specific Interest Rates, 3-month Euribor, and ECB Deposit Facility Rate

In Table 7, we establish a cointegration relationship between the bank-specific interest rates, the 3-month Euribor, and the ECB Deposit Facility Rate. For the moment, we assume that there is only one cointegration relationship. From a mathematical standpoint, there can exist only one single cointegration relationship involving all four variables. Otherwise, we would be required to place zero restrictions on the matrix Π in Eq. (12), which would preclude the existence of a cointegration relationship including all four variables (Luetkepohl, 2006).

Table 7: Pedroni Four-variable Cointegration Test: Bank-specific Interest Rates, 3-month Euribor, and ECB DFR

Pedroni test for cointegration			
H_0:	No cointegration	Number of panels=	509
H_a:	All panels are cointegrated	Avg. number of periods=	44.686
Cointegrating vector:	Panel specific		
Panel means:	Included	Kernel:	Bartlett
Time trend:	Included	Lags:	0.00 (Newey-West)
AR parameter:	Panel specific	Augmented lags:	1
Cross-sectional means removed			
		Statistic	p-value
Modified Phillips-Perron t		−16.2215	0.0000
Phillips-Perron t		−27.5766	0.0000
Augmented Dickey-Fuller t		−34.5615	0.0000

Source: OeNB. Own calculations.
Test based on Pedroni (1999, 2004).
Software implementation via STATA comand xtcointtest pedroni.
Pedroni's test is characterized by the panel-specific cointegrating vector and AR parameter.
For each of the three test types applied, multiple specifications have been tested for robustness, all of which support the cointegration hypothesis. The current test includes a time trend and excludes cross-sectional means.

6. Cointegration Models

In this section, we estimate our cointegration models introduced in Section 4.2 where the results of the two-interest rate cointegration models are necessary steps to understand the importance of the three- and four-interest rate cointegration models. The aim is to test the two hypotheses proposed in Section 3.2, namely the "spread reduction hypothesis" and the "two true prices hypothesis".

In Section 6.1, we present the results on the pass-through between the bank-specific deposit rate and the bank-specific lending rate. Since we deal with two bank-specific interest rates, we estimate these specifications with the fixed effects estimator. Given our DAG in Figure 2, these results are confounded due to the endogeneity bias caused by leaving out the 3-month Euribor as shown in Section 6.2.

In Section 6.2, we estimate the pass-through between the 3-month Euribor and the bank-specific interest rates separately.[14] This has been done in the literature before, and we confirm the endogeneity bias in the results of Section 6.1. The results for the pass-through between the 3-month Euribor and the bank-specific lending rate give us the total effect of the 3-month Euribor on the bank-specific lending rate.

[14] In Appendix D, we estimate the pass-through between the ECB Deposit Facility Rate and the bank-specific interest rates.

Therefore, we estimate the unconfounded cointegrating vector for the bank-specific lending rate, the bank-specific deposit rate, and the 3-month Euribor in Section 6.3. These results also provide us with the direct effect of the 3-month Euribor on the bank-specific lending rate.

In Section 6.4, we use the DAG in Figure 3 to estimate the four-variable cointegrating vector between the lending rate, the deposit rate, the 3-month Euribor, and the ECB Deposit Facility Rate. We show that the ECB DFR is completely mediated through the 3-month Euribor. Only in a negative interest rate environment, we estimate direct effects of the ECB DFR on the bank-specific lending rates. We argue that this could be due to the impact of the targeted long-term refinancing operations (TLTROs).

6.1. Cointegration between Bank-Specific Lending and Deposit Rates

In this section, we present the results of the cointegration relationship between bank-specific lending and deposit rates. These results are the first step of the Engle-Granger procedure. Our main focus is on testing the two hypotheses proposed in Section 3.2, namely the "spread reduction hypothesis" and the "two true prices hypothesis".

In Table 8, we present the results for the fixed effects models specified in Eq. (6) and Eq. (7). We estimate a cointegration coefficient β (coefficient of the deposit rate) which is above one in all models. Following the discussion in Section 4.2 this suggests an overreaction of the lending rate, i.e., a change in the deposit rate causes a more than proportional change in the lending rate.

The estimated pass-through depends on the composition of loans in Austrian banks. Both Kok and Werner (2006) and De Graeve et al. (2007) find that the pass-through changes depending on the maturity of the products considered. In particular, mortgage loans, which have higher maturity, are found to have a pass-through higher than 1.

In the second column (FE Model 2), we test the "two prices hypothesis" separately, i.e., a change in the cointegration relationship under a negative 3-month Euribor. We find a statistically significant negative coefficient for "D^E x Non-bank DR", which would imply a "lower" pass-through between the bank-specific lending and deposit rate under a negative 3-month Euribor. The coefficient of "Non-bank DR" is 1.1944 and then we deduct -0.1530 if the 3-month Euribor is negative, which results in a pass-through of around 1.04. Given the legal and theoretical arguments in Section 3.1 and Section 3.2, we expected such a reduction.

In "FE Model 3", we test the "spread reduction" hypothesis. The coefficient of D^E is highly statistically significant and negative. Thus, we again observe a reduction in the interest rate spread as predicted by our previously mentioned legal and theoretical arguments, which is picked up by the dummy D^E. We note that the coefficients of the "intercept" (the average of all bank-specific fixed effects) and the "Non-bank DR" change compared to the "FE Model 1" and the "FE Model 2".

However, to finally assess whether the "two prices hypothesis", "spread reduction" or both hypotheses hold true, we need to analyze the results in column 4 (FE Model 4). In this specification, we find that the "spread reduction" hypothesis is more likely to hold. The coefficient of "D^E x Non-bank DR" is even positive but not significant.

Overall, in line with the majority of the literature (Borio and Hofmann, 2017; Claessens et al., 2018; Raunig and Sigmund, 2022), we also find that negative reference rates on average reduce the interest rate spread, therefore reduce the net interest rate margin and ultimately the return on assets of banks.

However, we cannot definitively determine which of the two hypotheses is correct. Given our DAG in Figure 2, it is likely that the results in Table 8 are biased due to confounding. It is therefore essential to check the results in Section 6.2, Section 6.3, and Section 6.4.

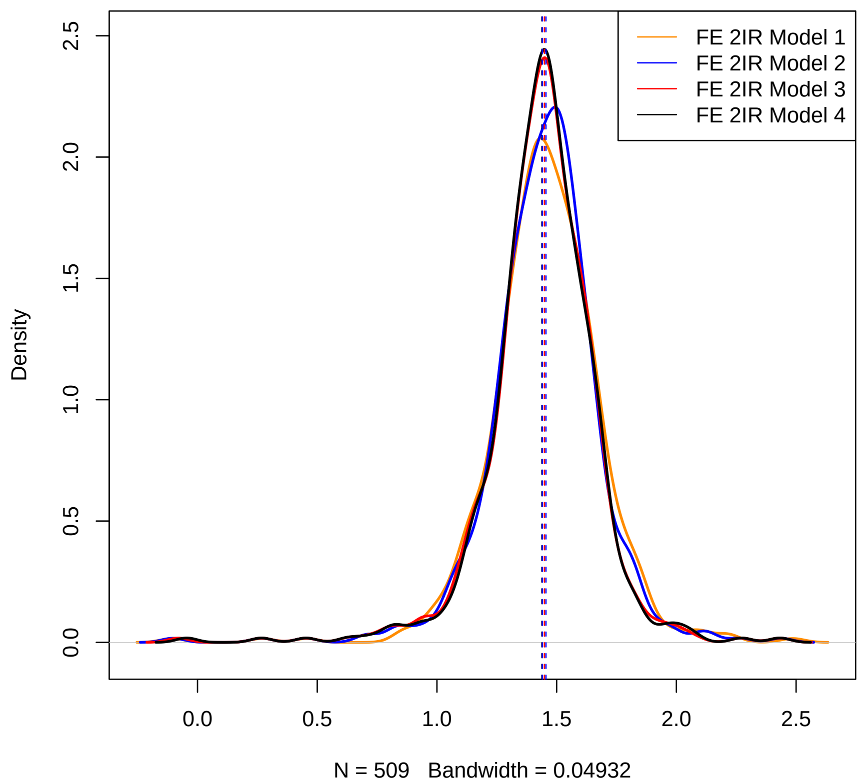
Table 8: Pass-Through FE: Lending and Deposit rates

	FE Model 1	FE Model 2	FE Model 3	FE Model 4
Intercept	1.3718***	1.3967***	1.5411***	1.5465***
	(0.0128)	(0.0190)	(0.0285)	(0.0289)
Non-bank DR	1.2078***	1.1944***	1.0917***	1.0838***
	(0.0204)	(0.0223)	(0.0286)	(0.0285)
D^E x Non-bank DR		−0.1530**		0.1753
		(0.0753)		(0.1186)
D^E			−0.1858***	−0.2231***
			(0.0236)	(0.0313)
Bank fixed effects	*yes*	*yes*	*yes*	*yes*
R-squared	0.86	0.86	0.87	0.87
Adj. R-squared	0.86	0.86	0.86	0.86
Number of obs.	23,313	23,313	23,313	23,313
Number of groups	509	509	509	509
Average. Obs. group	45.80	45.80	45.80	45.80
Min. Obs. group	26	26	26	26
Max. Obs. Group	52	52	52	52

Source: OeNB. Own calculations.
$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. We use cluster robust standard errors at the bank level.
The dependent variable is the bank-specific lending rate.
The explanatory variables are the intercept, which is the average of all bank-specific fixed effects, the non-bank deposit rate, the interaction term between the dummy variable D^E and the non-bank deposit rate, and the dummy variable D^E, which is 1 if the Euribor is negative and 0 otherwise.
The FE Model 1 refers to the specification in Eq. (6). In this model, we estimate the pass-through from the bank-specific deposit rate to the bank-specific lending rate.
The FE Model 2 refers to the specification in Eq. (7a). Here, we test if the cointegration between lending and deposit rates breaks down under a negative 3-month Euribor.
The FE Model 3 refers to the specification in Eq. (7b). Here, we test if a negative 3-month Euribor causes a spread reduction between the bank-specific lending and deposit rates.
The FE Model 4 refers to the specification in Eq. (7c). In this specification, we test the change of the cointegration and the spread reduction simultaneously.

