



# Measuring macroeconomic convergence and divergence within EMU using long memory

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## Abstract

This paper tests for convergence of EMU inflation rates and industrial production by testing for the existence of fractional cointegration relations. The notion of fractional cointegration allows for long-term equilibria with a higher degree of persistence than allowed for in the standard cointegration framework. Over the full sample from 1999:Q1–2021:Q4, we find evidence of fractional cointegration in both inflation and industrial production among many country pairs. Our results suggest some evidence for “convergence clusters” among either core or periphery countries in the case of inflation. Similarly, we find stronger evidence of cointegration pairs among core countries for industrial production compared to periphery or mixed core–periphery groups. Testing for a break in the persistence structure, the results show evidence of a break in the persistence of both inflation and industrial production in a number of countries. Inflation persistence is substantially higher after the break, suggesting a higher potential for diverging processes during economic crises. On the contrary, for the case of industrial production, persistence is lower during the post-crisis period.

**Keywords** EMU inflation rates · Industrial production · Fractional cointegration · Persistence breaks

**JEL Classification** F15 · F45 · C32

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## 1 Introduction

Ever since the idea of a European Monetary Union (EMU) was born, economists have discussed the need for member countries to converge in nominal and real terms in order to ensure the stability of the union. This follows from the concern that inflation differentials between member countries with a single monetary policy may lead to differences in real interest rates and in international competitiveness, thereby creating real divergence as measured in current account imbalances. These imbalances are difficult to address if the affected countries share a common currency and thus have permanently fixed nominal exchange rates and a single monetary authority (Mundell 1961).

Early studies before the start of EMU demonstrate some success in terms of nominal convergence of the member states (Beliu and Higgins 2004), whereas others use cointegration analysis to demonstrate potential long-run stability problems with respect to macroeconomic dynamics in the so-called “periphery” countries Italy, Spain and Portugal, Haug et al. (2000). However, the initial convergence in inflation rates was somewhat reversed after the start of EMU, resulting in persistent inflation differentials, where groups of countries showed inflation rates persistently above or below the EMU average (ECB 2003). On the one hand, such differences may imply that countries with below-average per-capita real GDP levels are experiencing a catching-up growth process with temporary above-average real growth and inflation rates (Blanchard and Giavazzi 2002). As long as the catching-up process leads to convergence in productivity levels, it may be regarded as a temporary phenomenon. On the other hand, however, persistent differences in inflation rates within a monetary union impair the efficiency of monetary policy. Since the ECB can only target average inflation within the union, in such a situation monetary policy may be overly expansive in regions with above-average inflation rates. Hence, these regions experience real appreciation, while regions with below-average inflation rates experience real depreciation. The loss in international competitiveness of regions within the monetary union and the resulting current account deficits bears the danger of potentially large economic costs in case of a current account adjustment, Borio and Disyatat (2011), Gnimassoun and Mignon (2016). Indeed, the economic crises following the financial crisis of 2008 and the European sovereign debt crisis after 2010 led to a real depreciation in the “periphery” countries through deflation with large losses in real GDP and employment.

Convergence in levels of inflation rates or industrial production within EMU countries can thus not be confirmed empirically so far. In this paper, we test for a long-run fractionally cointegrated relationship between inflation rates and industrial production (IP) of EMU countries. The existence of such fractionally cointegrated relationships may be related to the concept of economic convergence: Rather than implying convergence in levels, it implies that inflation or industrial production of any two EMU countries has a stable long-run relationship in the sense that a linear combination of the two series is less persistent than the series themselves. This framework thus accounts for potentially persistent deviations from the long-run equilibrium. Importantly, the existence of a long-run equilibrium nevertheless implies that the economies of the currency union with fractional cointegration relationships will eventually return to their stable long-run equilibrium.

To be precise, in this paper we test for fractional cointegration in the weak and the strong sense. That is, we test for the existence of a long-run equilibrium of the inflation and industrial production differentials. When testing for fractional cointegration in the weak sense, we may also find a degree of persistence in the differentials in the non-stationary range. As this still establishes a mean-reverting property of the differentials, we still call this a long-term equilibrium. We are aware that this is an extremely wide and possibly arguable definition of fractional cointegration and of a long-run equilibrium as the residual process is non-stationary with an increasing variance in this case. We still have decided to include these results in the paper as the used methodology covers this case and as we see a reduction in persistence to a mean reverting process. We further include nonzero constants in our cointegration regressions allowing for a non-vanishing difference in the levels of the inflation rates and the industrial production. Thus, in terms of a more strict definition of convergence, it could be said that fractional cointegration is a necessary condition for convergence, but still a weaker concept than, for instance, convergence in levels.

How do different measures of economic convergence relate to economic policy? Convergence in levels for inflation rates and IP would imply that the business cycles of EMU countries converge and the common monetary policy is better able to stabilize individual countries' inflation rates and business cycles. Convergence in the sense that inflation rates or IP have a stable cointegration relationship would imply the existence of a stable long-run equilibrium between the countries, to which they return after shocks disturbing the equilibrium. Thus, even if persistent differentials in levels exist, the monetary union would be stable in the sense that the countries would not drift further apart and the common monetary policy could act within this stable relationship. The same is true in principal if instead of an  $I(0)/I(1)$  cointegration relationship, there exists a fractional cointegration relationship between EMU countries. However, depending on the persistence of the series, it may take longer to return to the long-run equilibrium after a shock. This implies that it may be potentially more difficult for a common monetary policy to stabilize inflation rates or business cycles across the union than under the previous two definitions of economic convergence.

Testing for the existence of a long-run equilibrium with fractional cointegration has the advantage of allowing the degree of integration to take any real number on the unit interval. Therefore, the framework allows for higher flexibility by allowing the long-run equilibrium to be a mean-reverting rather than a short-memory stationary process. Evidence for fractional cointegration with long memory in the equilibrium errors then indicates the existence of a long-run equilibrium, while at the same time deviations from this equilibrium may be very persistent. In contrast with the previous literature, we account for the full EMU period including the financial crisis period from 2008 onwards. However, this makes our analysis vulnerable to spurious results through changes in the convergence mechanism and thus in the cointegrating relation. We therefore apply the regression-based Lagrange Multiplier test introduced by Martins and Rodrigues (2014) to test for structural breaks in the order of integration and estimate the break dates.

