



**Effects of Covid-19 on Euro Area GDP and Inflation:
Demand vs. Supply Disturbances**

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This paper analyzes the macroeconomic effects of the Covid-19 epidemic on Euro Area (EA) GDP and inflation, using a stylized New Keynesian model. Covid is interpreted as a combination of aggregate demand and aggregate supply disturbances. Offsetting aggregate demand and supply changes are shown to account for the stability of EA inflation, in the face of Covid. The evidence presented here indicates that Covid-induced aggregate demand and supply shifts were persistent. An aggregate supply contraction is identified as the dominant force driving the sharp fall of EA GDP in 2020.

JEL codes: E31, E32, E43, E52, E65.

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1. Introduction

The global Covid-19 health crisis that erupted in early 2020 has triggered a sharp contraction in worldwide real activity. This paper studies the response of Euro Area (EA) GDP and inflation to the Covid crisis. The Covid epidemic is a very large and truly *unexpected* and *exogenous* disturbance. This distinguishes Covid from standard macro shocks in “normal” times. Due to its huge size, the Covid shock is likely to have dominated other macroeconomic disturbances in 2020-21. Thus it is plausible that macroeconomic developments, in 2020-21, were mainly caused by Covid. Covid thus provides a unique laboratory for analyzing the determination of real activity and prices in the face of a large exogenous disturbance. Understanding the transmission of exogenous disturbances is, e.g., important for designing effective policy responses. A vast (and growing) literature has analyzed the economic repercussions of Covid.¹ Early studies on the macroeconomic effects of Covid include Eichenbaum et al. (2020) who incorporated an epidemiological model into a Real Business Cycle framework; and Guerrieri et al. (2020) and Pfeiffer et al. (2020) who considered New-Keynesian models.

The contribution of the present paper is to provide *simple* analytics of the macroeconomic transmission of Covid, using a stylized New Keynesian model. An important feature of the analysis here is that it compares the adjustment to the Covid shock in a liquidity trap, i.e. a situation in which the zero lower bound (ZLB) constraint for the nominal interest rate binds, to adjustment when the ZLB constraint does *not* bind. The framework is used to assess the relative role of aggregate demand (AD) and aggregate supply (AS) shifts, during Covid. The use of a liquidity trap model is motivated by the fact that Covid hit the EA (and other advanced economies) in a situation of persistently ultra-low interest rates. With monetary policy interest rates at the zero lower bound (ZLB), the central bank cannot stimulate real activity by lowering the policy interest rate.² AS shifts are modeled as total factor productivity (TFP) shocks, while AD shifts are modeled as shocks to the household subjective discount rate.

As documented below, Covid induced a reduction of EA GDP of about 7.8% in 2020, but Covid only had a negligible effect on inflation. The model suggests that the macroeconomic situation under Covid must be interpreted as the outcome of *joint* AD and AS shocks, whose

¹ The IDEAS/RePec database lists approx. 15000 economic research papers related to Covid [May 2021].

² Liquidity traps have also been considered in a small number of other macroeconomic studies of Covid, however, the focus of those studies is different. For example, Fornaro and Wolf (2020) use an endogenous growth model of a liquidity trap to highlight possible adverse long-term effect on productivity (‘scarring’); Pfeiffer et al. (2020) and Clemens and Roeger (2021) use rich quantitative models with a ZLB to analyze fiscal policy responses to Covid.

offsetting effects stabilized inflation. The muted response of inflation indicates that Covid did not affect the output gap, so that the Covid-induced contraction of GDP corresponds to the contraction that would have obtained in a flex-price economy. The model suggests that Covid amounted to a 7.8% drop in EA TFP during 2020; this AS disturbance was accompanied by a fall in the subjective rate of time preference, that stabilized the natural real interest rate.

The size of the concomitant model-inferred AD and AS shocks that reproduce the actual GDP contraction of 2020, at an unchanged inflation rate, is *invariant* to the persistence of these shocks, and to other model parameters.

However, the model-inferred *relative* contribution of AD vs. AS shocks to the GDP contraction, in a liquidity trap, is sensitive to the assumed shock persistence. When the Covid-induced AD and AS shifts are assumed very transient, the liquidity trap model attributes the Covid GDP contraction to a fall in AD (low household demand). However, the (predicted) slow recovery of EA output in 2021 indicates that the adverse AD and AS shifts induced by Covid are persistent (annual autocorrelation: 0.6). Under realistic shock persistence, the liquidity trap model attributes the Covid output contraction in 2020 to the negative effect of Covid on AS. However, AS and AD shifts mattered equally for the observed stability of inflation. In a liquidity trap, persistent negative AS shifts *lower* inflation, while persistent adverse AD shifts *raise* inflation. If Covid had solely affected AS, the EA would thus have experienced a sharp *fall* in inflation and a contraction in GDP that would have been deeper than the actual contraction, according to the liquidity trap model; that model suggests that the contraction in AD had a *stabilizing* effect on EA GDP during the Covid crisis.

Interestingly, a model version that abstracts from the ZLB constraint (and assumes that the central bank sets the policy rate according to a Taylor rule) produces the same estimates of the Covid-induced AD and AS shifts, as the liquidity trap model. In that no-liquidity-trap model version, the Covid output contraction is unambiguously interpreted as an AS shift (irrespective of shock persistence). However, a model version without ZLB constraint predicts that if Covid had solely affected AS, the EA would have experienced a sharp *rise* in inflation and a contraction in GDP that would have been smaller than the actual contraction.

Section 2 presents empirical evidence on the EA macroeconomy during Covid. Sect. 3 presents the model. Sect. 4 interprets the EA macroeconomy during Covid through the lens of the model. Sect. 5 concludes.

2. The EA macroeconomy under Covid

Table 1 reports predicted and realized annual EA macro variables for the years 2019-2021, as published by the European Commission (EC) in its November 2019 and May 2021 Economic Forecasts (European Commission (2019, 2021)).³ Cols. (1)-(3) are predictions for 2019-2021 taken from the EC November 2019 forecast.⁴ Col. (4) shows predictions for 2021 from the May 2021 Forecast. Cols. (5),(6) show actual (realized) variables for 2019 and 2020, respectively (as reported in the May 2021 Forecast). Cols. (7),(8) show pre-Covid forecast errors, i.e. the difference between actual variables in 2019 and 2020 and the corresponding EC predictions made in Nov. 2019. Finally, Col. (9) shows forecast revisions, between Nov. 2019 and May 2021, for 2021 variables.