As a robustness check, we look at the distribution of the cointegration vector by estimating Eq. (6) and Eq. (7) for each bank individually. The results can be found in Figure 4.

Figure 4: Densities of the Estimated Deposit Rate Coefficients across Models.



The figure shows the densities of the estimated deposit rate coefficients for all FE models specified in Eq. (6) and Eq. (7), which are estimated on an individual bank level. The densities of the estimated coefficients should be compared to the coefficients of "Non-bank DR" in Table 8.

6.2. Cointegration between Bank-specific Rates and the 3-month Euribor

As mentioned in Section 3 which is also reflected in our specifications in Section 6.1, the 3-month Euribor is the most important reference rate for Austrian banks. As a result, we present the estimated cointegration relationship between the bank-specific deposit rate and the 3-month Euribor in Table 9, as well as the estimated cointegration relationship between the bank-specific lending rate and the 3-month Euribor in Table 10.

In Table 9 in model "DR on 3M Euribor 1", we estimate a cointegration vector of less than 1. Given that the majority of non-bank deposits are term deposits, the cointegration vector is around 0.80, which is well within an interval of 0.65 to 0.88 constructed from the coefficients reported in the literature (Mojon, 2000; De Bondt et al., 2005; Kok and Werner, 2006; De Graeve et al., 2007; Gropp et al., 2014).

Table 9: Cointegration: Deposit rate and 3-month Euribor

	DR on 3M Euribor 1	DR on 3M Euribor 2	DR on 3M Euribor 3	DR on 3M Euribor 4
Intercept	0.4938***	0.5340***	0.5918***	0.5863***
	(0.0012)	(0.0039)	(0.0035)	(0.0042)
3-month Euribor	0.7935***	0.7540***	0.7006***	0.7065***
	(0.0070)	(0.0067)	(0.0059)	(0.0062)
D^E x 3M Euribor		0.1921***		−0.1039***
		(0.0201)		(0.0213)
D^E			−0.1590***	−0.1853***
			(0.0065)	(0.0059)
Bank fixed effects	*yes*	*yes*	*yes*	*yes*
R-squared	0.81	0.82	0.82	0.82
Adj. R-squared	0.81	0.81	0.82	0.82
Number of obs.	23,319	23,319	23,319	23,319
Number of groups	509	509	509	509
Average. Obs. group	45.81	45.81	45.81	45.81
Min. Obs. group	26	26	26	26
Max. Obs. Group	52	52	52	52

Source: Own calculations. OeNB. ECB SDW.
$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. We use cluster robust standard errors at the bank level.
The dependent variable is the bank-specific deposit rate.
In all models, we include an intercept, which is the average of all bank-specific fixed effects.
DR on 3M Euribor 1 includes the 3-month Euribor as the only exogenous variable.
In DR on 3M Euribor 2, we include the 3-month Euribor and D^E x 3M Euribor which is the interaction term between the 3-month Euribor and a dummy which takes the value of 1 if the 3-month Euribor is negative and 0.
In DR on 3M Euribor 3, we include the 3-month Euribor and the D^E which is a dummy variable and takes the value of 1 if the 3-month Euribor is negative and 0 otherwise.
In DR on 3M Euribor 4, we include 3-month Euribor, the D^E x 3M Euribor and the D^E.

Table 10 presents the cointegration relationship between the bank-specific lending rate and the 3-month Euribor. Drawing upon Figure 2 and adopting the terminology of causal inference by Pearl (2009), since the bank-specific deposit rate is a mediator (VanderWeele, 2015), we can estimate the "total effect" of the 3-month Euribor on the bank-specific lending rate in Table 10.

In the models "LR on 3M Euribor 2" and "LR on 3M Euribor 4", we see evidence that the cointegration relationship between the bank-specific lending rate and the 3-month Euribor breaks down, since the coefficient of "D^E x 3M Euribor" is statistically significant and positive. This is empirical evidence for the "two true prices hypothesis". For example, the cointegration relationship between the lending rate and the 3-month Euribor of around 1 in model "LR on 3M Euribor 2" is reduced by around 0.36 under a negative 3-month Euribor indicated by the coefficient of "D^E x 3M Euribor", since 0.36 is multiplied by the negative 3-month Euribor. Remarkably, the coefficient of 0.36 is in line with Raunig and Sigmund (2022), who use a sample of 1,200 euro area banks and find a reduction of 0.41 in the return on assets under a negative 3-month Euribor.

There is also empirical evidence for the "spread reduction hypothesis", since the coefficient D^E is statistically significant and negative in "LR on 3M Euribor 3" and "LR on 3M Euribor 4".

Table 10: Cointegration: Lending rate and 3-month Euribor

	LR on 3M Euribor 1	LR on 3M Euribor 2	LR on 3M Euribor 3	LR on 3M Euribor 4
Intercept	1.9498^{***}	2.0247^{***}	2.0259^{***}	2.0403^{***}
	(0.0018)	(0.0067)	(0.0066)	(0.0077)
3-month Euribor	1.0686^{***}	0.9952^{***}	0.9966^{***}	0.9811^{***}
	(0.0107)	(0.0100)	(0.0089)	(0.0095)
D^E x 3M Euribor		0.3579^{***}		0.2703^{***}
		(0.0345)		(0.0345)
D^E			-0.1233^{***}	-0.0549^{***}
			(0.0120)	(0.0107)
Bank fixed effects	*yes*	*yes*	*yes*	*yes*
R-squared	0.85	0.85	0.85	0.85
Adj. R-squared	0.85	0.85	0.85	0.85
Number of obs.	23,409	23,409	23,409	23,409
Number of groups	509	509	509	509
Average. Obs. group	45.99	45.99	45.99	45.99
Min. Obs. group	26	26	26	26
Max. Obs. Group	52	52	52	52

Source: Own calculations. OeNB. ECB SDW.
$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. We use cluster robust standard errors at the bank level.
The dependent variable is the bank-specific lending rate.
In all models, we include an intercept, which is the average of all bank-specific fixed effects.
We estimate the four models specified in Eq. (9).
LR on 3M Euribor 1 includes the 3-month Euribor as the only exogenous variable.
In LR on 3M Euribor 2, we include the 3-month Euribor and D^E x 3M Euribor which is the interaction term between the 3-month Euribor and a dummy which takes the value of 1 if the 3-month Euribor is negative and 0.
In LR on 3M Euribor 3, we include the 3-month Euribor and the D^E which is a dummy variable and takes the value of 1 if the 3-month Euribor is negative and 0 otherwise.
In LR on 3M Euribor 4, we include 3-month Euribor, D^E x 3M Euribor and the D^E.

6.3. Cointegration between Lending Rate, Deposit Rate, and 3-month Euribor

In this section, we present the results of the first step of the Engle-Granger procedure for the cointegration relationship between bank-specific interest rates and the 3-month Euribor.

In Table 11, the cointegrating vector has now two components, the coefficients of "Non-bank DR" and "3-month Euribor". These two coefficients are remarkably stable across all four models. In particular, the coefficient of the 3-month Euribor represents now the direct effect of the 3-month Euribor on the lending rate. From Table 10 we know that the total 3-month Euribor effect is around 1. The indirect effect is around 0.5 (indirect effect = total effect - direct effect) and is mediated through the deposit rate, which has a coefficient of around 0.7.

By referring to "FE 3IR Model 4" in Table 11, we gain a significantly clearer understanding if any of our two hypotheses hold true. There is a statistically and economically significant change in the cointegration relationship between the 3-month Euribor and the lending rate. On average, under a negative 3-month Euribor, the direct effect of the 3-month Euribor on the lending rate is increased by 0.36. Unfortunately for banks, this means that under a negative 3-month Euribor, the pass-through of the 3-month Euribor to the lending rate is reduced by $0.36 \cdot (-0.57)$, considering the minimum 3-month Euribor observed during our sample period. Banks cannot fully compensate for this reduction by increasing their spread, as indicated by the positive coefficient of D^E in model "FE Model 4".