We estimate the degree of fractional long memory for inflation and industrial production (IP) in 11 EMU countries for the period from 1999:Q1 to 2021:Q4 where we distinguish between "core" and "periphery" countries. We further test for the existence

of fractional cointegration relationships for inflation and IP among all country pairs of our sample and estimate the memory of the residuals  $d_v$  by using narrow-band least squares estimation for the cointegrating vector  $\beta$ . We find evidence of fractional cointegration in inflation rates among both “core” and “periphery” country groups, with only little evidence for convergence in mixed core–periphery country pairs. Particularly regarding core inflation, it seems that there is stronger co-movement among core countries compared to periphery countries. Moreover, inflation rates in both core and periphery countries show evidence of higher persistence since the beginning of the financial crisis. In terms of real convergence, our results suggest that especially neighboring countries with a strong integration of both trade and labor markets show evidence of real convergence. Moreover, real convergence seems to be stronger among core countries compared to periphery countries. We also find evidence of a break-point in persistence of IP. In contrast with our results for inflation, the results suggest lower, rather than higher persistence after the financial crisis.

Our paper builds on previous work by some of the authors in Leschinski et al. (2021). Using the fractional cointegration methodology, Leschinski et al. (2021) provide empirical evidence for periods of convergence and divergence for long-term EMU government bonds that coincide with bull and bear market periods in the stock market. Specifically, stronger market integration is associated with bull market periods and is more intense among core countries than among periphery countries. Periods of disintegration coincide with bear market periods. Their results thus imply time variation in the degree of convergence of EMU government bonds, with the possibility of divergence even before the financial crisis of 2008. Moreover, the authors report evidence of disintegration in government bonds for all countries during the period of the financial crisis and the European sovereign debt crisis from 2008 onwards.

Our paper further relates to the previous literature using fractional cointegration methods to measure macroeconomic convergence between European economies. In an early study, Beliu and Higgins (2004) use fractional cointegration tests to evaluate the convergence of inflation, long-term interest rates and industrial production of 14 EU countries vis-à-vis Germany. The sample (1957–2001) covers the period until the Euro cash changeover, whereas we focus on the period after the start of EMU in 1999. The authors present evidence of nominal convergence in inflation and long-term interest rates, as these series are fractionally cointegrated with the German counterpart. However, the equilibrium errors display long memory, so that any deviation from equilibrium will be persistent. The authors find no evidence of fractional cointegration in industrial production and, thus, no evidence for real convergence. Meller and Nautz (2012) test for differences in inflation dynamics among European countries before and after EMU using panel estimates of fractional cointegration. Their results suggest that inflation persistence converged and was significantly reduced with the introduction of EMU. More recently, Hualde and Iacone (2017b) analyze both level inflation and inflation differentials between EMU country pairs allowing for long memory and cointegration with the test procedure derived in Hualde and Iacone (2017a). Their results suggest that the “core” economies of EMU are more integrated than the “periphery” countries, as the latter show more persistent inflation differentials. Similarly, Karanasos et al. (2016) study convergence of inflation among EMU countries for the period 1980–2013 using a broad range of test methods, which includes tests allowing for long

memory and for structural breaks. Similar to the study by Hualde and Iacone (2017b), the authors present evidence for three clubs of convergence consisting of “core” EMU countries, while there is evidence of divergence in inflation for the remaining countries. We extend these previous studies, as we account for the effects on nominal and real convergence of the recent period of economic turmoil following the financial crisis in 2008. This means that we test for changes in the cointegration relation and especially for changes in the persistence of the inflation and industrial production differentials. In addition, we compare the results from several semiparametric tests for fractional cointegration by Chen and Hurvich (2006a), Wang et al. (2015) and Souza et al. (2018).

Other studies applying the concept of fractional cointegration evaluate, for instance, the catching-up process of developing countries in terms of economic growth. Both Dufrenot et al. (2012) and Stengos and Yazgan (2014) show that structural factors such as governance and human capital play a crucial role in determining the speed and sustainability of economic growth. Stengos et al. (2018), in a later study, explore the persistence of convergence among countries and the formation of clubs of similar countries based on their economic growth rates. Also, the stability of money demand functions (Caporale and Gil-Alana 2005), the effect of inflation targeting regimes on inflation persistence (Canarella and Miller 2017) or the effect of a monetary policy shock when long memory in the output gap and inflation is accounted for Lovcha and Perez-Laborda (2018).

The remainder of the paper is structured as follows. The econometric methodology of fractional cointegration with long memory is detailed in Sect. 2. Section 3 describes the data set. The results of our analysis are presented and discussed in Sect. 4. Finally, Sect. 5 summarizes and concludes.

## 2 Methodology

Inflation and industrial production persistence in Europe has attracted renewed attention since the foundation of EMU and the implementation of a common monetary policy among the member countries. Persistence is here measured by the order of integration of the inflation series. If this order of integration  $d$  fulfills  $0 < d < 0.5$ , the series is said to exhibit stationary long memory or stationary long-range dependence resulting in a hyperbolic decay of the autocorrelation function and therefore in a slow decay of dependencies between observations far away from each other. Also the impulse responses show a hyperbolic decay. For  $0.5 < d < 1$ , the series is non-stationary, but still mean reverting in the sense that the expected time for returning to its mean is finite. Therefore, the concept of long memory or fractional integration widens the traditional  $I(1)/I(0)$  duality by allowing for highly persistent equilibrium processes.

A significant number of empirical studies that have been adopted in recent years support the existence of long-range dependence in inflation rates. Baillie et al. (2002), Canarella and Miller (2016), Canarella and Miller (2017) Hassler and Wolters (1995), Kumar and Okimoto (2007) and Meller and Nautz (2012) among others measure persistence as a fractionally integrated process. Moreover, fractional integration tech-

niques are able to capture convergence among inflation policies and detect persistence shifts more consistently than the  $I(1)/I(0)$  approach, as assumptions about the  $I(0)$  process of inflation process or the short-run persistence structure are not required (Kumar and Okimoto 2007). Inflation convergence requires the existence of a stable equilibrium relationship, but not exact equality between the inflation rates. A similar definition of convergence can also be applied to real economic variables, such as industrial production (IP).