The forecast errors for 2019 variables (Col. (7)) are very small, but the forecast errors for 2020 variables (Col. (8)) are substantial, and so are the forecast revisions for 2021 variables (Col. (9)). I interpret the forecast errors for 2020 variables, and the forecast revisions for 2021 variables, as (largely) reflecting the effect of Covid. Due to its large size and unexpected nature, the Covid shock is likely to have swamped the effect of other unexpected disturbances in 2020 (as argued above).

In November 2019 the European Commission predicted EA GDP (Y) and private consumption (C) growth rates (year-on-year, y-o-y) and inflation (π) for 2020 of 1.2%, 1.2% and 1.5%, respectively (see Col. (1), Table 1). Actual 2020 growth rates/inflation were -6.6%, -8.0% and 1.5%, respectively (Col. (6)). Thus the realized growth rates of EA GDP and consumption in 2020 were 7.8 and 9.2 percentage points (ppt) below predicted values (Col. (8)). By contrast, realized EA inflation in 2020 equaled predicted inflation.

Between the November 2019 and May 2021 forecasts, we note a +3.1% revision of y-o-y predicted GDP growth for 2021 (Col. (9)). That forecast revision amounts to a -4.7% revision in the predicted *level* of 2021 GDP.⁵ Thus, Covid is predicted to have a persistent negative effect on the level of future GDP. By contrast, we notice only a very small revision in 2021 inflation: -0.3% (Col. (9)).

³ The EC Economic Forecast is published twice a year (spring and autumn).

⁴ Statistics for 2019 shown in Col. (1) are predictions, as these statistics were published before the end of 2019.

⁵ The level of 2021 GDP predicted in the May 2021 EC forecast falls short by 4.7 ppt of the GDP level that would have obtained if the 2020 and 2021 growth rates predicted in Nov. 2019 had actually materialized: $(-6.6\%+4.3\%)-(1.2\%+1.2\%)=-4.7\%$.

These are the key empirical observations that the theoretical model below will address. In summary: Covid triggered a sharp contraction of GDP that is predicted to be persistent; by contrast, Covid did not change inflation in 2020, and its effect on predicted 2021 inflation is very muted.

Table 1 also reports predicted and actual growth rates of EA government consumption (G), investment (I), employment (L) and of labor productivity (Y/L) in 2020 and 2021; also shown is the actual and predicted (merchandise) trade balance/GDP ratio (NX/Y). Covid only had a very small effect on EA government consumption in 2020 (-0.2%), it depressed 2020 investment by 9.2%, and it led to a slight trade balance improvement, +0.6 ppt (see Col. (8)). Thus, Covid had a combined effect on EA government consumption and the trade balance that is negligible compared to the large GDP contraction. The theoretical model discussed below will abstract from government consumption and foreign trade (a closed economy will be considered). The Covid-induced contraction of investment in 2020 was roughly of the same proportion as the contraction in private consumption; as the EA consumption/GDP ratio (about 55%) is much higher than the investment/GDP ratio (20%), the collapse in EA private consumption accounts for the bulk of the fall in EA GDP, in 2020. For analytical tractability, the theoretical model will abstract from physical capital and investment.

3. Model economy

A standard New Keynesian model is considered (e.g., Kollmann, 2001a,b, 2002, 2004, 2005, 2008). The model assumes a closed economy with: a representative household; a central bank; monopolistically competitive firms that produce a continuum of intermediate goods indexed by $s \in [0,1]$ using labor; competitive firms that bundle intermediates into a homogeneous final good. The household consumes the final good, supplies labor and owns all firms. The central bank sets the short-term nominal interest rate. Intermediate goods prices are sticky; all other prices and the wage rate are flexible. The labor market is competitive.

3.1. The representative household

The intertemporal preferences of the representative Home household are described by $E_0 \sum_{t=0}^{\infty} \beta^t \Psi_t \left\{ \ln(C_t) - \frac{1}{1+1/\eta} (L_t)^{1+1/\eta} \right\}$ where C_t and L_t are final consumption and aggregate hours

worked at date t . $0 < \beta < 1$ is the household's steady state subjective discount factor and $\eta > 0$ is the Frisch labor supply elasticity. $\Psi_t > 0$ is a stationary exogenous preference shock that alters the household's rate of time preference. The household equates the marginal rate of substitution between leisure and consumption to the real wage rate, which implies

$$(1/C_t)(W_t/P_t) = (L_t)^{1/\eta}. \quad (1)$$

There is a market for a one-period riskless nominal bond (in zero net supply). The *nominal* interest rate on that bond is r_t between periods t and $t+1$. The gross nominal rate is denoted $R_t \equiv 1 + r_t$. The household's Euler equation for this bond is:

$$R_t \cdot E_t \beta (\Psi_{t+1}/\Psi_t) (C_t/C_{t+1}) / \Pi_{t+1} = 1, \quad (2)$$

where $\Pi_{t+1} \equiv P_{t+1}/P_t$ is the gross inflation rate between t and $t+1$. If Ψ_t follows a stationary AR(1) process, as assumed below, then a positive shock to the date t preference shifter Ψ_t lowers the expected subjective discount factor $E_t \beta \Psi_{t+1}/\Psi_t$ between dates t and $t+1$, and thus the shock raises the household's subjective discount rate. In what follows, I will hence refer to the preference shock Ψ_t as a (subjective) discount rate shock. A rise in Ψ_t can be interpreted as a positive aggregate demand shock as, for a given real interest rate, it boosts desired current consumption (by inducing the household to substitute future consumption by current consumption).

3.2. Firms

The final good is produced using the technology $Y_t \equiv \left\{ \int_0^1 (y_t(s))^{(\nu-1)/\nu} ds \right\}^{\nu/(\nu-1)}$, with $\nu > 1$, where Y_t is date t final output. $y_t(s)$ is the quantity of type- s intermediate. Let $p_t(s)$ be the nominal price of that intermediate. Cost minimization in final good production implies $y_t(s) = (p_t(s)/P_t)^{-\nu} Y_t$, where $P_t \equiv \left\{ \int_{s=0}^1 p_t(s)^{1-\nu} ds \right\}^{1/(1-\nu)}$ is a price index for intermediate goods. Perfect competition implies that the final good price is P_t (its marginal cost).

The technology for producing intermediate good s is $y_t(s) = \theta_t L_t(s)$, where $L_t(s)$ is the labor input at date t , while $\theta_t > 0$ is an exogenous stochastic productivity parameter (identical for all intermediate good producers). θ_t is an aggregate supply shock.

