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Funding behaviour of debt management offices and the ECB's public sector purchase programme

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Abstract

This paper investigates whether the funding behaviour of euro area debt management offices (DMOs) changed with the start of the ECB's Public Sector Purchase Programme (PSPP). Our results show that (i) lower yield levels and (ii) PSPP purchases supported higher maturities at issuance. The former indicates a behaviour of "locking in low rates for longer", while the latter suggests the existence of an additional "demand effect" of the PSPP on DMO strategies beyond the PSPP's effect via yields. The combined impact of the PSPP via these channels amounts to maturity extensions at issuance of about one year in our estimation.

JEL classification: E52, E58, E63, H63

Key words: Central bank asset purchases, unconventional monetary policy, public debt management, sovereign debt maturity structure

Non-technical summary

The conduct of large scale asset purchases programmes by central banks can impact government bond supply. This paper investigates how the funding behaviour of public Debt Management Offices (DMOs)[1] has been affected by the ECB's Public Sector Purchase Programme (PSPP).

In response to changes in funding conditions, DMOs regularly optimise the maturity structure of debt with regard to a trade-off between debt servicing costs, which usually increase with debt maturity, and refinancing risks, which decrease with debt maturity. By alleviating funding conditions, asset purchase programmes are likely to affect the trade-off faced by DMOs. This should have observable impacts on their financing behaviour if DMOs continue to act in line with their expected economic behaviour.

We address the following research questions: Did the PSPP lead to an extension of maturities issued by euro area DMOs via the lowering of government bond yields, as DMOs wanted to lock in low rates for longer? Are there additional demand effects arising from the PSPP, which affected the issuance maturities targeted by DMOs beyond the PSPP's effect on yields? An additional "demand" effect of the PSPP on funding behaviour could arise from the higher probability that eligible securities, and in particular longer-dated securities, could be absorbed by the market. To address these questions, we empirically investigate the relationship between the weighted average maturity (WAM) at issuance and (i) the cost of issuance, measured by government bond yields and (ii) a demand variable, measured by PSPP gross purchases as a share of total issuance. We estimate our empirical models in a monthly sample of seven euro area countries between 2009 and 2019.

We gauge the economic significance of our results by assessing estimates for the PSPP's effect on term premia and data on PSPP gross purchases as a share of total issuance through the lens of our model. For the euro area "Big 4" countries, France, Germany, Italy and Spain that represent three quarters of the euro area GDP, our estimates suggest the following impact of the PSPP on public funding maturities. (i) The reduced yield level over the PSPP episode led to a lengthening of issuance maturities by seven months on average. (ii) The increased demand for PSPP-eligible bonds led to a lengthening of issuance maturities by six months on average. The overall monthly average effect of the PSPP on issuance maturities is, accordingly, about one year, or 27% compared to the average issuance maturity of the Big 4 countries before the

[1] DMOs are entities that are operationally responsible for public debt management.

PSPP of about four years. We argue that the maturity extension by euro area governments does not represent a change in DMO behaviour as a consequence of the PSPP. Instead it represents an economically-rational response to the altered cost-risk trade-off faced by DMOs, whereby overall funding costs, term premia and risks (in particular risks of failure to generate demand) are reduced. It is the intention of the PSPP to alleviate financing conditions for the whole economy and DMOs reacted endogenously in response to the changed conditions.

This paper represents a first assessment of an interaction between asset purchase programmes and DMO funding behaviour in the euro area. By providing empirical evidence of a link between asset purchase programmes and longer-dated public debt, this paper is a basis for further work on the economic impact of maturity extension by DMOs during the PSPP and its potential relevance for the transmission of monetary policy. We illustrate that DMO funding behaviour can to some extent be predicted, such as the responsiveness to yields and potentially demand factors. This opens the possibility to also treat DMO funding maturities as endogenous in impact estimations of central bank purchase programmes.

1 Introduction

The conduct of large-scale asset purchases programmes by central banks can impact government bond supply. This paper investigates how the funding behaviour of public Debt Management Offices (DMOs) has been affected by the ECB's Public Sector Purchase Programme (PSPP).[2] We analyse, in particular, the maturity of newly issued securities before the start of the PSPP and over the first entire phase of net asset purchases in a panel of seven euro area countries between December 2009 and April 2019.