In general, (fractional) cointegration is an equilibrium concept where the persistence of the cointegrating residual  $d_v$  determines the speed of adjustment toward the cointegration equilibrium  $\beta'X_t$ , and shocks have no permanent influence on the equilibrium as long as  $d_v < 1$  holds. We therefore allow for fractional cointegration and consider a bivariate system of the form

$$X_{1t} = c_1 + \xi_1 Y_t + \Delta^{-(d-b_1)} u_{1t} \mathbb{1}_{\{t>0\}} \tag{1}$$

$$X_{2t} = c_2 + \xi_2 Y_t + \Delta^{-(d-b_2)} u_{2t} \mathbb{1}_{\{t>0\}} \tag{2}$$

$$Y_t = \Delta^{-d} e_t \mathbb{1}_{\{t>0\}}, \tag{3}$$

where the coefficients  $c_1, c_2, \xi_1,$  and  $\xi_2$  are finite,  $0 \leq b_1, b_2 \leq d, L$  is the lag-operator, the fractional differences  $\Delta^d Y_t = (1 - L)^d Y_t$  are defined in terms of generalized binomial coefficients such that

$$(1 - L)^d = \sum_{k=0}^{\infty} \binom{d}{k} (-1)^k L^k = \sum_{k=0}^{\infty} \pi_k L^k,$$

with  $\binom{d}{k} = \frac{d(d-1)(d-2)\dots(d-(k-1))}{k!},$

and  $e_t$  and  $u_t = (u_{1t}, u_{2t})'$  are martingale difference sequences. The memory of both  $X_{1t}$  and  $X_{2t}$  is determined by  $Y_t$  so that they are integrated of the same order  $d$ , denoted by  $X_t \sim I(d)$ , where the memory parameter is restricted to  $d \in (0, 1]$  and  $X_t = (X_{1t}, X_{2t})'$ . Since it is assumed that  $u_{1t} = u_{2t} = e_t = 0$  for all  $t \leq 0$ , the processes under consideration are fractionally integrated of type-II. For a detailed discussion of type-I and type-II processes, we refer to Marinucci and Robinson (1999). The spectral density of  $X_t$  can be approximated by

$$f_X(\lambda) \sim \Lambda_j(d) G \overline{\Lambda_j(d)}, \quad \text{as } \lambda \rightarrow 0^+, \tag{4}$$

where  $G$  is a real, symmetric, finite, and non-negative definite matrix,  $\Lambda_j(d) = \text{diag}(\lambda^{-d} e^{i\pi d/2}, \lambda^{-d} e^{i\pi d/2})$  is a  $2 \times 2$  diagonal matrix and  $\overline{\Lambda_j(d)}$  is its complex conjugate transpose. The periodogram of a process  $X_t$  is defined through the discrete Fourier transform  $w_X(\lambda_j) = \frac{1}{\sqrt{2\pi T}} \sum_{t=1}^T X_t e^{i\lambda_j t}$  as  $I_X(\lambda_j) = w_X(\lambda_j) \overline{w_X(\lambda_j)}$ , with Fourier frequencies  $\lambda_j = 2\pi j/T$  for  $j = 1, \dots, \lfloor T/2 \rfloor$ , where the operator  $\lfloor \cdot \rfloor$  returns the integer part of its argument.

The two series  $X_{1t}$  and  $X_{2t}$  are said to be fractionally cointegrated, if there exists a linear combination

$$\beta' X_t = v_t,$$

so that the cointegrating residuals  $v_t$  are fractionally integrated of order  $I(d - b)$  for some  $0 < b \leq d$ . Obviously, for the model in Eqs. (1) to (3), this is the case for every multiple of the vector  $\left(1, -\frac{\xi_1}{\xi_2}\right)'$  and  $b = \min(b_1, b_2)$ .

We restrict ourselves to a bivariate setup as is common in the literature to avoid identification problems.

According to the definition above, we thus test if among all pairs of EMU countries there exists an equilibrium relationship between the inflation rates or between IP ( $X_{1t}$  and  $X_{2t}$ ), such that the persistence of deviations from the equilibrium denoted by  $v_t$  is reduced compared to that of the individual series. The degree of long memory  $d - b$  in the cointegrating residual determines the persistence of deviations from the long-run equilibrium. The existence of a fractional cointegration relationship is then taken as evidence for economic integration.

### 3 Data

We conduct the analysis of macroeconomic convergence for 11 EMU countries: Austria, Belgium, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Portugal and Spain. As is common in the literature, we term the group of Austria, Belgium, Finland, France, Germany and the Netherlands the “core countries” of EMU, while we call the group of Greece, Italy, Ireland, Spain and Portugal the “periphery countries.” The data sample is obtained from Eurostat and ranges from 1999:Q1 to 2021:Q4. Our sample thus contains the initial EMU country members and starts with the official start of the EMU with the ECB acting as single central bank for the monetary union.

Data for inflation rates are seasonally unadjusted Harmonized Indices of Consumer Prices for all items, with 2015 as base year (2015 = 100). We seasonally adjust each series by using the X-13 R package, developed by the United States Census Bureau. Then, we define annualized inflation rates for each country  $i$  as

$$\pi_{it} = 1200(\log(HCPI_{it}) - \log(HCPI_{it-1}))$$

The series are shown for all countries in our sample in Fig. 1 in appendix. Visual inspection suggests that all EMU countries in our sample experienced a drop in inflation at the start of the financial crisis in 2008, with somewhat more volatile inflation rates after 2008. The general level of inflation seems to be slightly lower after the financial crisis for both core and periphery countries with a rapid increase at the end of the observation period most likely caused by the consequences of the COVID-19 pandemic and the Ukraine crisis. Overall, inflation rates in the periphery countries seem more volatile than those in the core countries.



Data for industrial production are seasonally adjusted and taken in logarithms with 2015 as base year (2015 = 100). The data are shown in Fig. 2 in appendix. As in the case of inflation rates, the pronounced drop in industrial production in 2008 is clearly visible in all countries of our sample. Another drop can be seen for all countries in 2020 during the COVID-19 pandemic. Interestingly, all countries seem to stabilize close the Euro area average after the financial crisis. Not surprisingly the volatility of industrial production seems rather low.