Intermediate good producers face quadratic price adjustment costs. The real profit, in units of final output, of the firm that produces intermediate good s is:

$$\pi_t(s) \equiv (p_t(s) - W_t/\theta_t)y_t(s)/P_t - \frac{1}{2}\psi \cdot ([p_t(s) - \Pi \cdot p_{t-1}(s)]/P_{t-1})^2, \quad \psi > 0,$$

where W_t is the nominal wage rate. The last term in this equation is the real price adjustment cost, where Π is the steady state gross inflation rate. At date t , the firm sets $p_t(s)$ to maximize the present value of profits $E_t \sum_{\tau=0}^{\infty} \rho_{t,t+\tau} \pi_{t+\tau}(s)$, where $\rho_{t,t+\tau}$ is the household's intertemporal marginal rate of substitution in consumption between periods t and $t+\tau$. All intermediate good firms face identical decision problems, and they produce identical quantities and set identical prices: $p_t(s) = P_t \quad \forall s \in [0,1]$.

3.3. Monetary policy

The central bank sets the nominal interest rate r_t , subject to the zero lower bound (ZLB) constraint $r_t \geq 0$, i.e. $R_t \geq 1$.

3.4. Market clearing

Markets for intermediates clear as intermediate goods producers meet all demand at posted prices. Labor market clearing requires $L_t = \int_{s=0}^1 L_t(s) ds$. Final good market clearing requires $C_t = Y_t$, where $Y_t = \theta_t L_t$ is GDP.

3.5. Solving the model

I linearize all model equations around a deterministic steady state. Let $\hat{x}_t \equiv (x_t - x)/x$ denote the relative deviation of a variable x_t from its steady state value $x \neq 0$ (variables without time subscript denote steady state values). Using the market clearing condition $C_t = Y_t$, the linearised Euler equation (2) can be written as:

$$\widehat{R}_t = E_t \{ \widehat{\Pi}_{t+1} + \widehat{Y}_{t+1} - \widehat{Y}_t + \widehat{\Psi}_t - \widehat{\Psi}_{t+1} \}. \quad (3)$$

Linearizing the first-order condition of the intermediate good firms' decision problem gives a standard 'forward-looking' Phillips equation:

$$\widehat{\Pi}_t = \kappa_w \cdot \widehat{mc}_t + \beta E_t \widehat{\Pi}_{t+1}, \quad (4)$$

where $mc_t = (W_t/\theta_t)/P_t$ is real marginal cost (deflated by the final good price) in the intermediate good sector (e.g., Kollmann, 2002). $\kappa_w > 0$ is a coefficient that is a decreasing function of the price adjustment cost parameter ψ . Using the nominal wage implied by the labor supply equation (1), and the conditions $C_t = Y_t$ and $Y_t = \theta_t L_t$, one can express real marginal costs as $mc_t = (Y_t/\theta_t)^{1+1/\eta}$, which implies

$$\widehat{mc}_t = \frac{1+\eta}{\eta} (\widehat{Y}_t - \widehat{\theta}_t). \quad (5)$$

In a flex-price economy ($\kappa_w = \infty$), real marginal cost would be constant. Thus, (5) implies $\widehat{Y}_t^{Flex} = \widehat{\theta}_t$, where \widehat{Y}_t^{Flex} denotes GDP under flexible prices. Define the output gap \widehat{z}_t as the deviation of GDP from its flex-price level:

$$\widehat{z}_t \equiv \widehat{Y}_t - \widehat{Y}_t^{Flex}. \quad (6)$$

Using this definition, the Phillips curve (4) can be expressed as:

$$\widehat{\Pi}_t = \kappa \cdot \widehat{z}_t + \beta E_t \widehat{\Pi}_{t+1}, \quad \text{with } \kappa \equiv \kappa_w \cdot \frac{1+\eta}{\eta}, \quad (7)$$

while the Euler equation (3) can be written as

$$\widehat{R}_t = E_t \{ \widehat{\Pi}_{t+1} + \widehat{z}_{t+1} - \widehat{z}_t \} + \widehat{R}_t^{nat}, \quad \text{with } \widehat{R}_t^{nat} \equiv E_t \{ [\widehat{Y}_{t+1}^{Flex} - \widehat{Y}_t^{Flex}] - [\widehat{\Psi}_{t+1} - \widehat{\Psi}_t] \}. \quad (8)$$

\widehat{R}_t^{nat} is the risk-free gross real interest rate between dates t and $t+1$ (expressed in deviation from the steady state gross rate) that would obtain under flexible prices. I refer to \widehat{R}_t^{nat} as the natural real interest rate.

The Phillips curve (7) implies that the output gap is a function of current and expected future inflation: $\widehat{z}_t = \frac{1}{\kappa} \{ \widehat{\Pi}_t - \beta E_t \widehat{\Pi}_{t+1} \}$. Substituting this expression into the Euler equation (8) gives:

$$\widehat{R}_t = -\frac{1}{\kappa} \widehat{\Pi}_t + (1 + \frac{1+\beta}{\kappa}) E_t \widehat{\Pi}_{t+1} - \frac{\beta}{\kappa} E_t \widehat{\Pi}_{t+2} + \widehat{R}_t^{nat}. \quad (9)$$

I refer to (9) as the 'Euler-Phillips' equation.

Assume that TFP and the discount rate shock follow stationary univariate AR(1) processes with autocorrelations $0 \leq \rho_\theta < 1$ and $0 \leq \rho_\psi < 1$, respectively:

$$\hat{\theta}_{t+1} = \rho_\theta \hat{\theta}_t + \varepsilon_{t+1}^\theta, \quad \hat{\Psi}_{t+1} = \rho_\psi \hat{\Psi}_t + \varepsilon_{t+1}^\Psi,$$

where $\varepsilon_{t+1}^\theta, \varepsilon_{t+1}^\Psi$ are mean-zero innovations. Then, the natural real interest rate is given by

$$\hat{R}_t^{nat} = -(1-\rho_\theta)\hat{\theta}_t + (1-\rho_\psi)\hat{\Psi}_t. \quad (10)$$

Thus, the natural real interest rate is a decreasing function of TFP and an increasing function of the discount rate shock. Note that $0 \leq \rho_\theta < 1$ implies that a positive shock to TFP lowers the expected *future* growth rate of TFP. In a flex-price economy, this entails a fall in the expected future growth rate of GDP and consumption, which lowers the natural real interest rate. A positive shock to the subjective discount rate between dates t and $t+1$ likewise raises the natural real interest rate between t and $t+1$.