A noteworthy observation is that in FE 3IR Model 4, the coefficient of the "non-bank DR", which constitutes the other part of the cointegrating vector, remains unchanged even in the presence of a negative 3-month Euribor as indicated by the statistically and economically insignificant coefficient of "D^E x DR".

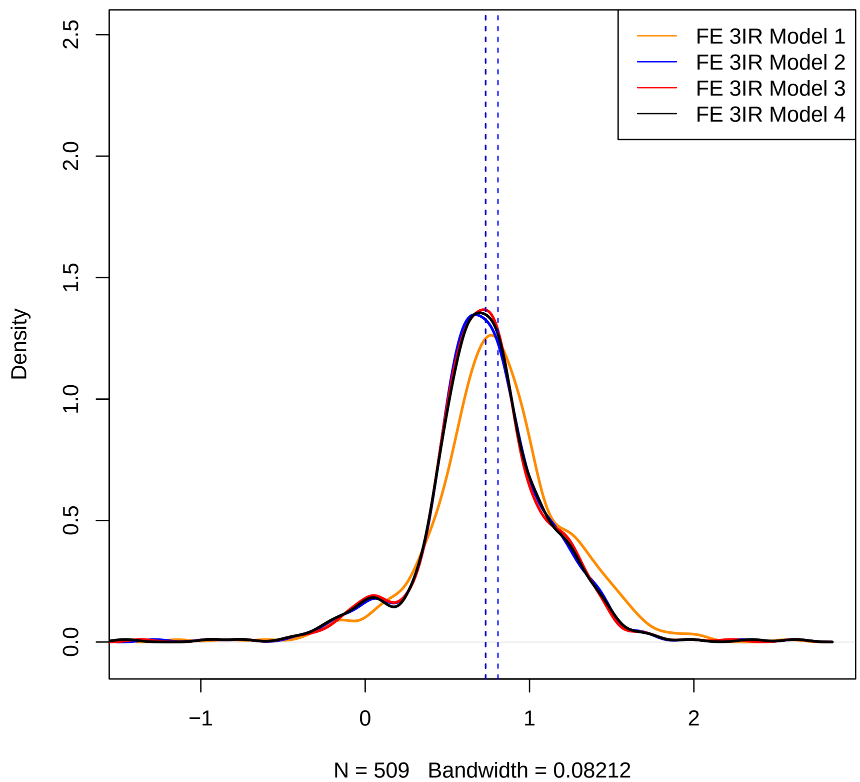
Table 11: Cointegration FE: Lending Rate, Deposit Rates, and 3-month Euribor

	FE 3IR Model 1	FE 3IR Model 2	FE 3IR Model 3	FE 3IR Model 4
Intercept	1.6075***	1.6468***	1.6152***	1.6305***
	(0.0209)	(0.0233)	(0.0240)	(0.0243)
Non-bank DR	0.6932***	0.6848***	0.6909***	0.6972***
	(0.0409)	(0.0416)	(0.0415)	(0.0436)
3-month Euribor	0.5190***	0.4884***	0.5145***	0.4905***
	(0.0304)	(0.0307)	(0.0288)	(0.0306)
D^E x DR		0.0884*		−0.0334
		(0.0514)		(0.0916)
D^E x 3M Euribor		0.2194***		0.3618***
		(0.0354)		(0.0637)
D^E			−0.0108	0.0889**
			(0.0120)	(0.0364)
Bank fixed effects	*yes*	*yes*	*yes*	*yes*
R-squared	0.89	0.89	0.89	0.89
Adj. R-squared	0.89	0.89	0.89	0.89
Number of obs.	23,313	23,313	23,313	23,313
Number of groups	509	509	509	509
Average. Obs. group	45.80	45.80	45.80	45.80
Min. Obs. group	26	26	26	26
Max. Obs. Group	52	52	52	52

Source: Own calculations. OeNB. ECB SDW.
$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. We use cluster robust standard errors at the bank level.
The dependent variable is the bank-specific lending rate.
In all models, we include an intercept, which is the average of all bank-specific fixed effects.
In FE 3IR Model 1, we include the non-bank deposit rate and the 3-month Euribor as the exogenous variables. This is the specification in Eq. (8a).
In FE 3IR 3M Euribor 2, we include the non-bank deposit rate, the 3-month Euribor, the D^E x DR, which is the interaction term between the non-bank deposit rate and the D^E, which takes the value of 1 if the 3-month Euribor is negative and 0 otherwise. This is the specification in Eq. (8b).
In FE 3IR 3M Euribor 3, we include the non-bank deposit rate, the 3-month Euribor, and the D^E, which is a dummy variable and takes the value of 1 if the 3-month Euribor is negative and 0 otherwise. This is the specification in Eq. (8c).
In FE 3IR 3M Euribor 4, we include the non-bank deposit rate, the 3-month Euribor, the D^E x DR, the D^E x 3M Euribor, and the D^E. This is the specification in Eq. (8d).

Again, we look at the distribution of the cointegration vector by estimating Eq. (8) for each bank individually. We repeat this robustness check for all other specifications in Table 11 as well. The results can be found in Figure 5. In Figure 5, we see a remarkably narrow probability density function around the mean of the estimated coefficient for the bank-specific deposit rate, which is part of the cointegrating vector.

Figure 5: Densities of Estimated Coefficients of the Bank-specific Deposit Rate.



The figure shows the densities of the cointegration vector with the non-bank deposit rate for all FE 3IR models in Table 11, which are estimated on an individual bank level.

6.4. Cointegration between Lending, Deposit Rates, 3-month Euribor and the ECB Deposit Facility Rate

In Table 12, we estimate the effects of the ECB DFR and the 3-month Euribor on the lending rate without the mediation through the bank-specific deposit rate. In model “LR on DFR, 3M Euribor 4”, we observe the now familiar change of the cointegration relationship under a negative 3-month Euribor and a negative ECB DFR. Interestingly, the pass-through of the ECB DFR on the lending rate is much higher under a negative ECB DFR, since the coefficient of “D^{DFR} x ECB DFR” is statistically significant and negative. This coefficient is then multiplied by a negative ECB DFR, which increases the pass-through. Banks change their lending rate setting criteria, by calculating a margin over the TLTRO rate, which is connected to the ECB DFR.

Table 12: Cointegration: Lending Rate, 3-month Euribor and ECB DFR

	LR on DFR, 3M Euribor 1	LR on DFR, 3M Euribor 2	LR on DFR, 3M Euribor 3	LR on DFR, 3M Euribor 4
Intercept	2.1074***	2.1435***	2.1545***	2.1742***
	(0.0058)	(0.0092)	(0.0094)	(0.0100)
ECB DFR	0.7463***	0.6256***	0.6194***	0.6571***
	(0.0281)	(0.0283)	(0.0266)	(0.0283)
3-month Euribor	0.6585***	0.6651***	0.6613***	0.6289***
	(0.0167)	(0.0175)	(0.0169)	(0.0172)
D^{DFR} x ECB DFR		0.0639		−0.6629***
		(0.0556)		(0.0436)
D^{E} x 3M Euribor		0.2137***		0.6259***
		(0.0457)		(0.0383)
D^{DFR}			−0.0605***	−0.1577***
			(0.0109)	(0.0112)
D^{E}			−0.0514***	−0.0323***
			(0.0106)	(0.0079)
R-squared	0.85	0.85	0.85	0.85
Adj. R-squared	0.85	0.85	0.85	0.85
Number of obs.	23, 409	23, 409	23, 409	23, 409
Number of groups	509	509	509	509
Average. Obs. group	45.99	45.99	45.99	45.99
Min. Obs. group	26	26	26	26
Max. Obs. Group	52	52	52	52

***$p < 0.01$; **$p < 0.05$; *$p < 0.1$. We use cluster robust standard errors at the bank level.
The dependent variable is the bank-specific lending rate.
In all models, we include an intercept, which is the average of all bank-specific fixed effects.
In the model 'LR on DFR, 3M Euribor 1", we include the 3-month Euribor and the ECB Deposit Facility Rate (ECB DFR) as the exogenous variables.
In the model "LR on DFR, 3M Euribor 2", we include the ECB Deposit Facility Rate (ECB DFR), the 3-month Euribor, the interaction term Dummy D^{DFR} x ECB DFR, and the interaction term D^{E} x 3-month Euribor.
The D^{DFR} x ECB DFR is the interaction term between the DFR and a dummy, which takes the value of 1 if the ECB DFR is negative and 0.
The D^{E} x 3-month Euribor is the interaction term between the 3-month Euribor and a dummy, which takes the value of 1 if the 3-month Euribor is negative and 0.
In the model "LR on DFR, 3M Euribor 3", we include the ECB Deposit Facility Rate, the 3-month Euribor, the Dummy D^{DFR}, and the Dummy D^{E}.
In the model "LR on DFR, 3M Euribor 4", we include the non-bank deposit rate, the ECB Deposit Facility Rate (ECB DFR), the 3-month Euribor, the interaction term D^{DFR} x DFR, the interaction term D^{E} x 3-month Euribor, the Dummy D^{DFR}, and the Dummy D^{E}.