## 4 Empirical results

### 4.1 Analysis of convergence and divergence of EMU inflation rates

#### 4.1.1 Measuring the degree of long memory in EMU inflation rates

In this section, following Kumar and Okimoto (2007), we model inflation rates as a fractionally integrated process and estimate the memory parameters as a measure of persistence for the largest economies in the EMU. Memory parameters for each country are shown in Table 1, where we differentiate between the core economies and the periphery countries. For our estimation, we use the exact local Whittle estimator of Shimotsu (2010) with a 0.7 bandwidth  $d$ -value ( $m = T^{0.7}$ ). As a direct extension of Shimotsu and Phillips (2005), this estimator has the advantage of allowing for nonzero means, while the properties of consistency and asymptotically normal distribution for all values of  $d$  continue to hold. The estimator is given by:

$$\hat{d}_{\text{ELW}} = \operatorname{argmin}_{-1 < d < 3.5} \left\{ \log \hat{G}_m(d) - d \left( \frac{2}{m} \sum_{j=1}^m \log \lambda_j \right) \right\}$$

where  $\lambda_j = 2\pi j/T$ ,  $\hat{G}_m(d) = m^{-1} \sum_{j=1}^m I_{\Delta^d x}(\lambda_j)$ , and  $I_{\Delta^d x}(\lambda)$  denotes the periodogram of the fractionally differenced process  $(1 - L)^d(X_t)$ .

Similar to other findings in the literature (Hualde and Iacone 2017a; Meller and Nautz 2012), inflation persistence is higher for the periphery countries. Memory parameters are larger in the periphery countries, ranging from 0.76 in Spain to 1.05 in Italy. In fact, the mean values of the order of fractional integration are 0.6 and 0.88 for core and periphery countries, respectively.

#### 4.1.2 Testing for fractional cointegration in EMU inflation rates

We apply a number of semiparametric tests for the null hypothesis of no fractional cointegration. The advantage of semiparametric methods is that we do not impose any assumptions on the short-run behavior of the series, apart from mild regularity conditions. Thus, we can avoid spurious findings that might arise due to misspecification. Research on semiparametric tests for fractional cointegration has been an active field in recent years, and there exist a variety of competing approaches. Whereas some



**Table 1** Memory estimates for inflation rates

	Austria	Belgium	Finland	France	Germany	Netherlands	Mean
	0.44	0.97	0.53	0.48	0.24	0.91	0.6
Lower CI	0.24	0.77	0.33	0.28	0.04	0.71	
Upper CI	0.64	1.17	0.74	0.68	0.44	1.11	
	Greece	Ireland	Italy	Portugal	Spain		Mean
	0.94	0.81	1.05	0.82	0.76		0.88
Lower CI	0.74	0.60	0.85	0.61	0.55		
Upper CI	1.15	1.01	1.26	1.02	0.96		

Exact local Whittle estimates of  $d$  with bandwidth  $m = T^{0.7}$  and 95% Confidence Intervals (CI)

approaches rely on the spectral representation of multivariate long memory processes and test whether the spectral matrix  $G$  has full rank or not, other tests are residual-based and test for the strength of integration of the cointegration residuals. To make sure that our results are robust to the way of testing, we apply tests from both strands of the literature.

Souza et al. (2018) use the fractionally differenced process  $\Delta^d X_t$  and the fact that the determinant  $D_{\Delta^d}(\lambda)$  of  $f_{\Delta^d X}(\lambda)$  is of the form  $D_{\Delta^d}(\lambda) \sim \tilde{G}|1 - e^{-i\lambda}|^{2b}$ , where  $\tilde{G}$  is a scalar constant and  $0 < \tilde{G} < \infty$ . An estimate of  $b$  can therefore be obtained via a log-periodogram regression and the null hypothesis that  $b = 0$  can be tested based on the resulting estimate. We denote this spectral-based test in the following as SRFB18.

The test of Wang et al. (2015) (denoted by WWC15) is based on the sum over the fractionally differenced process  $\Delta^{\hat{d}_v} X_{2t}$ , where  $\hat{d}_v$  is an estimate of the memory from the cointegrating residuals obtained using a consistent estimator for the cointegrating vector  $\beta$  such as the narrow-band least squares estimator of Robinson (1994), Robinson and Marinucci (2003), and Christensen and Nielsen (2006), among others. In contrast with that, the test of Chen and Hurvich (2006a) (denoted by CH06) is directly based on  $\hat{d}_v$ , but the cointegrating space is estimated by the eigenvectors of the averaged and tapered periodogram matrix local to the origin. Obviously, these two tests are residual-based.

Leschinski et al. (2020) suggest that the three testing procedures have better performance among a group of eight semiparametric tests, particularly when testing for fractional cointegration. In bivariate cases, SRFB18 presents the best performance. Following their findings, we perform all tests at the 5% significance level. The bandwidth is selected as  $m = T^{0.7}$  for all three testing procedures.<sup>1</sup> The trimming parameter  $r$  is set to 3 for SRFB18 and the integer for averaging the periodogram is 25 for CH06. As fractional cointegration needs as a core assumption that the order of integration is equal between the series, we use pairwise tests as suggested by Robinson and Yajima (2002) to test for the equality of the memory parameters. The results shown in Table 2 suggest that the hypothesis of a common memory parameter is rejected for the case of Germany with Netherlands and the periphery group, as well as for the cases of Bel-

<sup>1</sup> We also use two different bandwidths,  $m = T^{0.65}$  and  $m = T^{0.75}$ . Our main findings are similar for both cases.

gium and France with both Greece and Italy at the 5% significance level. Therefore, these pairs are not included in our analysis. Next, we test for pairwise cointegrating relationships under the null hypothesis of no fractional cointegration.

An example of our analysis is in Table 11 in appendix where we report the test results for Germany as the reference country, since it is the largest economy within the EMU. There is evidence for fractional cointegration of inflation rates with the German counterpart in all four countries we were allowed to test. For the cases of Austria and Belgium, the null hypothesis is rejected for all three testing procedures. Finland and France suggest inflation convergence for two out of three testing procedures. We repeat the testing procedures for all possible pairs.

As a second step, we estimate the cointegration vector  $\beta$  as well as the memory parameters  $d_v$  by using narrow-band least squares estimation. Robinson (1994) shows that NBLS estimation is consistent under stationary cointegration whereas an OLS approach might not retain consistency.

We thus repeat the NBLS estimation between all EMU country pairs and we present the estimated values of the memory of the residuals in Table 3. Numbers in parentheses refer to the memory reduction parameter,  $b$ . Only the cases where the hypothesis of a common memory parameter is not rejected, at least one of the testing procedures are statistically significant and the memory of  $d_v$  is less than the memory of both of the individual series are presented. We repeat the analysis without testing the hypothesis of a common memory parameter and the results are the same. As can be seen in Table 3, results are not symmetric as it is expected for cointegration relations. This is due to the irregular behavior of the inflation series during the crisis period. It is well known that such data irregularities can lead to asymmetric cointegration (see, for example, Enders and Siklos 2001). Last, memory reduction parameters for inflation rates range between 0.11 and 0.68. Therefore, our analysis tests for both weak and strong fractional cointegration. It can also be seen that the reductions in the memory parameter are not trivial.