3.6. Liquidity trap

This paper focuses on equilibria that obtain when the ZLB binds permanently, i.e. $R_t = 1 \quad \forall t$. A liquidity trap can, for example, arise when the central bank follows a Taylor-style interest rate rule. Then pessimistic household expectations about future inflation and GDP can push the nominal interest rate to the ZLB (Benhabib et al. (2001a,b), Kollmann (2021a,b)). The assumption of a permanent liquidity trap is solely made for analytical convenience. Kollmann (2021a,b) studies equilibria with self-fulfilling (expectations-driven) equilibria in which, in each period, the economy can escape from the liquidity trap with positive probability. When the escape probability from a liquidity trap is sufficiently small (i.e. when the liquidity trap is expected to last long), shock transmission is very similar to transmission in a permanent liquidity trap (Kollmann (2021a,b)).

The motivation for analyzing the effect of Covid using a model with a liquidity trap is that Covid hit the EA (and other advanced economies) in an environment of persistently ultra-low interest rates. The European Central Bank's (ECB) policy rate has been at (or very close to) the ZLB since November 2013; a departure from this low-interest rate policy does not seem to be on the agenda of ECB decision makers, as of this writing. In normal times, the ECB would be

able to counteract adverse shocks by cutting the policy interest rate. This is not possible, in a liquidity trap.⁶

In a permanent liquidity trap, $\widehat{R}_t=0$ holds.⁷ The Euler-Phillips equation (9) then becomes

$$0 = -\frac{1}{\kappa}\widehat{\Pi}_t + (1 + \frac{1+\beta}{\kappa})E_t\widehat{\Pi}_{t+1} - \frac{\beta}{\kappa}E_t\widehat{\Pi}_{t+2} + \widehat{R}_t^{nat}. \quad (11)$$

$0 < \beta < 1$ and $\kappa > 0$ imply that one of the characteristics roots of this expectational difference is strictly larger than unity, while the other root is smaller than unity. This implies that equation (11) has multiple non-explosive solutions (Blanchard and Kahn (1980)). Following the liquidity trap models of Mertens and Ravn (2014), Roeger (2015), Arifovic et al. (2018), Aruoba et al. (2018), Kollmann (2021a,b) and de Beaufort (2021), I consider minimal-state-variable (MSV) equilibria in which inflation is a function of the contemporaneous fundamental forcing variables that drive the natural real interest rate, i.e. of TFP and the discount rate shock:

$$\widehat{\Pi}_t = \lambda_\theta \widehat{\theta}_t + \lambda_\psi \widehat{\Psi}_t, \quad (12)$$

where λ_θ and λ_ψ are coefficients. Substitution of the inflation decision rule (12) and of the formula for the natural real interest rate (10) into the Euler-Phillips equation (11) gives:

$$0 = \left\{ -\frac{1}{\kappa}\lambda_\theta \widehat{\theta}_t + (1 + \frac{1+\beta}{\kappa})\lambda_\theta \rho_\theta \widehat{\theta}_t - \frac{\beta}{\kappa}\lambda_\theta (\rho_\theta)^2 \widehat{\theta}_t \right\} + \left\{ -\frac{1}{\kappa}\lambda_\psi \widehat{\Psi}_t + (1 + \frac{1+\beta}{\kappa})\lambda_\psi \rho_\psi \widehat{\Psi}_t - \frac{\beta}{\kappa}\lambda_\psi (\rho_\psi)^2 \widehat{\Psi}_t \right\} - (1 - \rho_\theta)\widehat{\theta}_t + (1 - \rho_\psi)\widehat{\Psi}_t.$$

This equation holds for arbitrary values of $\widehat{\theta}_t$ and $\widehat{\Psi}_t$ if and only if

$$\lambda_\theta = (1 - \rho_\theta)/\Gamma(\rho_\theta) \quad \text{and} \quad \lambda_\psi = -(1 - \rho_\psi)/\Gamma(\rho_\psi), \quad (13)$$

$$\text{with } \Gamma(x) \equiv -\frac{1}{\kappa} + (1 + \frac{1+\beta}{\kappa})x - \frac{\beta}{\kappa}x^2. \quad (14)$$

It can readily be seen that $\Gamma(x) < 0$ holds for $0 \leq x < \rho^*$, and $\Gamma(x) > 0$ for $\rho^* < x \leq 1$, where $0 < \rho^* < 1$ is a root of the polynomial $\Gamma(x)$, i.e. $\Gamma(\rho^*)=0$.⁸ Thus,

⁶ The analysis here abstracts from unconventional monetary policies (such as Quantitative Easing, QE, or Negative Interest Rate Policy, NIRP) that have been conducted by the ECB since the global financial crisis of 2008-09. In March 2020, the ECB launched an asset purchases program (the ‘‘Pandemic Emergency Purchases Program’’, PEPP) that aims to counter the economic effects of the Covid crisis. Hohberger et al. (2019), Kabaca et al. (2020) and Altavilla et al. (2021) show that unconventional ECB policies have, to some extent, acted as a substitute for conventional interest rate policy, during the period of ultra-low policy rates. Wu and Zhang (2019) show that the effect of US QE can be captured with a ‘shadow’ federal funds rate that is not constrained by the ZLB, and that follows a Taylor-type rule. Explicitly modeling unconventional monetary policy is beyond the scope of the simple framework used in the paper here. However, below I consider a model variant in which the nominal interest rate is not constrained by the ZLB to address the possibility that unconventional monetary policies acted as a substitute for conventional interest rate policy, during the Covid crisis.

⁷ In an equilibrium with a permanent liquidity trap, $R=1$ holds in steady state. Linearization around the liquidity trap steady state thus implies $\widehat{R}_t=0 \quad \forall t$.

$$\lambda_\theta < 0, \lambda_\psi > 0 \text{ holds for } \rho_\theta, \rho_\psi < \rho^*; \text{ and } \lambda_\theta > 0, \lambda_\psi < 0 \text{ holds for } \rho_\theta, \rho_\psi > \rho^*. \quad (15)$$

This shows that a (sufficiently) transitory rise in TFP shock *lowers* inflation in a liquidity trap, while a persistent positive TFP shock *raises* inflation. A transitory positive discount rate shock *raises* inflation, while a transitory positive discount rate shock *lowers inflation*.