In response to changing funding conditions and subject to adequate demand across maturities, DMOs regularly optimise the maturity structure of debt with regard to a trade-off between debt servicing costs, which usually increase with debt maturity, and refinancing risks, which decrease with debt maturity. This optimisation has been formalised, e.g., by Greenwood et al. (2015). By alleviating funding conditions, asset purchase programmes are likely to improve the trade-off faced by DMOs, which should have observable impacts on their financing in terms of cost of funding and/or maturity at issuance.

It is well established that asset purchase programmes led to a decrease in sovereign bond yields over the last years.[3] Estimates from term structure models for the euro area imply that the PSPP compressed sovereign bond term premia via the duration channel significantly (Eser et al., 2019). The yield compression implies that DMOs can, ceteris paribus, fund cheaper in particular at longer maturities.

Beyond the direct effect resulting from the compression of the yield curve, an additional "demand" effect of the PSPP on funding behaviour could arise when DMOs expect that a larger amount of eligible longer-dated securities could be absorbed by the market and in view of the ECB's lower price sensitivity relative to private-sector market participants.

The Italian DMO, for example, notes in its 2016 annual report that *"[the] Treasury was able to issue large volumes of debt with maturities of more than 10 years while securing a much lower extra cost than historical average. These issuance choices became possible mainly thanks to two factors: on the one hand - obviously - PSPP that can absorb a substantial quantity of bonds of all maturities including the longer term ones (up to 31 years of residual maturity); on the*

[2] Debt Management Offices are entities that are operationally responsible for public debt management. They can either be part of the ministry of finance or the ministry can delegate operational responsibility to them. See, for example, Wolswijk and de Haan (2005) for further details.

[3] See, for example, D'Amico et al. (2012), D'Amico and King (2013), Li and Wei (2013), Altavilla et al. (2015), Andrade et al. (2016), and De Santis and Holm-Hadulla (2020).

other hand, a relatively high number of investors shifting to very long maturities, as a result of the strong reduction of yields on shorter maturities traditionally chosen by these investors" (Dipartimento del Tesoro, 2016, page 28).

This excerpt suggests that a demand effect was indeed perceived by the Italian DMO during 2016, whereby stronger issuance of longer-dated securities became possible due to the additional demand for such bonds in the secondary market, both from the ECB and from other investors.[4]

This paper quantifies the importance of the direct yield effect and the demand effect and addresses the following research questions: Did the PSPP lead to an extension of maturities issued by euro area DMOs via the lowering of government bond yields, as DMOs wanted to lock in low rates for longer? Are there additional demand effects arising from the PSPP, which affected the issuance maturities targeted by DMOs beyond the PSPP's effect on yields? To address these questions, we empirically investigate the relationship between the weighted average maturity (WAM) at issuance and (i) the cost of issuance, measured by government bond yields and (ii) a demand variable, measured by PSPP gross purchases as a share of total issuance. We estimate our empirical models using the common correlated effects estimator by Pesaran (2006) to account for the strong cross-sectional dependencies that we find in our data. We also estimate local projections (see Jordà, 2005) of WAM at issuance to high-frequency yield shocks taken from Altavilla et al. (2019) that allow for a causal interpretation of our results. While some empirical evidence has started emerging on the link between yields and DMO issuance behaviour, the relationship of the latter to central bank asset purchases has to the best of our knowledge not been analysed systematically to date.

Our results show that a one percentage point decrease in 10-year government bond yields leads to an increase of the WAM at issuance by about five months. A ten percentage points higher ratio of PSPP gross purchases to issuance volume contributes to an increase of the WAM at issuance by about one month. The statistical significance and order of magnitude of these findings is robust over sub-samples, in presence of several DMO-specific and macro control variables, as well as to different estimation methods. Spanning from December 2009 to April 2019, our sample covers a period of high policy relevance. Specifically, the period covers the euro area sovereign debt crisis from 2010 to 2013 as well as the implementation of the full first period of net asset purchases under the PSPP that was announced in January 2015 and ended in December 2018.

[4] Under the PSPP, the ECB conducts purchases in the secondary market only and hence does not buy securities from the issuers directly in the primary market.