For the core countries, inflation rates between Germany, Austria and the rest of the countries are estimated to have the strongest cointegration relation, as the adjustment to equilibrium is achieved faster after potential shocks ( $d_v$  ranges between  $-0.24$  and  $0.48$ ). Belgium, France, Finland and the Netherlands are all estimated to have fractional cointegration relationships, but with slower adjustment to equilibrium overall.

For the periphery countries (see the lower part of Table 3), cointegration relationships exist between the pairs of Greece–Portugal and Italy–Spain. A few mixed core–periphery cointegration pairs exist between Netherlands with Ireland, Italy and Portugal, as well as between Belgium and Spain. On average, we observe a stronger ‘convergence club’ among the core countries.

As a robustness check, we re-estimate pairwise fractional cointegration for core inflation. Specifically, we obtain the Harmonized Consumer Price Index excluding energy and unprocessed food from Eurostat. The data sample covers the period between Q1.2000 and Q4.2021 due to missing values for the majority of the countries. We seasonally adjust the series and obtain the annualized core inflation rates as described in Sect. 3. The memory estimations of core inflation rates are presented in Table 13 in appendix. The memory estimations of the cointegrating residuals along with the memory reduction parameters are shown in Table 4.

**Table 2** Pairwise testing for common memory integration in inflation rates

EMU countries	Belgium	Finland	France	Germany	Netherlands	Greece	Ireland	Italy	Portugal	Spain
Austria	0.09	0.09	0.35	1.72	1.13	1.90	0.74	1.82	0.53	1.15
Belgium		0.01	0.28	1.59	1.26	2.15**	0.89	2.06**	0.64	1.23
Finland			0.23	1.52	1.18	1.85	0.87	1.78	0.61	1.09
France				1.37	1.39	2.36**	1.12	2.51**	0.91	1.57
Germany					2.69**	3.41**	2.47**	3.36**	2.10**	2.47**
Netherlands						0.77	0.38	0.49	0.6	0.14
Greece							1.15	1.15	1.36	1.05
Ireland								0.97	0.24	0.28
Italy									1.26	0.81
Portugal										0.51

Results of Robinson and Yajima (2002) test. \*\*Denotes significance of the test statistic at the 5% level where the critical value is 1.9599

**Table 3** Pairwise fractional cointegration on inflation rates

	Austria	Belgium	Finland	France	Germany	Netherlands	Greece	Ireland	Italy	Portugal	Spain
Austria			0.26 (0.27)	0.22 (0.26)	-0.24 (0.68)						
Belgium											0.44 (0.53)
Finland	0.42 (0.11)					0.33 (0.58)					
France	0.27 (0.21)				0.12 (0.36)						
Germany	-0.14 (0.58)			0.00 (0.76)							
Netherlands			0.48 (0.43)					0.41 (0.5)	0.61 (0.44)	0.54 (0.37)	
Greece										0.69 (0.25)	
Ireland								0.62 (0.29)			
Italy								0.5 (0.55)			0.5 (0.55)
Portugal							0.54 (0.4)				
Spain		0.52 (0.45)							0.56 (0.35)		

ELW estimates,  $d_{ij}$ , based on bandwidth  $m = T^{0.7}$ . Numbers in parentheses refer to memory reduction parameters

**Table 4** Pairwise fractional cointegration on core inflation rates

	Austria	Belgium	France	Germany	Netherlands	Ireland	Italy	Portugal	Spain
Austria		0.18 (0.14)		0.08 (0.24)					
Belgium	0.06 (0.26)			0.14 (0.18)					
France							0.59 (0.41)		
Germany	0.00 (0.32)	0.16 (0.12)							
Netherlands							0.82* (0.18*)		
Ireland								0.64 (0.43)	
Italy					0.83* (0.17*)			0.85 (0.22)	
Portugal			0.75 (0.25)			0.54 (0.53)	0.96 (0.11)		0.66 (0.52)
Spain								0.63* (0.55*)	

ELW estimates,  $d_b$ , based on bandwidth  $m = T^{0.7}$ . Numbers in parentheses refer to memory reduction parameters. \*Cases which the main assumption of equal memory parameters does not hold

Comparing our results for fractional cointegration of EMU inflation (Table 3) and core inflation rates (Table 4), we find even less evidence of nominal convergence in mixed core–periphery country pairs with respect to core inflation. Similar to our previous results for overall inflation in Table 3, nominal convergence in core inflation seems to be stronger among core country groups than among periphery country groups, as it is suggested by the lower estimates of the memory  $d_v$ . We repeat the analysis without testing for equal memory parameters. Here, we find in addition evidence of cointegration between Italy–Netherlands and Portugal–Spain.

#### 4.1.3 Testing for a break in fractional integration of EMU inflation rates

In addition to our analysis of fractional cointegration, we test for a single break in the order of fractional integration in inflation rates. This allows us to test whether persistence and thereby potential convergence or divergence processes in inflation changed over time. This could be due, for instance, to the disruptions of the global financial crisis and the European sovereign debt crisis. Hence, we perform a regression-based Lagrange Multiplier test introduced by Martins and Rodrigues (2014) that generalizes the conventional integration approaches to the fractional integrated process context. Their method is based on the recursive forward and reverse estimation of the Hassler and Breitung (2002) and Robinson (1994) test statistics. The  $X_t$  series is first filtered as in (1–3) and persistence changes occur in the interval  $[\tau T]$ , with  $\tau \in [\Lambda_l, \Lambda_u]$  and  $0 < \Lambda_l < \Lambda_u < 1$  as is usually assumed in the structural breaks literature. Then, the auxiliary regression is given by:

$$x_t = \phi(\tau)x_{t-1}^* + e_t, t = 2, \dots, [\tau T] \quad (5)$$

where  $x_t = (1 - L)^{d_0}y_t$  and  $x_{t-1}^* = \sum_{j=1}^{t-1} \frac{x_{t-j}}{j}$ . The test statistic is formed by recursively estimating (5), the least squares t-statistic for  $\hat{\phi}(\tau) = 0$  and the auxiliary regression in the time-reversed series for the remaining  $(1 - \tau)T$  observations. This method is able to work with unknown date of the shifts, trends and serial correlations.