For intuition about the role of shock persistence for the response of inflation in a liquidity trap, consider the case where the autocorrelation of shocks is close to unity. Then $\widehat{\Pi}_t \approx E_t \widehat{\Pi}_{t+1} \approx E_t \widehat{\Pi}_{t+2}$, so that the Euler-Phillips equation (11) implies that $\widehat{\Pi}_t \approx -\widehat{R}_t^{nat}$, i.e. a fall in the natural real interest rate raises inflation. This explains why a persistent rise in TFP (that depresses the natural real interest rate; see (10)) triggers an increase in inflation. Similar logic explains why a persistent positive taste shock (that raises the natural rate) lowers inflation.

Conversely, when shocks are i.i.d., then a date t shocks does not affect expected future inflation, and the Euler-Phillips equation (11) implies $\widehat{\Pi}_t = \kappa \widehat{R}_t^{nat}$. Therefore, a purely transitory rise in TFP lowers inflation, while a transitory positive discount rate shock raises inflation.

Expected future inflation is

$$E_t \widehat{\Pi}_t = \lambda_\theta \rho_\theta \widehat{\theta}_t + \lambda_\psi \rho_\psi \widehat{\Psi}_t. \quad (16)$$

As the output gap is given by $\widehat{z}_t = \frac{1}{\kappa} \{\widehat{\Pi}_t - \beta E_t \widehat{\Pi}_{t+1}\}$, we find (from (12),(16)) that

$$\widehat{z}_t = \frac{1}{\kappa} (1 - \beta \rho_\theta) \lambda_\theta \cdot \widehat{\theta}_t + \frac{1}{\kappa} (1 - \beta \rho_\psi) \lambda_\psi \cdot \widehat{\Psi}_t. \quad (17)$$

Therefore, a persistent positive TFP shocks raises the output gap, while a transitory TFP increase lowers the output gap. Conversely, a persistent positive discount rate shocks lowers the output gap, while a transitory positive discount rate shock raises the output gap.

Note that GDP is given by $\widehat{Y}_t = \widehat{z}_t + \widehat{Y}_t^{flex}$ (see (6)). Thus, (17) implies

$$\widehat{Y}_t = [1 + \frac{1}{\kappa} (1 - \beta \rho_\theta) \lambda_\theta] \cdot \widehat{\theta}_t + \frac{1}{\kappa} (1 - \beta \rho_\psi) \lambda_\psi \cdot \widehat{\Psi}_t. \quad (18)$$

A persistent TFP increase (with $\rho_\theta > \rho^*$ so that $\lambda_\theta > 0$) always raises GDP; a transitory TFP increase (with $\rho_\theta < \rho^*$) lowers GDP if prices are sufficiently sticky, i.e. when the slope of the

⁸ $\phi^* = a/2 - \{(a/2)^2 - 1/\beta\}^{0.5}$ with $a \equiv (1 + \beta + \kappa)/\beta$.

Phillips curve κ is small. A persistent positive discount rate shock lowers GDP, while a transitory positive discount rate shock raises GDP.⁹

3.7. Model solution without ZLB constraint (Taylor rule)

It is interesting to compare shock transmission in the liquidity trap to transmission when the ZLB constraint does not bind, so that the central bank can adjust the policy rate, in response to disturbances. This Section abstracts from the ZLB and assumes that the central bank sets the short-term interest rate as a function of the inflation rate, according to a Taylor rule:

$$\widehat{R}_t = \gamma \widehat{\Pi}_t, \quad \gamma > 1, \quad (19)$$

where the parameter γ captures the response of the policy rate to inflation. The ‘Taylor principle’ is assumed to hold ($\gamma > 1$): a 1% rise in gross inflation triggers a rise in the gross policy rate by more than 1%.

When the monetary policy rule (19) applies, the Euler-Phillips equation (9) becomes

$$\gamma \widehat{\Pi}_t = -\frac{1}{\kappa} \widehat{\Pi}_t + (1 + \frac{1+\beta}{\kappa}) E_t \widehat{\Pi}_{t+1} - \frac{\beta}{\kappa} E_t \widehat{\Pi}_{t+2} + \widehat{R}_t^{nat}. \quad (20)$$

The Taylor principle $\gamma > 1$ ensures that both characteristic roots of (20) are large than unity (in absolute value), which ensures that (20) has a unique non-explosive solution of the form

$$\widehat{\Pi}_t = \mu_\theta \widehat{\theta}_t + \mu_\Psi \widehat{\Psi}_t, \quad (21)$$

where μ_θ and μ_Ψ can readily be determined using the method of undetermined coefficients:

$$\mu_\theta = (1 - \rho_\theta) / \{-\gamma + \Gamma(\rho_\theta)\} \quad \text{and} \quad \mu_\Psi = -(1 - \rho_\Psi) / \{-\gamma + \Gamma(\rho_\Psi)\}. \quad (22)$$

$\gamma > 1$ implies that $-\gamma + \Gamma(x) < 0$ holds $\forall 0 \leq x \leq 1$. Thus, $\mu_\theta < 0$ and $\mu_\Psi > 0$. GDP is now given by:

$$\widehat{Y}_t = [1 + \frac{1}{\kappa}(1 - \beta\rho_\theta)\mu_\theta] \cdot \widehat{\theta}_t + \frac{1}{\kappa}(1 - \beta\rho_\Psi)\mu_\Psi \cdot \widehat{\Psi}_t. \quad (23)$$

Away from the ZLB, a positive TFP shock lowers inflation, irrespective of the persistence of the shock; the shock raises GDP when the inflation coefficient of the Taylor rule γ is sufficiently large (which ensures that $\mu_\theta < 0$ is sufficiently small in absolute value, so that the coefficient of

⁹ (18) shows that a persistent *negative* TFP shock triggers an output contraction that is greater than the fall in TFP. Guerrieri et al. (2020) develop a multi-sector, incomplete-markets model in which a negative supply shock lowers output more than the shock; the authors refer to a supply shock with this feature as a ‘Keynesian’ supply shock. The analysis here illustrates that ‘Keynesian’ supply shocks arise in a standard liquidity trap model.

TFP in (23) is positive). Away from the ZLB, a positive discount rate shock raises inflation and GDP irrespective of shock persistence (provided $\gamma > 1$).

4. Interpreting Covid and the EA macroeconomy through the lens of the model

This Section discusses model calibration, presents simulated shock responses, and interprets the adjustment of the EA economy to Covid in 2020-21 through the lens of the model.

4.1. Estimating Covid-induced TFP and discount rate shocks

As the data in Table 1 are annual, I use an annual model calibration.¹⁰ Covid was an unexpected event in 2020 that triggered persistent shifts in TFP and household preferences. I label the year 2020 as $t=0$.