In Table 13, we see that the coefficient of "ECB DFR" is relatively small in all models, which means that the direct effect on the lending rate is not important, justifying the simplified DAG in Figure 2 and the results in Section 6.3.

However, we estimate a negative coefficient for "D^{DFR} x ECB DFR". This means that under a negative ECB DFR, the direct effect of the ECB DFR on the LR becomes statistically significant and negative. We interpret this result in the following way. A negative ECB DFR was almost immediately followed by the introduction of the targeted long-term refinancing operations (TLTROs) of the ECB.

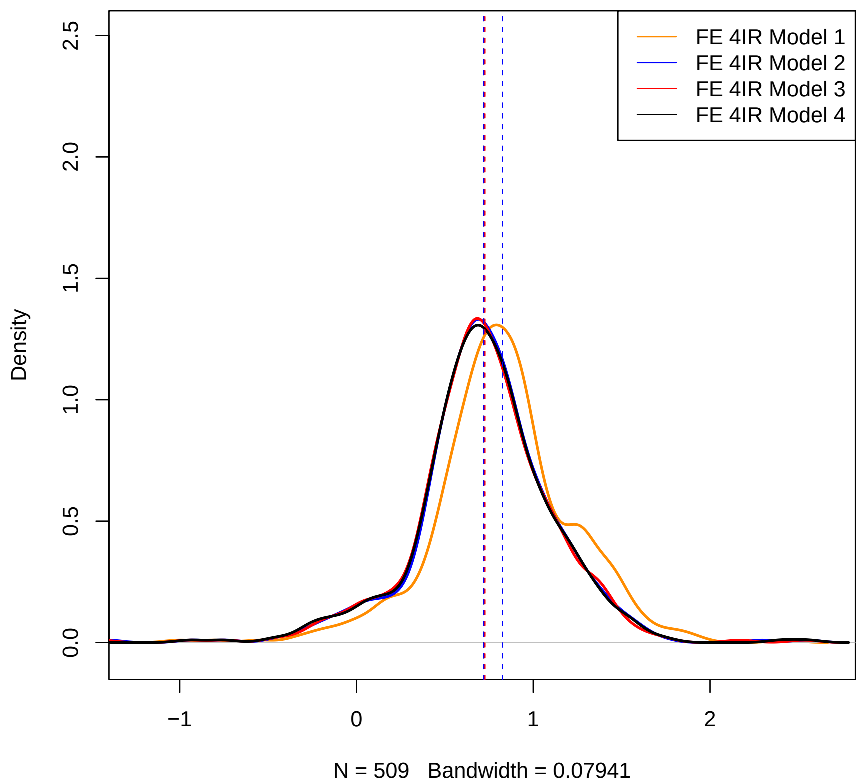
The TLTRO rate was conditional on some lending volume criteria and explicitly on the ECB Deposit Facility Rate. Hence, banks change their lending rate setting criteria by calculating a margin over the TLTRO rate, i.e., the negative coefficient −0.3413 is multiplied by the negative ECB Deposit Facility Rate (e.g., −0.5), which results in a positive spread. Such a strong direct effect of the ECB Deposit Facility Rate on the lending rate cannot be observed in a positive interest rate environment, as shown by the coefficients of ECB DFR in Table 13 which are between 5 and 8 basis points.

Table 13: Cointegration: Lending Rate, Deposit Rates, 3-month Euribor and ECB DFR

	LR on DR, DFR and 3M E. 1	LR on DR, DFR and 3M E.2	LR on DR, DFR and 3M E.3	LR on DR, DFR and 3M E.4
Intercept	1.6197^{***}	1.6160^{***}	1.5930^{***}	1.6092^{***}
	(0.0281)	(0.0305)	(0.0328)	(0.0341)
Non-bank DR	0.6893^{***}	0.7026^{***}	0.7023^{***}	0.7070^{***}
	(0.0429)	(0.0451)	(0.0451)	(0.0482)
ECB DFR	0.0485	0.0780^{**}	0.0831^{**}	0.0672^{*}
	(0.0385)	(0.0356)	(0.0344)	(0.0391)
3-month Euribor	0.4955^{***}	0.4670^{***}	0.4880^{***}	0.4721^{***}
	(0.0232)	(0.0271)	(0.0241)	(0.0243)
D^{DFR} x DR		-0.0005		-0.0155
		(0.0410)		(0.1032)
D^{DFR} x ECB DFR		-0.4688^{***}		-0.3413^{***}
		(0.0998)		(0.0764)
D^{E} x DR		-0.0002		-0.0155
		(0.0438)		(0.0815)
D^{E} x 3M Euribor		0.5763^{***}		0.5340^{***}
		(0.0913)		(0.0535)
D^{DFR}			0.0806^{***}	0.0279
			(0.0117)	(0.0602)
D^{E}			-0.0466^{***}	0.0197
			(0.0109)	(0.0365)
R-squared	0.89	0.89	0.89	0.89
Adj. R-squared	0.89	0.89	0.89	0.89
Number of obs.	23,313	23,313	23,313	23,313
Number of groups	509	509	509	509
Average. Obs. group	45.80	45.80	45.80	45.80
Min. Obs. group	26	26	26	26
Max. Obs. Group	52	52	52	52

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. We use cluster robust standard errors at the bank level.
The dependent variable is the bank-specific lending rate.
In all models, we include an intercept, which is the average of all bank-specific fixed effects.
In the model "LR on DR, DFR and 3M E. 1", we include the non-bank deposit rate, the 3-month Euribor and the ECB Deposit Facility Rate (ECB DFR) as the exogenous variables. This is the specification in Eq. (10a).
In the model "LR on DR, DFR and 3M E. 2", we include the non-bank deposit rate, the 3-month Euribor, the ECB Deposit Facility Rate (ECB DFR), the interaction term D^{DFR} x DR, the interaction term D^{DFR} x ECB DFR, the interaction term D^{E} x DR, and the interaction term D^{E} x 3M Euribor. This is the specification in Eq. (10b).
In the model "LR on DR, DFR and 3M E. 3", we include the non-bank deposit rate, the ECB Deposit Facility Rate, the 3-month Euribor, the Dummy D^{DFR}, and the Dummy D^{E}. This is the specification in Eq. (10c).
In the model "LR on DR, DFR and 3M E. 4", we include the non-bank deposit rate, the ECB Deposit Facility Rate (ECB DFR), the 3-month Euribor, the interaction term D^{DFR} x DR, the interaction term D^{DFR} x ECB DFR, the interaction term D^{E} x DR, the interaction term D^{E} x 3M Euribor, the Dummy D^{DFR}, and the Dummy D^{E}. This is the specification in Eq. (10d).

Figure 6: Densities of Estimated Coefficients of the Bank-specific Deposit Rate.



The figure shows the densities of the cointegration vector with the non-bank deposit rate for all FE 4IR models in Table 13, which are estimated on an individual bank level.

7. Vector Error Correction Model

In this section, we present the results of the second step of the cointegration procedure defined in Eq. (12). The dependent variables are the year-on-year changes in the bank-specific lending and deposit rates. From the different cointegration models we estimated in Section 6 in the first step of the cointegration procedure, we choose the lagged residuals from “FE Model 4” (Table 8), “FE DOLS Model 4” (Table C.18), and “FE 3IR Model 4” (Table 11) which all allow for a spread reduction and a change in the cointegration relationship under a negative 3-month Euribor.

First, we discuss the coefficients of the current and lagged Δ 3M Euribor. These are important coefficients that indicate how the bank-specific lending and deposit rates are adjusted gradually over time. Usually, a change in the policy rates by an ECB decision leads to a change in the reference rates (e.g., the 3-month Euribor). Remarkably, the coefficients of Δ 3M Euribor and of Δ 3M Euribor (t-1) are of greater magnitude in the Δ LR equation than in the Δ DR equation. This is consistent with the results in Section 6.2 where we show that the cointegration vector of the 3-month Euribor is much higher in the lending rate equation in Table 10 than in the deposit rate equation in Table 9. An initial shock in the 3-month Euribor rate is absorbed primarily by the $\Delta LR_{i,t}$ equation, whereas its impact on the $\Delta DR_{i,t}$ equation is relatively modest.

However, this beneficial effect for banks during periods of rising interest rates is not persistent. The negative coefficients of $\Delta DR(t-1)$, $\Delta DR(t-2)$, and $\Delta DR(t-3)$ bring down the ΔLR after the initial Δ 3M Euribor shock. These adjustments work together with the speed of adjustment coefficients (α_1, α_2) from Eq. (13), which we discuss next.

The vector of the adjustment coefficients (α) has two components.[15] First, α_1, which is negative in the $\Delta LR_{i,t}$ equation in all specifications in Table 14, implies that the $LR_{i,t}$ adjusts to the long-run equilibrium cointegration relationship described in Eq. (7c), Eq. (C.1d) and Eq. (8d). As mentioned before, when the lending rate is "above" the equilibrium, the distance to the deposit rate is greater than in equilibrium, meaning the residuals are positive. The negative α_1 multiplied by the positive residuals ceteris paribus causes a negative $\Delta LR_{i,t}$, which reduces $LR_{i,t}$. On the contrary, when the lending rate falls below equilibrium, and the residuals are negative, the negative sign of the adjustment coefficients multiplied by the residuals suggests a positive $\Delta LR_{i,t}$ such that the distance between the two rates moves back to the long-run equilibrium.