In what follows, we will denote by  $\hat{s}$  the estimated point of the persistence shift and by  $d_1$  the order of integration before the shift and by  $d_2$  the order of integration after the break. Table 5 suggests evidence of a structural break in inflation persistence for eight out of the eleven EMU countries. Specifically, Belgium, France, Greece, Ireland, Italy and Spain's estimated breakpoints ( $\hat{s}$ ) occur from Q2.2006 to Q2.2008. This corresponds to the time period covering the beginning of the subprime crisis, i.e., a heightened level of financial stress, to the beginning of the global financial crisis following the default of Lehman Brothers on September 15, 2008. Comparing  $d_1$  and  $d_2$ , the results suggest a shift from  $-0.5 < d < 0.5$  to  $0 < d < 1$  at the time of  $\hat{s}$ , that is an increase in inflation persistence after the break. The alternative hypothesis of decreasing memory holds for the case of Portugal in Q3.2010.

In summary, we find that inflation persistence since the beginning of EMU is non-stationary mean-reverting for the majority of the sample. A test in persistence change is showing evidence of breaks in the beginning of the financial crisis where we observe memory parameters below 0.5 in the pre-crisis period, and substantially higher values

**Table 5** Persistence change test for inflation rates

EMU country	Test-statistic	Date	$d_1$	$d_2$
Belgium	-2.4**	Q4/2006	0.21	0.86
France	-5.62***	Q3/2006	-0.28	0.61
Germany	-1.83*	Q3/2005	-0.12	0.11
Greece	-5.32***	Q3/2007	0.06	1.15
Ireland	-3.32***	Q2/2008	0.3	0.67
Italy	-6.29***	Q3/2007	0.28	1.24
Portugal	-4.54***	Q3/2010	0.83	0.42
Spain	-5.49***	Q2/2006	-0.05	0.81

\*, \*\*, \*\*\* Indicate levels of significance at 10%, 5%, 1%, respectively. “ $d_1$ ” and “ $d_2$ ” refer to the memory parameters of the respective sub-period of the estimated breakpoint

**Table 6** Memory estimates for industrial production

	Austria	Belgium	Finland	France	Germany	Netherlands	Mean
	1.00	0.97	1.03	0.76	1.03	0.97	0.96
Lower CI	0.8	0.77	0.83	0.56	0.83	0.77	
Upper CI	1.21	1.18	1.24	0.97	1.24	1.18	
	Greece	Ireland	Italy	Portugal	Spain		Mean
	1.20	0.94	0.92	0.87	1.02		0.99
Lower CI	1.00	0.74	0.71	0.67	0.82		
Upper CI	1.41	1.15	1.12	1.08	1.23		

Exact local Whittle estimates of  $d$  with bandwidth  $m = T^{0.7}$  and 95% Confidence Intervals(CI)

in the post-crisis period. Moreover, the increase in inflation persistence during the crisis period implies potentials for inflation divergence. Finally, while we find evidence of fractional cointegration in inflation among the full sample, the core countries tend to be fractionally cointegrated with a faster speed of adjustment, see also Hualde and Iacone (2017b) and Karanasos et al. (2016).

## 4.2 Analysis of convergence and divergence of EMU industrial production

### 4.2.1 Measuring the degree of long memory of EMU industrial production

Following the analysis of convergence in EMU inflation rates in the previous section, we next investigate the convergence of industrial production between the same countries. First, as in Sect. 4.1.1 we estimate the memory parameter of each country. Results are presented in Table 6.

We observe that the memory estimates of all cases are nonstationary mean-reverting or nonstationary as  $d > 0.5$  or  $d \approx 1$ , except of Greece which exceeds the value of 1.



#### 4.2.2 Testing for fractional cointegration of EMU industrial production

Next, we test for fractional cointegration in EMU industrial production among all possible country pairs. In Table 7, the hypothesis of memory equality is not rejected at any of the cases. Similar to the previous section, we present in Table 12 in appendix the test results for cointegration between industrial production in Germany and the remaining EMU countries.

Table 8 reports the NBS estimates of the memory parameters,  $d_v$ , of the IP fractional cointegration relation along with the memory reduction parameters in all country-pairs. Here, IP convergence is suggested mostly between core countries. For instance, German IP is fractionally cointegrated with Austria and the Netherlands. This result mirrors the strong integration of these economies via trade links and labor market integration. Similar arguments apply to the fractional cointegration between Belgium and the Netherlands and among the periphery countries between Portugal and Spain.

We check for the robustness of our results in Table 8 by testing for fractional cointegration relationships in real GDP. Specifically, we obtain data for the chain-linked volumes of GDP at 2015 market prices from Eurostat starting in Q1.1999 until Q4.2021. The memory estimates of the logarithm of the real GDP are presented in Table 14 in appendix, whereas the memory estimates of the cointegration residuals are shown in Table 9.

In line with our previous results for IP in Table 8, we find that convergence in real log GDP is suggested mainly between the core countries of EMU. Spain is the only periphery country to be fractionally cointegrated with an EMU country (Finland). Thus, we have no evidence of fractional cointegration among periphery-country pairs.

#### 4.2.3 Testing for a break in fractional integration of EMU industrial production

Finally, we apply the test by Martins and Rodrigues (2014) to test for a single break in the order of fractional integration in EMU industrial production. The results are shown in Table 10. As can be seen, we find a significant break in IP persistence in six out of the eleven countries between Q1.2009 until Q2.2011. Here, all countries have experienced a decrease in IP persistence after the estimated breakpoint. This is in line with the previously mentioned observation that the financial crisis resulted in convergence of the industrial production to the Euro area average for all countries. As a consequence, IP is more stable with less pronounced swings and therefore a lower degree of persistence.