Let dx_t denote the Covid-induced deviation of a variable x_t from its no-Covid trajectory in period $t \geq 0$. From (7), $d\hat{\Pi}_t = \kappa \cdot dz_t + \beta E_t d\hat{\Pi}_{t+1}$ for $t \geq 0$. As documented above, Covid had zero effect on EA inflation in 2020, and a negligible effect on predicted inflation in 2021. Because of the muted effect of Covid on EA inflation, the model infers that the shock had (essentially) zero effect on the output gap: $d\hat{z}_0 = 0$. This implies that $d\hat{Y}_0 = d\hat{Y}_0^{Flex} = d\hat{\theta}_0$.

The model thus infers that, in the EA, the Covid event of 2020 amounted to a negative TFP shock: $d\hat{\theta}_0 < 0$. From the model solution for inflation, in a liquidity trap (see (12), (13)), we see that $d\hat{\Pi}_0 = E_0 d\hat{\Pi}_1 = 0$ imply:

$$0 = \{(1-\rho_\theta)/\Gamma(\rho_\theta)\} \cdot d\hat{\theta}_0 - \{(1-\rho_\psi)/\Gamma(\rho_\psi)\} \cdot d\hat{\Psi}_0 \quad (24)$$

$$\text{and } 0 = \{(1-\rho_\theta)/\Gamma(\rho_\theta)\} \rho_\theta \cdot d\hat{\theta}_0 - \{(1-\rho_\psi)/\Gamma(\rho_\psi)\} \rho_\psi \cdot d\hat{\Psi}_0. \quad (25)$$

Clearly, (24) and (25) imply

¹⁰ Quarterly data show that the EA GDP contraction was strongest in 2020q1 (-3.8% quarter on quarter, q-o-q, change) and 2020q2 (-11.6%); this was followed by a rebound in 2020q3 (+12.5% q-o-q), but there was a further GDP contraction in 2020q4 (-0.7%) due to the second wave of the epidemic in the autumn-winter 2020-21. The q-o-q changes of the EA GDP deflator were 0.5%, 1.0%, -1.1% and 0.9%, respectively in 2020q1-q4. These q-o-q inflation changes suggest that, at the quarterly frequency, aggregate demand and aggregate supply changes were not perfectly synchronized, by contrast to the perfect correlation between AD and AS shifts at the annual frequency (see below). However, the key stylized fact driving the results of the paper, namely that inflation changes were more muted than the massive GDP changes during Covid, also holds in quarterly data. For simplicity, the paper focuses on annual data and an annual model calibration. A quarterly model would need to address that the second wave of the epidemic was possibly anticipated by households—this might require specifying a richer time series model of the Covid shocks than that simple AR(1) processes assumed in the annual calibration.

$$d\hat{\theta}_0 = d\hat{\Psi}_0 \quad (26)$$

$$\text{and } \rho_\theta = \rho_\psi. \quad (27)$$

Because of the muted effect of Covid on actual inflation in 2020 and on predicted inflation in 2021, the model infers that the aggregate supply (TFP) and aggregate demand (discount rate) shifts in 2020 induced by Covid had exactly offsetting effects on inflation, and that these shifts had the same persistence (autocorrelation). The common autocorrelation of both forcing variables will be denoted by $\rho \equiv \rho_\theta = \rho_\psi$. The subsequent analysis will be based on (26) and (27). It is straightforward to see (from (21),(22)) that (26) and (27) are also implied by the model variant without ZLB constraint.¹¹

The notion that EA firms suffered “technological” regress during Covid may seem debatable. The negative effect of Covid on aggregate supply can also reflect partial or complete government-ordered firm shutdowns (to slow the spread of the virus), or a reduction in household labor supply (as workers fear infection while commuting to work or interacting in-person with co-workers and customers). The latter may be captured by replacing the household’s period utility by $\ln(C_t) - \frac{1}{1+1/\eta} (L_t/\Xi_t)^{1+1/\eta}$, where $\Xi_t > 0$ is an exogenous shock. Note that a fall in Ξ_t raises the disutility of labor. It is straightforward to see that a 1% fall in Ξ_t and a 1% fall in TFP θ_t have *identical* effects on inflation and GDP. The analysis of the role of TFP shocks for the EA macroeconomy during Covid can thus be rephrased in terms of labor supply shifts induced by Covid.

Given the contraction of EA GDP by 7.8% in 2020, the model-inferred estimate of Covid-induced TFP and preference shifts in $t=0$ is, thus:

$$d\hat{\theta}_0 = d\hat{\Psi}_0 = -7.8\%.$$

When (27) holds, then the autocorrelation of GDP is $\rho \equiv \rho_\theta = \rho_\psi$ as can be seen from (18). The autocorrelation of GDP responses to Covid thus allows to obtain an estimate of the persistence of the Covid-induced aggregate supply and demand shifts. As discussed in Sect.2, Covid triggered a -4.7% revision in the predicted *level* of 2021 GDP, i.e. Covid is predicted to

¹¹ The zero response of the natural real interest rate to the Covid-induced aggregate supply and demand shocks implies that a central bank that is unconstrained by the ZLB would not change its policy rate, in response to those shocks.

have a persistent negative effect on the level of future GDP. The ratio of the predicted 2021 GDP contraction to the 2020 GDP contraction is 0.6 ($= (-4.7\%)/(-7.8\%)$). This suggests that the annual autocorrelation of the Covid-induced shift GDP is $\rho=0.6$. The baseline model calibration below thus sets $\rho=0.6$.

Note that the estimated GDP autocorrelation $\rho=0.6$ due to Covid is in the same range, but slightly smaller, than the autocorrelation of (detrended) EA GDP in pre-Covid times. The autocorrelation of detrended log EA GDP (annual) before Covid (1999-2019) is roughly 0.65.¹²

4.2. Calibrating structural model parameters

The other model parameters are set at values that are standard in annual macro models. I assume $\beta=0.99$, which implies a 1% per annum steady state riskless real interest rate. The Frisch labor supply elasticity is set at unity, $\eta=1$, a conventional value in macro models. The slope coefficient of the Phillips curve (7) is calibrated by exploiting the observational equivalence between the linearized Phillips curve under price adjustment costs assumed here (see (4)) and the Phillips curve implied by Calvo-type (1983) staggered price setting. Empirical evidence, based on quarterly data for the EA, suggests that Calvo-equivalent price stickiness is about 4 quarters, i.e. the estimated probability that a firm does not re-optimize its price in a given quarter is about 0.75 (Kollmann (2001a); Giovannini et al. (2019)). Based on this evidence, I set the Phillips curve slope at $\kappa=2.9674$, in the present calibration to annual frequency.¹³

4.3. Simulated shock responses

Table 2 reports model-predicted impact responses of inflation, GDP and the nominal interest rate (R) to a 1% TFP shock and to a 1% preference shock, respectively. Panel (a) shows predicted responses in the liquidity trap. Panel (b) shows responses that obtain when the ZLB does not bind and the central bank follows a Taylor rule--the inflation coefficient of the interest rate rule (19) is set at the conventional value $\gamma_\pi=1.5$.