Second, α_2, which is positive in the $\Delta DR_{i,t}$ equation in all specifications in Table 14, also implies that the $DR_{i,t}$ adjusts to the long-run equilibrium cointegration relationship as described in Section 4.3. In short, when the deposit rate is too high, the residuals in the cointegration equation are negative, so the $\Delta DR_{i,t}$ has to be negative, which requires a positive α_2. When the deposit rate is too low, the residuals in the cointegration equation are positive, so the $\Delta DR_{i,t}$ has to be positive, which again requires a positive α_2.

The other bank-specific variables mainly serve as control variables. Log total assets has a small but statistically significant positive coefficient in the ΔLR-equation and a negative coefficient in the ΔDR-equation. A higher share of lagged non-bank deposits, which measures a bank's dependence on market and interbank market funding, leads to a reduction in $\Delta LR_{i,t}$ and $\Delta DR_{i,t}$. The share of sight deposits has a positive but economically insignificant effect on $\Delta LR_{i,t}$ and $\Delta DR_{i,t}$. Since these deposits can be withdrawn from a bank either without notice or after a very short

[15] These are the coefficients of ϵ_{t-1}: FE Model 4, ϵ_{t-1}: FE DOLS Model 4, and ϵ_{t-1}: FE 3IR Model 4.

notice period, banks must adjust their lending and deposit rates more significantly. A higher share of central bank deposits allows banks to significantly reduce their deposit rate. Banks can substitute non-bank deposits with central bank liabilities (e.g., targeted long-term refinancing operations).

In accordance with Gambacorta (2008), nominal GDP growth, which is a proxy for loan demand, has a positive and significant influence on $\Delta LR_{i,t}$. We find that inflation has a positive impact on the deposit rate. We argue that higher inflation puts pressure on the deposit rate, since non-bank customers expect some kind of compensation.

In the system GMM (Blundell and Bond, 1998), it is possible to include an intercept, which controls for potential time trends in $\Delta LR_{i,t}$ and $\Delta DR_{i,t}$.

Table 14: VECM: Loan and deposit rate growth with FE OLS and FE DOLS residuals

	VECM Fixed Effects Residuals		VECM Fixed Effects DOLS Residuals		VECM Fixed Effects 3IR Residuals	
	Δ LR	Δ DR	Δ LR	Δ DR	Δ LR	Δ DR
Δ LR (t-1)	0.1651***	−0.0167***	0.1614***	−0.0176***	0.1797***	−0.0099**
	(0.0145)	(0.0038)	(0.0152)	(0.0038)	(0.0147)	(0.0039)
Δ LR (t-2)	0.1026***	−0.0029	0.1034***	−0.0040	0.1011***	−0.0055
	(0.0089)	(0.0040)	(0.0091)	(0.0041)	(0.0089)	(0.0040)
Δ LR (t-3)	0.0589***	−0.0070*	0.0592***	−0.0054	0.0595***	−0.0087**
	(0.0124)	(0.0041)	(0.0130)	(0.0039)	(0.0124)	(0.0041)
Δ DR (t-1)	−0.0150	0.3658***	−0.0177	0.3720***	−0.0153	0.3596***
	(0.0293)	(0.0181)	(0.0305)	(0.0175)	(0.0291)	(0.0185)
Δ DR (t-2)	−0.0923***	0.0841***	−0.0981***	0.0820***	−0.0923***	0.0845***
	(0.0247)	(0.0112)	(0.0266)	(0.0122)	(0.0245)	(0.0113)
Δ DR (t-3)	−0.0732***	−0.0363***	−0.0777***	−0.0376***	−0.0682***	−0.0426***
	(0.0256)	(0.0119)	(0.0264)	(0.0117)	(0.0252)	(0.0120)
Δ 3M Euribor	0.3259***	0.0139	0.3153***	0.0220**	0.3302***	0.0096
	(0.0207)	(0.0103)	(0.0225)	(0.0090)	(0.0206)	(0.0104)
Δ 3M euribor (t-1)	0.1995***	0.1554***	0.2159***	0.1352***	0.1749***	0.1613***
	(0.0312)	(0.0162)	(0.0356)	(0.0144)	(0.0310)	(0.0164)
Δ 3M euribor (t-2)	0.0099	−0.0256*	0.0027	−0.0055	0.0118	−0.0249*
	(0.0339)	(0.0146)	(0.0364)	(0.0152)	(0.0339)	(0.0147)
Δ 3M euribor (t-3)	−0.1366***	0.0538***	−0.1352***	0.0504***	−0.1356***	0.0537***
	(0.0293)	(0.0125)	(0.0297)	(0.0127)	(0.0292)	(0.0125)
Δ 3M euribor (t-4)	0.1715***	0.0136*	0.1734***	0.0127	0.1654***	0.0158**
	(0.0169)	(0.0078)	(0.0168)	(0.0077)	(0.0169)	(0.0078)
D^E	−0.0197***	0.0496***	−0.0182***	0.0499***	−0.0224***	0.0540***
	(0.0059)	(0.0036)	(0.0060)	(0.0033)	(0.0058)	(0.0037)
ϵ_{t-1}: FE Model 4	−0.0623***	0.0317***				
	(0.0089)	(0.0034)				
ϵ_{t-1}: FE DOLS Model 4			−0.0589***	0.0298***		
			(0.0094)	(0.0036)		
ϵ_{t-1}: FE 3IR Model 4					−0.1014***	0.0109***
					(0.0104)	(0.0040)
Log Total Assets	0.0035**	−0.0054***	0.0031*	−0.0053***	0.0046***	−0.0054***
	(0.0017)	(0.0008)	(0.0017)	(0.0008)	(0.0017)	(0.0008)
Share non-bank deposits (t-1)	−0.0695***	−0.0269***	−0.0699***	−0.0286***	−0.0509**	−0.0261***
	(0.0199)	(0.0100)	(0.0200)	(0.0101)	(0.0202)	(0.0100)
Tier 1 ratio (t-1)	0.0003	−0.0003**	0.0003	−0.0003**	0.0005	−0.0003**
	(0.0003)	(0.0001)	(0.0003)	(0.0001)	(0.0003)	(0.0001)
Liquidity Ratio (t-1)	−0.0000	0.0000	−0.0001	0.0001	−0.0002	0.0001
	(0.0003)	(0.0002)	(0.0003)	(0.0002)	(0.0003)	(0.0002)
LLP ratio smoothed (t-1)	0.0556***	−0.0846*	0.0489***	−0.1087**	0.0452***	−0.0612
	(0.0153)	(0.0440)	(0.0179)	(0.0487)	(0.0142)	(0.0455)
Net non-interest income ratio	0.0005***	−0.0002*	0.0004***	−0.0001	0.0005***	−0.0002**
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Share sight deposits (t-1)	0.0003**	0.0002***	0.0003**	0.0002***	0.0004***	0.0001***
	(0.0001)	(0.0000)	(0.0001)	(0.0000)	(0.0001)	(0.0000)
Share CB deposits (t-1)	−0.0009	−0.0024***	−0.0011	−0.0026***	0.0002	−0.0019**
	(0.0017)	(0.0009)	(0.0017)	(0.0009)	(0.0017)	(0.0008)
Inflation Rate	−0.0122***	0.0237***	−0.0111***	0.0231***	−0.0145***	0.0247***
	(0.0037)	(0.0019)	(0.0036)	(0.0018)	(0.0036)	(0.0020)
Nominal GDP growth	0.2175***	−0.0061	0.2023***	−0.0021	0.2343***	−0.0278
	(0.0553)	(0.0268)	(0.0554)	(0.0241)	(0.0553)	(0.0268)
Intercept	−0.0206	−0.0205	−0.0189	−0.0188	−0.0507	−0.0244
	(0.0330)	(0.0156)	(0.0326)	(0.0158)	(0.0335)	(0.0159)
Bank fixed effects	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*
Number of Observations	17,324	17,324	17,176	17,176	17,324	17,324
Number of Groups	507	507	507	507	507	507
Obs per group: min	5	5	5	5	5	5
avg	34.20	34.20	33.90	33.90	34.20	34.20
max	48	48	48	48	48	48
Hansen test of overid: statistics:	6.19	6.19	7.19	7.19	5.45	5.45
nof para:	4	4	4	4	4	4
p-value:	0.19	0.19	0.13	0.13	0.24	0.24

$^{***} p < 0.01$; $^{**} p < 0.05$; $^{*} p < 0.1$. We calculate Windmeijer corrected robust standard errors (Windmeijer, 2005) at the bank level.
The dependent variables are the change in the bank-specific lending rate ($\Delta LR_t = LR_{i_t} - LR_{i,t-1}$) and in the bank-specific deposit rate ($\Delta DR_t = DR_{i_t} - DR_{i,t-1}$).
Based on Andrews and Lu (2001), we select $p = 3$ for the lagged dependent variables. We add the current value and four lags of ΔEuribor to capture the dynamic adjustment process of the bank-specific interest rates. The D^E is a dummy variable that takes the value of 1 if the 3-month Euribor is negative and 0 otherwise.
EC FE Model 4 (t-1) is the error correction term defined in Eq. (13) based on the FE Model 4 in Table 8. EC FE DOLS Model 4 (t-1) is the error correction term based on FE DOLS Model 4 in Table C.18. EC FE 3IR Model 4 (t-1) is the error correction term based on FE 3IR Model 4 in Table 11.
Log Total Assets is the logarithm of total assets. Share non-bank deposits (t-1) is defined as non-bank deposits divided by total assets lagged by one quarter. Tier 1 ratio (t-1) is the lagged Tier 1 capital ratio. Liquidity Ratio (t-1) is the sum of bonds and cash reserves divided by total assets, lagged by one quarter. LLP ratio (t-1) is the ratio of non-bank loan loss provision to non-bank loans lagged by 1 quarter. Net non-interest income ratio is the sum of non-interest income divided by total assets. Share sight deposits (t-1) are sight deposits divided by the sum of sight and term deposits. Share CB deposits are defined as central bank deposits (including TLTROs) divided by total assets.