### 5 Conclusion

In this paper, we apply methods of fractional cointegration to investigate the degree of real and nominal convergence between EMU countries. Specifically, we model both inflation rates and industrial production as fractionally integrated processes and estimate the memory parameters as a measure of persistence. Alternatively, other approaches looking at long-run equilibria can be based on the fractional cointegrated

**Table 7** Pairwise testing for common memory integration in industrial production

EMU countries	Belgium	Finland	France	Germany	Netherlands	Greece	Ireland	Italy	Portugal	Spain
Austria	0.01	0.27	0.47	0.06	0.40	1.04	0.28	0.67	0.12	0.30
Belgium		0.26	0.47	0.06	0.39	1.04	0.26	0.23	0.11	0.29
Finland			0.68	0.19	0.59	0.82	0.01	0.05	0.08	0.1
France				0.58	0.25	1.67	0.66	1.11	0.74	1.15
Germany					0.36	0.96	0.15	0.20	0.06	0.26
Netherlands						1.25	0.55	0.46	0.35	0.52
Greece							0.87	0.94	1.12	0.9
Ireland								0.05	0.08	0.11
Italy									0.18	0.1
Portugal										0.27

Results of Robinson and Yajima (2002) test. \*\* Denotes significance of the test statistic at the 5% level where the critical value is 1.9599

**Table 8** Pairwise fractional cointegration on industrial production

	Austria	Belgium	Germany	Netherlands	Italy	Portugal	Spain
Austria		0.85 (0.15)	0.95 (0.10)		0.88 (0.12)		
Belgium	0.85 (0.15)						
Germany	0.94 (0.10)			0.95 (0.10)			
Netherlands			0.93 (0.10)				
Italy	0.88 (0.12)						
Portugal							0.76 (0.26)
Spain						0.79 (0.23)	

ELW estimates,  $d_V$ , based on bandwidth  $m = T^{0.7}$

**Table 9** Pairwise fractional cointegration on real GDP

	Austria	Belgium	Finland	France	Germany	Netherlands	Spain
Austria		0.85 (0.10)		0.78 (0.15)	0.86 (0.11)		
Belgium	0.86 (0.10)						
Finland							0.78 (0.27)
France	0.76 (0.17)					0.77 (0.19)	
Germany	0.86 (0.11)						
Netherlands				0.81 (0.15)			
Spain			0.78 (0.27)				

ELW estimates,  $d_V$ , based on bandwidth  $m = T^{0.7}$

VAR approach as detailed in Johansen (2008), Johansen and Nielsen (2010) and Johansen and Nielsen (2012). The analysis covers the full EMU period from 1999:Q1 to 2021:Q4 for the 11 initial EMU countries consisting of both “core” and “periphery” countries. Moreover, we test for breaks in persistence with the test by Martins and Rodrigues (2014). We are aware that it is a possible drawback of our approach that it

**Table 10** Persistence change test for industrial production

EMU country	Test-statistic	Date	$d_1$	$d_2$
Austria	-2.50***	Q4/2010	1.14	0.87
France	-2.74***	Q1/2011	1.51	0.48
Germany	-2.27**	Q2/2011	1.29	0.72
Italy	-2.38**	Q3/2010	1.43	1.02
Portugal	-4.77***	Q1/2009	1.22	0.38
Spain	-2.45***	Q1/2009	1.37	0.74

\*\*, \*\*\*Indicate levels of significance at 5%, 1%, respectively. " $d_1$ " and " $d_2$ " refer to the memory parameters of the respective subperiod of the estimated breakpoint

is only possible to test for one break at a time and subsample analyses are necessary when testing for multiple breaks.

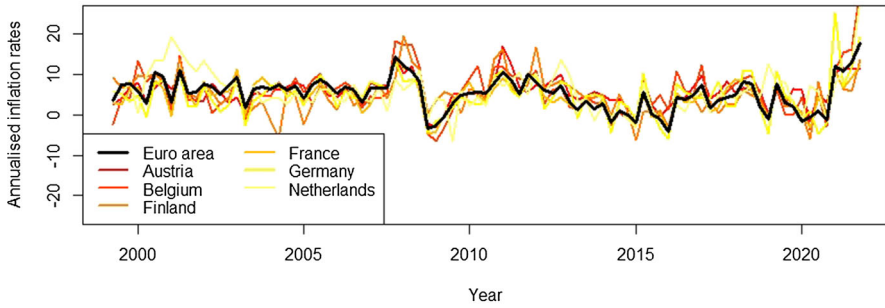
To test for the existence of fractional cointegration relationships for inflation and IP among all country pairs of our sample, we estimate the memory parameters of the residuals  $d_v$  of the fractional cointegration relation using the NBLs estimation on the cointegrating vector  $\beta$ .

We find evidence of fractional cointegration among EMU countries for both inflation and real IP growth. In the case of inflation, the results suggest more cointegration relations among core or among periphery countries. This implies the existence of separate "convergence clubs" within EMU inflation rates over the whole estimation period. This could be an indicator of macroeconomic divergence processes. In the case of EMU industrial production, we find stronger evidence of fractional cointegration among neighboring countries and specifically among core-country pairs.

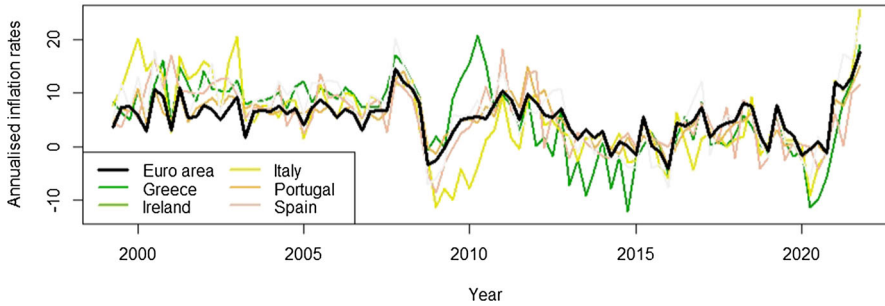
In addition, our results suggest breaks in the persistence of both inflation rates and industrial production for a majority of countries in our sample. In the case of inflation rates, we find lower persistence before the financial crisis in 2007–2008 and substantially higher persistence in the crisis period. The higher persistence of the series during the crisis period carries the danger of diverging processes in case of asymmetric shocks. In the case of industrial production, persistence swings are less pronounced, which leads to a more stable IP after the estimated breakpoints.

To sum up, our analysis gives a detailed picture of time-variation in real and nominal convergence processes since the start of the EMU. While especially inflation in EMU countries has become more persistent after the financial and the European sovereign debt crisis, we still find evidence of fractional cointegration in many country-pairs for the full sample period. Still, in light of the recession and the rise in inflation after the COVID-19 pandemic and the attack on Ukraine, our results tell a cautious tale about the potential vulnerability of macroeconomic convergence within EMU during economic crisis periods.