¹² The autocorrelations of linearly detrended, quadratically detrended and HP filtered logged real annual GDP (1999-2019) are 0.67, 0.65 and 0.63, respectively.

¹³ Under Calvo price setting, the slope of the Phillips curve (4) is $\kappa_w=(1-D)(1-\beta D)/D$, where D is the probability that an individual firm keeps its price unchanged in a given period. As estimates based on quarterly data suggest $D=0.75$, I set the probability of non-price adjustment at $(0.75)^4$, in the annual model calibration here. This implies $\kappa_w=1.48373$. The assumed labor supply elasticity ($\eta=1$) then entails $\kappa=\kappa_w(1+\eta)/\eta=2.9674$.

Column 1 of Table 2 shows shock responses under the baseline calibration (shock persistence $\rho=0.6$, 4-quarter Calvo-equivalent price stickiness). Col. (2) assumes less persistent shocks, $\rho=0.1$, while Col. (3) assumes more persistent shocks, $\rho=0.9$ (Cols. (2),(3) assume baseline price stickiness). Col. (4) lowers the Calvo-equivalent price stickiness to two quarters, and Col. (5) sets the Calvo-equivalent price stickiness at 8 quarters (while assuming $\rho=0.6$).

Away from the ZLB, a Taylor-style monetary policy rule entails that the central bank cuts the policy rate, in response to a positive TFP shock, and that it raises the policy rate in response to a positive discount rate shock (see Panel (b), Table 2). Away from the ZLB, a positive TFP shock lowers inflation, while a positive discount rate shock raises inflation. In all 5 model variants, the Taylor-rule-based monetary policy (away from the ZLB) delivers GDP responses to TFP shocks that are positive, but slightly smaller than the shock response under flexible prices; the GDP response to a positive discount rate shock is positive, but weak. In fact, predicted shock responses are close to the response under flexible prices, except when the shock is very transient (Col. (3)), or prices are very sticky (Col. (5)). (Nota bene: under flexible prices, a 1% TFP increase raises GDP by 1%, and a discount rate shock has zero effect on GDP.)

In the liquidity trap, the interest rate cannot adjust to shocks (Panel (a), Table 2). Under the baseline Phillips curve slope κ , the critical value for the shock autocorrelation ρ^* (that is decisive for the sign of the inflation response to shocks) is $\rho^*=0.215$ (see (14),(15)). The baseline shock autocorrelation $\rho=0.6$ thus exceeds the critical persistence ρ^* . Under the baseline calibration (Col. (1)), the model predicts hence that, in the liquidity trap, a positive TFP shock raises inflation and the GDP gap, while a positive discount rate shock lowers inflation and the GDP gap.

However, quantitatively, the response of GDP, in the baseline liquidity trap model variant, is relatively similar to the flex-price GDP response: GDP rises by 1.1% in response to the TFP shock, and GDP falls by 0.1% in response to the discount rate shock; these responses are close to the 1% and 0% responses under flexible prices. The intuition for this is that persistent shocks (as assumed in the baseline calibration) have a muted effect on the natural real interest rate; those shocks thus have a relatively weak effect on inflation, and hence their effect on GDP is close to the flex-price response.

This logic explains why, when shocks are more persistent than in the baseline specification (see Col. (3) where $\rho=0.9$ is assumed), then shock responses are even closer to the flex-price responses. As might be expected, the model variant with lower price stickiness too generates GDP responses (in the liquidity trap) that are close to the flex-price responses (see Col. (4)). By contrast, the GDP response to shocks is magnified -- and it thus differs more from the flex-price response -- when greater price stickiness is assumed (Col. (5)).¹⁴ The model variant with less persistent shocks (see Col. (2) where $\rho=0.1$ is assumed) is the only model variant in Table 2 that deliver qualitatively different inflation and GDP responses than the baseline calibration. This is so because $\rho < \rho^*$ holds in Col. (2). In the liquidity trap, a transient TFP increase ($\rho=0.1$) lowers inflation and GDP, while a transient positive discount rate shock gives a big boost to inflation and GDP.

4.4. Decomposing the GDP contraction during Covid

Remarkably, the size of the concomitant model-inferred AD and AS shocks $d\hat{\theta}_0 = d\hat{\Psi}_0 = -7.8\%$ that reproduce the 7.8% Covid-induced GDP contraction of 2020, at an unchanged inflation rate, is *invariant* to shock persistence or to other model parameters; it is furthermore common to the liquidity trap model and to the “no ZLB” model variant (in which monetary policy follows a Taylor rule).¹⁵

However, the model-inferred *relative* contribution of Covid-induced TFP and discount rate changes to the GDP contraction, differs across model variants.

In all model variants without ZLB constraint, the output contraction is largely attributed to the TFP shock. Away from the ZLB, the adverse Covid-induced discount factor shock contributes to the fall in GDP, but its influence on GDP is weak. The model variants without ZLB constraint predict that if Covid had solely affected aggregate supply, the EA would have

¹⁴The critical shock persistence is (ρ^*) is 0.0332 in the low-price-stickiness model variant of Col. (4) and 0.4729 in the high-price-stickiness case of Col. (5). Thus, $\rho^* < \rho$ holds in Cols. (4) and (5), which explains why the *qualitative* inflation and GDP responses are the same as under the baseline calibration.

¹⁵ This helps to understand why, for *all* model variants, the sum of the inflation responses to a 1% TFP shock and to a 1% preference shock is 0, while the sum of the GDP responses to both shocks is 1%, as can be seen in Table 2. For example, in the baseline liquidity trap model version, a 1% TFP shock raises GDP by 1.1%, while a 1% preference shock lowers GDP by 0.1%. Thus the response of GDP to simultaneous 1% TFP and 1% preference shocks is 1.1% - 0.1% = 1%.

experienced a sharp rise in inflation and a contraction in GDP that would have been smaller than the actual contraction.