8. Conclusion

We established a cointegration relationship between bank-specific deposit rates, bank-specific lending rates, the 3-month Euribor, and the ECB Deposit Facility Rate. We tested two theoretically derived hypotheses on whether negative reference rates and related Supreme Court decisions change the cointegration relationship between these bank-specific interest rates. The first hypothesis would result in a spread reduction between bank-specific lending and deposit rates. The second hypothesis would result in a change of the cointegration relationship between the bank-specific interest rates and the 3-month Euribor.

Our findings confirm the realization of our second hypothesis ("two true prices hypothesis"), resulting in a statistically and economically significant reduction in the spread between bank-specific lending and deposit rates. This reduction is observed only after estimating an unconfounded cointegrating vector by including the 3-month Euribor. Consistent with the standard theory (Klein, 1971; Ho and Saunders, 1981), negative reference rates lead to separate "true prices" for loans and deposits.

On the other hand, we find no statistically significant change in the cointegration coefficient of the bank-specific lending and deposit rates, but a statistically and economically significant change in the cointegration coefficient of the bank-specific lending rate and the 3-month Euribor. The estimated change in the cointegration coefficient explains the empirical findings in Borio and Hofmann (2017); Claessens et al. (2018); Molyneux et al. (2019); Freriks and Kakes (2021); Raunig and Sigmund (2022), which show a reduction in the profitability of banks under negative reference rates.

In addition, we observe a considerably stronger and economically significant direct impact of the ECB Deposit Rate Facility on the lending rate in the context of a negative ECB Deposit Rate Facility. Given the nearly immediate introduction of the TLTROs following the negative ECB DFR, we posit that banks have adjusted their criteria for setting lending rates. It appears that banks are now incorporating the TLTRO rate, directly determined by the ECB Deposit Rate Facility, into their lending rate decisions.

In normal times (i.e., non-negative interest rate environment), the impact of the ECB Deposit Rate Facility on bank-specific interest rates appears to be largely mediated by the 3-month Euribor and the 3-month Euribor serves as a confounding variable, influencing both the bank-specific deposit and lending rates.

Furthermore, our estimation results indicate that the cointegration relationship remains relatively consistent across all banks. The prevailing direction within this cointegration relationship appears to be from the deposit rate to the lending rate. This inference is supported by the FE DOLS results, where we address potential endogeneity issues, which are closely aligned with the fixed effects results. To bolster this conclusion, we employ causal graphs to offer additional empirical support for this directional relationship.

In the VECM models, we show that changes in the 3-month Euribor have a stronger effect on the bank-specific lending rate than on the bank-specific deposit rate. Hence, banks profit from rising reference rates. The initial stronger impact on the lending rate is then reduced by the vector of adjustment coefficients (α) from the cointegration relationship and by the coefficients of the lagged dependent variables. These two effects bring the lending rate and the deposit rate back to the long-run equilibrium after a few quarters.

We show that the net interest income of banks rises in tandem with the elevation of reference rates. In particular, negative reference rates were a game changer, and banks cannot apply their standard interest rate setting behavior due to legal and economic constraints. Our results support the robust empirical evidence from prior research indicating that banks' profitability is adversely affected by negative reference rates. Furthermore, we show the mechanism behind this decline in the net interest income by applying the standard two-step cointegration procedure.

Our results are in line with the theoretical predictions of Eggertsson et al. (2023) that banks relying more heavily on deposit financing were less likely to reduce their lending rates in response to policy rate cuts once the deposit rate had reached its lower bound. For these banks, the change in the cointegration relationship of the 3-month Euribor and the lending rate is less important.

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Appendix A. Cointegration Tests: Bank-specific Rates with the Deposit Facility/3-month Euribor Rate

Table A.15: Kao Panel Cointegration test: Bank-specific Lending rate and Deposit rate.

Kao test for cointegration			
H_0:	No cointegration	Number of panels=	509
H_a:	All panels are cointegrated	Avg. number of periods=	43.587
Cointegrating vector:	Same		
Panel means:	included	Kernel:	Bartlett
Time trend:	Not included	Lags:	2.68 (Newey-West)
AR parameter:	Same	Augmented lags:	1
Cross-sectional means removed			
		Statistic	p-value
Modified Dickey-Fuller t		−35.6452	0.0000
Dickey-Fuller t		−35.6501	0.0000
Augmented Dickey-Fuller t		−16.2584	0.0000
Unadjusted modified Dickey-Fuller t		−79.2223	0.0000
Unadjusted Dickey-Fuller t		−48.0874	0.0000

Data sources: OeNB. Own calculations.
Test based on Kao (1999).
Software implementation via STATA comand xtcointtest kao.
For each of the three tests applied, several available specifications have been tested for robustness, all supporting the hypothesis of cointegration, the current removes cross-sectional means.

Table A.16: Westerlund Panel Cointegration test: Bank-specific Lending rate and Deposit rate.

Westerlund tests for cointegration			
H_0:	No cointegration	Number of panels=	509
H_a:	All panels are cointegrated	Avg. number of periods=	45.802
Cointegrating vector:	Panel specific		
Panel means:	Included		
AR parameter:	Panel specific		
		Statistic	p-value
Variance ratio		−21.0897	0.0000
Variance ratio (Cross-sectional means removed)		−7.7603	0.0000
Variance ratio (Time trend included)		−8.8074	0.0000

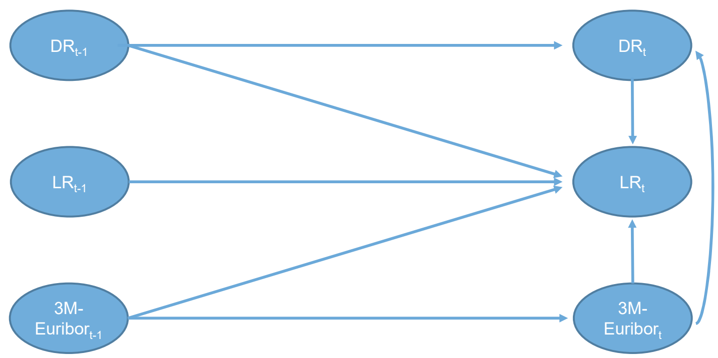
Data sources: OeNB. Own calculations.
Tests are based on Westerlund (2005).
Software implementation via STATA comand xtcointtest Westerlund.
The table reports three test statistics, each defined by different specifications.

Appendix B. Reverse Causality between Deposit and Lending Rates

In this section, we provide further evidence for the direction of the cointegration relationship from the 3-month Euribor to the deposit rate and then to the lending rate.

We mainly follow the discussion in Raunig (2023) and start with one slightly more complex DAG compared to Figure 2, which is shown in Figure B.7. In Figure 2, we assume that the *DR* causes the *LR* as represented by the directed arrow.

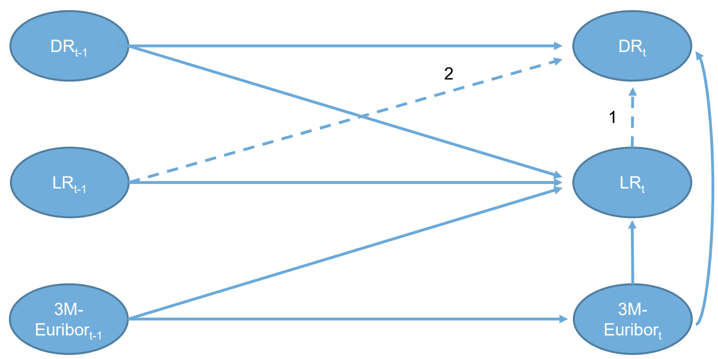
Figure B.7: Extended Directed Acyclic Graph: Bank-specific Interest Rates and 3-month Euribor



This figure shows the directed acyclic graph of the bank-specific lending rate (LR), the bank-specific deposit rate (DR), the 3-month Euribor (Euribor), and the lags of these variables. The directions of the arrows show the causal relationships between the variables.

Alternatively, it would be possible that the bank-specific lending rate would cause the bank-specific deposit rate, which would imply that the DAG in Figure B.8 was correct.