Moreover, our results suggest several implications for macroeconomic policies within the EMU: First, we do not find evidence of stable long-run relationships of inflation and industrial production in all country-pairs. This implies that macroeconomic convergence within EMU is far from complete. Hence, a high degree of cooperation in economic policy will be needed in order to push macroeconomic convergence fur-



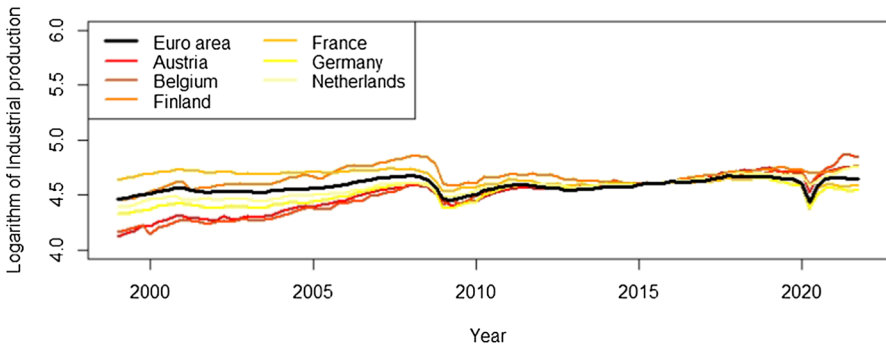
(a) Inflation rates in core countries



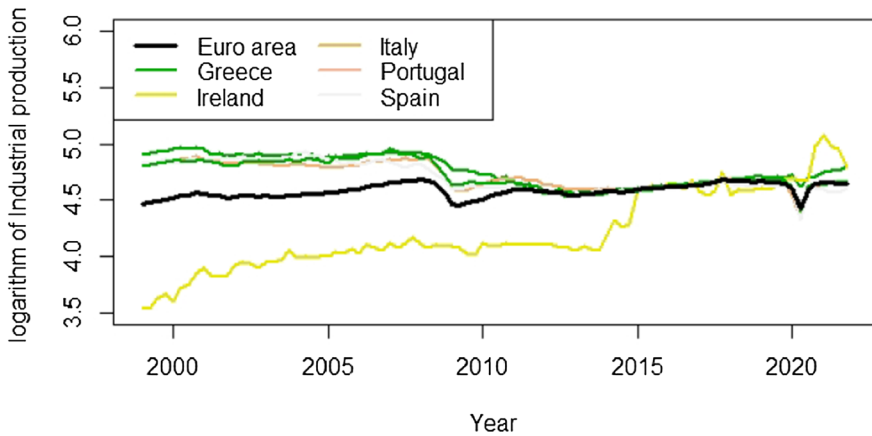
(b) Inflation rates in periphery countries

**Fig. 1** Inflation rates of EMU countries

ther. Second, there is evidence for separate “convergence clubs” within EMU both before and after the financial crisis of 2008. This implies a continuing threat of real appreciation or depreciation among countries in the currency union and potentially inefficiency of monetary policy if the inflation rates deviate persistently. Thus, a need for further country-specific policy measures to foster convergence also in terms of inflation is highlighted by our results. Third, estimating fractional cointegration relationships implies potentially long-lasting deviations from the long-run equilibrium in case of shocks occurring. Thus, even if our estimates find that long-run equilibria among country pairs exist, these equilibria may be persistently disturbed after shocks. This poses further challenges for economic policy in the monetary union.



(a) Log of industrial production index in core countries



(b) Log of industrial production index in periphery countries

Fig. 2 Industrial production rates of EMU countries

## Declarations

**Conflict of interest** The authors declare no conflict of interest.

## Appendix

The results of the three semiparametric tests we used in our analysis of pairwise fractional cointegration, with Germany as a reference country, are presented in Tables 11 and 12. The tests by Souza et al. (2018), Wang et al. (2015), Chen and Hurvich (2006b) are denoted as SRFB18, WWC15 and CH06, respectively. Here, the null hypothesis is no fractional cointegration.

**Table 11** Pairwise testing for stationary fractional cointegration in inflation rates

Germany/	SRFB18	WWC15	CH06
Austria	2.698**	39.166**	2.219**
Belgium	5.145**	36.7907**	3.3341**
Finland	4.0064**	6.1668**	0.8574
France	3.2392**	10.9415**	0.7339

Critical values at  $\alpha = 5\%$  are 1.960 for both SRFB18 and WWC15, as well as 1.386 for CH06. \*\*Denotes significance of the test statistic at the 5% level. Here,  $H_0$ : no fractional cointegration

**Table 12** Pairwise testing for stationary fractional cointegration in industrial production index

Germany/	SRFB18	WWC15	CH06
Austria	2.469**	1.6985	1.012
Belgium	1.487	1.6484	0.9535
Finland	1.4179	1.6596	0.6145
France	-1.9881	1.1663	-1.7366
Netherlands	4.8797**	1.7032	1.2495
Greece	-0.2130	1.3652	-1.772
Ireland	-1.715	0.9922	-0.4169
Italy	-2.3022	1.5109	-2.1674
Portugal	-2.1879	1.8423	-2.1039
Spain	-1.8027	1.3569	-1.8181

Critical values at  $\alpha = 5\%$  are 1.960 for both SRFB18 and WWC15, as well as 1.386 for CH06. \*\*Indicates significance at the 5% level. Here,  $H_0$ : no fractional cointegration

**Table 13** Memory estimates for core inflation rates

	Austria	Belgium	Finland	France	Germany	Netherlands	Mean
	0.32	0.28	1.33	0.81	0.23	0.97	0.66
Lower CI	0.114	0.069	1.123	0.599	0.016	0.759	
Upper CI	0.531	0.486	1.541	1.01	0.4345	1.17	
	Greece	Ireland	Italy	Portugal	Spain		Mean
	1.20	0.79	1.00	1.07	1.18		1.04
Lower CI	1.00	0.59	0.80	0.86	0.97		
Upper CI	1.41	1.01	1.21	1.28	1.39		

Exact local Whittle estimates of  $d$  with bandwidth  $m = T^{0.7}$  and 95% confidence intervals (CI)



**Table 14** Memory estimates for real GDP

	Austria	Belgium	Finland	France	Germany	Netherlands	Mean
	0.93	0.94	1.05	0.84	0.97	0.96	0.95
Lower CI	0.73	0.74	0.85	0.63	0.77	0.75	
Upper CI	1.13	1.14	1.25	1.04	1.18	1.16	
	Greece	Ireland	Italy	Portugal	Spain		Mean
	1.23	1.02	0.73	0.83	0.95		0.95
Lower CI	1.03	0.82	0.53	0.62	0.75		
Upper CI	1.44	1.22	0.94	1.03	1.16		

Exact local Whittle estimates of  $d$  with bandwidth  $m = T^{0.7}$  and 95% confidence intervals (CI)

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