In the baseline liquidity trap model, the Covid-induced GDP change too is largely driven by the TFP shock; the simultaneous discount rate shock counterbalances the TFP-induced GDP change, but again the effect of the discount rate shock on GDP is weak. The role of the TFP shock is especially strong when prices are very sticky (Col. (5)). The only liquidity trap model variant in which the GDP change is driven by the discount rate shock is the variant with very transitory shocks; see Col. (2) in Table 2. The simulations in Table 2 indicate thus that, for empirically plausible persistence of the Covid-induced AD and AS shifts, the effect of the AS shifts on GDP dominates clearly, in a liquidity trap.

The analysis here suggests, hence, that the Covid-induced GDP contraction was largely due to the adverse effect of Covid on aggregate supply. However, aggregate supply and demand shifts both mattered equally for the observed stability of inflation under Covid.

In a liquidity trap, persistent adverse AS shifts tend to lower inflation, while adverse demand shifts raise inflation. The liquidity trap model predicts that, if Covid had solely affected aggregate supply, the EA would have experienced a sharp fall in inflation and a contraction in GDP that would have been deeper than the actual contraction; the contraction in aggregate demand thus had a partially stabilizing effect on EA GDP, during Covid.

5. Conclusion

This paper has analyzed the macroeconomic effects of the Covid-19 epidemic on Euro Area (EA) GDP and inflation, using a stylized New Keynesian model. Offsetting aggregate demand and supply changes are shown to account for the stability of EA inflation, in the face of Covid. The evidence presented here indicates that Covid-induced aggregate demand and supply shifts were persistent. An aggregate supply contraction is identified as the dominant force driving the sharp fall of EA GDP in 2020.

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Table 1. Euro Area macroeconomic performance, 2019-2021 (predicted and actual)

	Forecast 11/2019			Forecast	Actual		Forecast error		Forecast revision
	2019	2020	2021	05/2021	2019	2020	11/2019		05/2021-11/2019
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Y	1.1	1.2	1.2	4.3	1.3	-6.6	0.2	-7.8	3.1
C	1.1	1.2	1.2	2.7	1.3	-8.0	0.2	-9.2	1.5
G	1.6	1.5	1.3	3.8	1.8	1.3	0.2	-0.2	2.5
I	4.3	2.0	1.9	6.7	5.7	-8.2	1.4	-10.2	4.8
NX/Y	2.9	2.8	2.7	3.4	3.0	3.4	-0.1	0.6	0.7
L	1.1	0.5	0.5	0.0	1.2	-1.6	0.1	-2.1	-0.5
Y/L	0.0	0.7	0.7	4.3	0.1	-5.0	0.1	-5.7	3.6
π	1.5	1.5	1.5	1.2	1.7	1.5	0.2	0.0	-0.3

Notes: Forecasted and realized year-on-year growth rates of 2019-2021 Euro Area (EA) real GDP (Y), private consumption (C), government consumption (G), investment (I), employment (L) and labor productivity (Y/L) are shown as well as the forecasted and realized GDP deflator (π) and net exports/GDP ratio (NX/Y). (Net exports pertain to the merchandise trade.) Growth rates are in percent (%); inflation and the NX/Y ratio are in percentage points (ppt).

Cols. (1)-(3) are predictions for 2019-2021 taken from the European Commission's (EC) Economic Forecast November 2019. (Statistics for 2019 shown in Col. (1) are predictions, as these statistics were published before the end of 2019.)

Col. (4) shows predictions for 2021 taken from the EC May 2021 Economic Forecast.

Cols. (5),(6) show actual (realized) variables for 2019 and 2020, respectively (as reported in the EC May 2021 Economic Forecast).

Cols. (7),(8) show the difference between actual variables in 2019 and 2020 and the corresponding EC predictions made in Nov. 2019. [Col.(7) = Col.(5)-Col.(1); Col.(8) = Col.(6)-Col.(2)]

Col. (9) shows forecast revisions, between Nov. 2019 and May 2021 EC forecasts, for 2021 variables. [Col.(9)=Col.(4)-Col.(3)].

Source: European Commission (2019, 2020).

Table 2. Model-predicted impact responses to 1% TFP (θ) and preference (Ψ) shocks

	Baseline	Less persistent shocks	More persistent shocks	Less sticky prices	More sticky prices
	$\rho=0.6$	$\rho=0.1$	$\rho=0.9$	$\rho=0.6$	$\rho=0.6$
	$\kappa=2.96$	$\kappa=2.96$	$\kappa=2.96$	$\kappa=28.14$	$\kappa=0.59$
	(1)	(2)	(3)	(4)	(5)
(a) Liquidity trap					
1% TFP increase					
Π	0.72	-5.14	0.11	0.66	1.21
Y	1.10	-0.58	1.00	1.01	1.84
R	0.00	0.00	0.00	0.00	0.00
1% preference shock					
Π	-0.72	5.14	-0.11	-0.66	-1.21
Y	-0.10	1.58	0.00	-0.01	-0.84
R	0.00	0.00	0.00	0.00	0.00
(b) Away from ZLB (Taylor rule)					
1% TFP increase					
Π	-0.41	-0.53	-0.16	-0.44	-0.34
Y	0.94	0.84	0.99	0.99	0.77
R	-0.61	-0.80	-0.24	-0.66	-0.51
1% preference shock					
Π	0.41	0.53	0.16	0.44	0.34
Y	0.06	0.16	0.01	0.01	0.23
R	0.61	0.80	0.24	0.66	0.51

Notes: Impact responses of inflation (Π), GDP (Y) and the nominal interest rate (R) to 1% innovations to TFP (θ) and to the preference shifter (Ψ) are shown. Responses of GDP are expressed in %; responses of inflation and interest rate are in percentage points (ppt). Responses pertain to annual variables.

ρ : autocorrelation of shocks; κ : slope of Phillips curve.

Panel (a) shows responses in a permanent liquidity trap; Panel (b) shows responses when the ZLB does not bind and the central bank follows a Taylor rule.

Col. (1): baseline calibration ($\rho=0.6$ and 4-quarter Calvo-equivalent price stickiness).

Cols. (2),(3): less persistent shocks ($\rho=0.1$) and more persistent shocks ($\rho=0.9$), respectively, than in baseline (same price stickiness as in baseline).

Cols. (4),(5): prices less sticky (2-quarter Calvo-equivalent) and more sticky (8-quarter Calvo-equivalent), respectively, than in baseline (same shock autocorrelation as in baseline).