Figure B.8: Another Directed Acyclic Graph: Bank-specific Interest Rates and 3-month Euribor



This figure shows the directed acyclic graph of the bank-specific lending rate (LR), the bank-specific deposit rate (DR), the 3-month Euribor (Euribor), and the lags of these variables. The directions of the arrows show the assumed causal relationships between the variables.

We can check if the arrow "1" in Figure B.8 can be established by checking local properties of the DAG. In particular, Raunig (2023) shows that we can set up two auxiliary dynamic panel models to find out if the direction of "1" is correct:

$$LR_{i,t} = \mu_i + \phi_1 LR_{i,t-1} + \phi_2 DR_{i,t-1} + \phi_3 \cdot Euribor_{t-1} + \epsilon_{1,i,t} \; , \tag{B.1a}$$

$$DR_{i,t} = \mu_i + \theta_1 DR_{i,t-1} + \theta_2 LR_{i,t-1} + \theta_3 \cdot Euribor_{t-1} + \epsilon_{2,i,t} \; , \tag{B.1b}$$

We basically have to check if $LR_{i,t}$ is a collider on the path ($LR_{i,t-1} \rightarrow LR_{i,t} \leftarrow DR_{i,t}$). If $LR_{i,t}$ is a collider on this path, then $DR_{i,t}$ is a contemporaneous cause of $LR_{i,t}$. If not, then $LR_{i,t}$ causes $DR_{i,t}$, and Figure B.8 would be the "correct" DAG. To establish that $LR_{i,t}$ is a collider, we need $\phi_1 \neq 0$ in Eq. (B.1a) and then $\theta_2 = 0$ in Eq. (B.1b).

In Table B.17, we see empirical evidence that $LR_{i,t}$ is a collider, since the coefficient of "Non-bank lending rate (-1)" ($\phi_1 = 0.3582$) is significantly different from 0 in the "Non-bank lending rate" model, and also the coefficient of

"Non-bank lending rate (-1)" ($\theta_2 = 0.0011$) is not significantly different from 0 in the non-bank deposit rate model. Hence, $LR_{i,t}$ is a collider on the path between $LR_{i,t-1}$ and $DR_{i,t-1}$, which implies that $DR_{i,t}$ is a contemporaneous cause of $LR_{i,t}$. Consequently, the DAG in Figure B.7 is correct, whereas the DAG in Figure B.8 is not.

The caveat of our analysis is that the DAG in Figure B.7 is not the same as the DAG in Figure 2, which is our model for the cointegration analysis. However, these two models are similar and one is nested in the other. We estimate the corresponding model to the DAG in Figure B.7 in the third column of Table B.17, which can be compared to the model "FE 3IR Model 4" in Table 11.

Table B.17: Auxiliary Dynamic Panel Models

	Non-bank lending rate	Non-bank deposit rate	Extended Non-bank lending rate
Non-bank LR (-1)	0.3582***	0.0011	0.3965***
	(0.0650)	(0.0196)	(0.0560)
Non-bank DR (-1)	0.0965	0.5782***	−0.0581
	(0.0921)	(0.0271)	(0.0633)
3-month Euribor (-1)	0.4989***	0.2469***	−0.1201***
	(0.0320)	(0.0136)	(0.0354)
Intercept	1.6572***	0.1404***	1.4260***
	(0.1506)	(0.0468)	(0.1262)
Non-bank DR			0.6128***
			(0.0708)
3-month Euribor			0.3315***
			(0.0153)
Bank fixed effects	*yes*	*yes*	*yes*
Number of Observations	22,236	22,189	22,186
Number of Groups	509	509	509
Obs per group: min	23	22	22
avg	43.70	43.60	43.60
max	50	50	50
Hansen test of overid: statistics:	370.72	404.12	183.57
nof para:	11	11	11
p-value:	0.00	0.00	0.00

Source: OeNB. Own calculations.
$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. We calculate Windmeijer corrected robust standard errors (Windmeijer, 2005).
The model is estimated by the system-GMM estimator (Blundell and Bond, 1998) implemented by Sigmund and Ferstl (2021).
The model Non-bank lending rate is given in Eq-.(B.1a). The model Non-bank deposit rate is given in Eq. (B.1b).
The model Extended Non-bank lending rate corresponds to the DAG in Figure B.7.

Appendix C. Pass-Through: Pass-Through FE DOLS: Lending and Deposit rates

We also estimate the now familiar four fixed effects DOLS models:

$$LR_{i,t} = \mu_i + \beta_1 \cdot DR_{i,t} + \sum_{p=0}^{P} \delta_{i,p} \Delta_{t-p} DR_{i,t} + \epsilon_{i,t} \,, \tag{C.1a}$$

$$LR_{i,t} = \mu_i + \beta_1 \cdot DR_{i,t} + \sum_{p=0}^{P} \delta_{i,p} \Delta_{t-p} DR_{i,t} + \gamma_1 \cdot D_t^E \cdot DR_{i,t} + \epsilon_{i,t} \,, \tag{C.1b}$$

$$LR_{i,t} = \mu_i + \beta_1 \cdot DR_{i,t} + \sum_{p=0}^{P} \delta_{i,p} \Delta_{t-p} DR_{i,t} + \gamma_2 \cdot D_t^E + \epsilon_{i,t} \,, \tag{C.1c}$$

$$LR_{i,t} = \mu_i + \beta_1 \cdot DR_{i,t} + \sum_{p=0}^{P} \delta_{i,p} \Delta_{t-p} DR_{i,t} + \gamma_1 \cdot D_t^E \cdot DR_{i,t} + \gamma_2 \cdot D_t^E + \epsilon_{i,t} \,. \tag{C.1d}$$

$\Delta_{t-s} DR_{i,t}$ is defined as $DR_{i,t} - DR_{i,t-1}$ for $p = 0$, $DR_{i,t-1} - DR_{i,t-2}$ for $p = 1$, etc. However, we do not take the leads of the first difference terms into account. Although the theoretical literature suggests using leads and lags, we believe that future values to explain current values make only theoretical sense. In any case, to eliminate any potential endogeneity bias, it is sufficient to include the current value of the absolute difference $\Delta_t DR_{i,t}$ ($p = 0$ and $P = 0$).

In Table C.18, we provide the first robustness checks for our results in Table 8 by estimating the same models with fixed effects DOLS. The results of the fixed effects DOLS estimations are similar to the fixed effects estimations. This similarity justifies the direction of the cointegration relationship chosen in Eq. (6).

Table C.18: Pass-Through FE DOLS: Lending and Deposit rates

	FE DOLS Model 1	FE DOLS Model 2	FE DOLS Model 3	FE DOLS Model 4
Intercept	1.3933***	1.4112***	1.5710***	1.5812***
	(0.0100)	(0.0189)	(0.0225)	(0.0224)
Non-bank DR	1.2058***	1.1952***	1.0686***	1.0534***
	(0.0203)	(0.0236)	(0.0264)	(0.0252)
D^E x DR		−0.1044		0.2402*
		(0.0810)		(0.1257)
D^E			−0.1853***	−0.2388***
			(0.0192)	(0.0261)
Bank fixed effects	*yes*	*yes*	*yes*	*yes*
R-squared	0.87	0.87	0.87	0.87
Adj. R-squared	0.86	0.86	0.87	0.87
Number of obs.	22,348	22,348	22,348	22,348
Number of groups	509	509	509	509
Average. Obs. group	43.91	43.91	43.91	43.91
Min. Obs. group	15	15	15	15
Max. Obs. Group	52	52	52	52

Source: OeNB. Own calculations.
*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$. We use cluster robust standard errors at the bank level.
The dependent variable is the bank-specific lending rate.
The explanatory variables are the intercept, which is the average of all bank-specific fixed effects, the non-bank deposit rate, the interaction term between the dummy variable D^E and the non-bank deposit rate, and the dummy variable D^E, which is 1 if the Euribor is negative and 0 otherwise.
Due to the large number of bank-specific DOLS coefficients, denoted as $\delta_{i,s}$ in Eq. (C.1), they are not presented in this table.
The FE DOLS Model 1 refers to the specification in Eq. (C.1a). In this model, we estimate the pass-through from the bank-specific deposit rate to the bank-specific lending rate.
The FE DOLS Model 2 refers to the specification in Eq. (C.1b). Here, we test if the cointegration between lending and deposit rates breaks down under a negative 3-month Euribor.
The FE DOLS Model 3 refers to the specification in Eq. (C.1c). Here, we test if a negative 3-month Euribor causes a spread reduction between the bank-specific lending and deposit rates.
The FE DOLS Model 4 refers to the specification in Eq. (C.1d). In this specification, we test the change of the cointegration and the spread reduction simultaneously.

Appendix D. Pass-Through: Lending and Deposit Rates with the ECB Deposit Facility Rate

In this section, we replace the 3-month Euribor by the ECB Deposit Facility Rate and estimate the same models as in Table 10 and Table 11. In Table D.19 we obtain the total effect of the ECB Deposit Rate Facility on the bank-specific lending rate and in Table D.20 we estimate the direct effect. We also test the now familiar "spread reduction hypothesis" and the "two true prices hypothesis". It is important to note that we analyze the pass-through between different maturities. The ECB Deposit Facility Rate is an overnight rate, while the bank-specific lending rate is an average rate across all maturities.

For the total effects of the ECB Deposit Rate Facility, we obtain the following results in Table D.19. The pass-through of the ECB Deposit Facility Rate is higher than the pass-through of the 3-month Euribor reported in

Table 10. However, the coefficient of the interaction term "D^{DFR} x DFR" is smaller than the corresponding coefficient of "D^{E} x 3M Euribor" in Table 10, which highlights the importance of the 3-month Euribor as the main reference rate for Austrian banks.

Table D.19: Total Effects: ECB Deposit Facility on Lending Rate

	LR on DFR 1	LR on DFR 2	LR on DFR 3	LR on DFR 4
Intercept	2.3540***	2.3874***	2.3917***	2.3988***
	(0.0023)	(0.0083)	(0.0074)	(0.0090)
ECB DFR	1.8918***	1.8011***	1.8009***	1.7782***
	(0.0190)	(0.0175)	(0.0139)	(0.0161)
D^{DFR} x DFR		0.1981***		0.1065**
		(0.0405)		(0.0448)
D^{DFR}			−0.0815***	−0.0581***
			(0.0124)	(0.0128)
Bank fixed effects	*yes*	*yes*	*yes*	*yes*
R-squared	0.84	0.85	0.85	0.85
Adj. R-squared	0.84	0.84	0.84	0.84
Number of obs.	23,409	23,409	23,409	23,409
Number of groups	509	509	509	509
Average. Obs. group	45.99	45.99	45.99	45.99
Min. Obs. group	26	26	26	26
Max. Obs. Group	52	52	52	52

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. We use cluster robust standard errors at the bank level.
The dependent variable is the bank-specific deposit rate.
In all models, we include an intercept, which is the average of all bank-specific fixed effects.
LR on DFR 1 includes the ECB Deposit Facility Rate as the only exogenous variable.
In LR on DFR 2, we include the ECB Deposit Facility Rate (ECB DFR) and D^{DFR} x DFR, which is the interaction term between the ECB Deposit Facility Rate and a dummy D^{DFR}, which takes the value of 1 if the DFR is negative and 0.
In LR on DFR 3, we include the ECB Deposit Facility Rate and the dummy D^{DFR} which is a dummy variable and takes the value of 1 if the DFR is negative and 0 otherwise.
In LR on DFR 4, we include ECB Deposit Facility Rate, the D^{DFR} x DFR and the D^{DFR}.

Table D.20: Direct Effects: Lending, Deposit rates and ECB Deposit Facility

	LR on DR and DFR M 1	LR on DR and DFR M 2	LR on DR and DFR M 3	LR on DR and DFR M 4
Intercept	1.7790***	1.7643***	1.7349***	1.7462***
	(0.0342)	(0.0392)	(0.0394)	(0.0407)
Non-bank DR	0.7221***	0.7249***	0.7381***	0.7413***
	(0.0440)	(0.0464)	(0.0462)	(0.0492)
ECB DFR	0.8634***	0.8728***	0.9163***	0.8669***
	(0.0584)	(0.0585)	(0.0542)	(0.0600)
D^{DFR} x DR		0.1228***		0.0068
		(0.0421)		(0.0959)
D^{DFR} x ECB DFR		0.0195		0.2060*
		(0.0393)		(0.1081)
D^{DFR}			0.0678***	0.1110*
			(0.0125)	(0.0603)
Bank fixed effects	*yes*	*yes*	*yes*	*yes*
R-squared	0.88	0.88	0.88	0.88
Adj. R-squared	0.88	0.88	0.88	0.88
Number of obs.	23,313	23,313	23,313	23,313
Number of groups	509	509	509	509
Average. Obs. group	45.80	45.80	45.80	45.80
Min. Obs. group	26	26	26	26
Max. Obs. Group	52	52	52	52

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. We use cluster robust standard errors at the bank level.
The dependent variable is the bank-specific lending rate.
In all models, we include an intercept, which is the average of all bank-specific fixed effects.
In the model "LR on DR and DFR M 1", we include the non-bank deposit rate and the ECB Deposit Facility Rate (ECB DFR) as the exogenous variables.
In the model "LR on DR and DFR M 2", we include the non-bank deposit rate, the ECB Deposit Facility Rate (ECB DFR), the interaction term D^{DFR} x DR, and the interaction term D^{DFR} x ECB DFR.
The D^{DFR} x DR is the interaction term between the non-bank deposit rate and a dummy which takes the value of 1 if the ECB DFR is negative and 0.
The D^{DFR} x ECB DFR is the interaction term between the ECB DFR and a dummy which takes the value of 1 if the ECB DFR is negative and 0.
In the model "LR on DR and DFR M 3", we include the non-bank deposit rate, the ECB Deposit Facility Rate, and the D^{DFR} which is a dummy variable and takes the value of 1 if the ECB DFR is negative and 0 otherwise.
In the model "LR on DR and DFR M 4", we include the non-bank deposit rate, the ECB Deposit Facility Rate (ECB DFR), the interaction term D^{DFR} x DR, the interaction term D^{DFR} x ECB DFR, and the D^{DFR}.

Appendix E. Net Interest Margin with the ECB Deposit Facility and the 3-month Euribor

In this subsection, we provide further robustness checks by regressing between the bank-specific net interest margin (NIM) on the ECB Deposit Facility and on the 3-month Euribor. The results provided in this section do not represent a cointegration relationship, since the net interest margin does not have a unit root. We again estimate our four now familiar specifications:

$$NIM_{i,t} = \mu_i + \beta_1 E_t + \epsilon_{i,t} \ , \tag{E.1a}$$

$$NIM_{i,t} = \mu_i + \beta_1 E_t + \gamma_1 D_t^E E_t + \epsilon_{i,t} \ , \tag{E.1b}$$

$$NIM_{i,t} = \mu_i + \beta_1 E_t + \phi_1 D_t^E + \epsilon_{i,t} \ , \tag{E.1c}$$

$$NIM_{i,t} = \mu_i + \beta_1 E_t + \gamma_1 D_t^E E_t + \phi_1 D_t^E + \epsilon_{i,t} \ , \tag{E.1d}$$

The results in Table E.21 can be compared to the results in Table 9 and Table 10. In particular, the coefficient of "3-month Euribor" in model NIM on 3M Euribor 1 (0.20) should be compared to the difference of the coefficients "3-month Euribor" in model "LR on 3-month Euribor 1" (1.07) and "3-month Euribor" in model "DR on 3-month Euribor" (0.79). The difference is 0.28 which is larger than 0.20 because in the NIM we include all interest income and interest expenses (also from the interbank market) and divide them by total assets.

Again, we find that the negative 3-month Euribor has a strong effect on the NIM. This can be seen from the highly significant coefficient of "D^E x 3M Euribor". This coefficient is positive and multiplied by a negative number when the 3-month Euribor is below 0%. It also highlights the fact that banks benefit from a higher 3-month Euribor as they have more room for increasing their interest rate spread components (a_i, b_i) as described in Eq. (3).

Table E.21: Net Interest Margin and 3-month Euribor

	NIM on 3M Euribor 1	NIM on 3M Euribor 2	NIM on 3M Euribor 3	NIM on 3M Euribor 4
Intercept	0.8695^{***}	0.9717^{***}	0.9319^{***}	0.9611^{***}
	(0.0017)	(0.0061)	(0.0053)	(0.0065)
3-month Euribor	0.2033^{***}	0.1033^{***}	0.1443^{***}	0.1129^{***}
	(0.0101)	(0.0093)	(0.0083)	(0.0087)
D^E x 3M Euribor		0.4885^{***}		0.5488^{***}
		(0.0317)		(0.0332)
D^E			-0.1012^{***}	0.0377^{***}
			(0.0099)	(0.0086)
Bank fixed effects	*yes*	*yes*	*yes*	*yes*
R-squared	0.73	0.74	0.73	0.74
Adj. R-squared	0.72	0.73	0.72	0.74
Number of obs.	23,223	23,223	23,223	23,223
Number of groups	509	509	509	509
Average. Obs. group	45.62	45.62	45.62	45.62
Min. Obs. group	23	23	23	23
Max. Obs. Group	52	52	52	52

Source: Own calculations. OeNB. ECB SDW.

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. We use cluster robust standard errors at the bank level.

The dependent variable is the bank-specific net interest margin. The net interest margin is defined as net interest income divided by total assets.

In all models, we include an intercept, which is the average of all bank-specific fixed effects.

NIM on 3M Euribor 1 includes the 3-month Euribor as the only exogenous variable.

In NIM on 3M Euribor 2, we include the 3-month Euribor and D^E x 3M Euribor which is the interaction term between the 3-month Euribor and a dummy which takes the value of 1 if the 3-month Euribor is negative and 0.

In NIM on 3M Euribor 3, we include the 3-month Euribor and the D^E which is a dummy variable and takes the value of 1 if the 3-month Euribor is negative and 0 otherwise.

In NIM on 3M Euribor 4, we include 3-month Euribor, the D^E x 3M Euribor and the D^E.

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