We gauge the economic significance of our results by assessing estimates for the PSPP's effect on term premia and data on PSPP gross purchases as a share of total issuance through the lens of our model. For the euro area "Big 4" countries, France, Germany, Italy and Spain that represent three quarters of the euro area GDP, our estimates suggest the following impact of the PSPP on public funding maturities. (i) The reduced yield level over the PSPP episode led to a lengthening of issuance maturities by 7 months on average. (ii) The increased demand for PSPP-eligible bonds led to a lengthening of issuance maturities by 6 months on average. The overall monthly average effect of the PSPP on issuance maturities is, accordingly, an increase of about one year, which compares to the average maturity of all debt outstanding of Germany, France, Italy and Spain before the PSPP of about six years.

Furthermore, we present a segmentation of our sample into countries that were more and less vulnerable to fiscal stress during the European sovereign debt crisis, respectively. Given the higher uncertainty and potentially higher roll-over risks, more vulnerable countries may have higher incentives to make use of a favourable market environment. Indeed, we find that these countries increase the maturity of their issuance relatively stronger in response to yield changes and PSPP purchases than less vulnerable countries.

The results of this paper are a basis for further work on the economic impact of maturity extension by DMOs during the PSPP and its potential relevance for the transmission of monetary policy. A key element in the transmission of accommodative monetary policy to the real economy is how lower market rates, in particular for longer-dated debt, improve financing conditions of borrowers. This alleviation in funding constraints contributes to an increase in aggregate demand and to a reduction of refinancing risk for the borrower.

A decline in public debt servicing costs and reductions in its refinancing risk enables governments to increase general public spending, alleviates financing restrictions for longer-term projects and/or reduces the overall tax burden and tax variability. Additionally, a possible improvement in debt sustainability may lead to a reduction of credit risk and thereby of yields, thus further propagating the beneficial effect.

Similar transmission effects could potentially be present across all sectors of the economy. In fact, non-financial corporations can also be found to adjust their maturity structure in response to central bank purchases of public debt. Following the "gap-filling" theory by Greenwood et al. (2010), firms issue longer when central bank asset purchases reduce the effective supply of long-term debt in the markets, given the inelastic demand of preferred-habitat-investors, such as insurance corporations.[5] This maturity extension of private-sector debt can also be understood as an intended consequence of central banks' asset purchase programmes, as it alleviates funding constraints of the private sector.

Our findings can also have implications for research that quantifies the duration channel of quantitative easing (QE) that works through a crowding-out of price-sensitive investors, who re-balance their portfolios towards riskier assets. When governments issue longer maturities, there is a crowding-in of price-sensitive investors due to the increased supply of longer-dated bonds, which are not purchased by the central bank, with a positive overall impact on government bond yields. This is in line with the arguments presented by Greenwood et al. (2014), who show that the issuance of longer-dated securities by the US Treasury following the start of QE counteracted between one and two thirds of the impact that QE had on yield levels. Performing this analysis based on our data and estimation results, we find that the maturity lengthening by euro area DMOs due to the yield and demand effect may have offset one third of the PSPP's effect on term premia. Estimations of the duration channel, which treat government funding maturity as unresponsive to yield and demand effects of QE (i.e. as an exogenous variable) may, therefore, overstate the total impact of the QE on yields since a portion may have been counteracted through maturity lengthening by governments.

The rest of the paper is structured as follows. After giving a review of the existing literature in Section 2, we provide a description of DMOs' objectives and behaviour in Section 3. Section 4 describes the data set and its properties as well as our econometric model to analyse DMO behaviour. All regression and local projection results as well as an illustration of their economic significance are provided in Section 5. We conclude the analysis in Section 6.

2 Review of the Existing Literature

This section offers a summary of the related literature focusing on three strands relevant for this work. The first strand of literature analyses characteristics as well as monetary policy implications of the maturity structure of government debt. The second strand argues that the maturity structure of debt issuance can be used as a tool of macroeconomic stabilisation policy itself. The third strand of literature analyses the behaviour of DMOs empirically.

Related to the first strand of literature, Vayanos and Vila (2021) formalise a term structure

[5] Foley-Fisher et al. (2016) and Badoer and James (2016) provide empirical evidence in support of this theory.

model of preferred-habitat investors, where risk-averse arbitrageurs conduct substitution across maturities. In their model, scarcity of securities that have a preferred-habitat investor base can drive up bond prices. The total supply of bonds is thereby a determinant of their yields and impacts the market price for duration risk.[6] Building on this model, Greenwood and Vayanos (2014) investigate how the supply and maturity distribution of public debt affects bond yields and expected returns. They find a positive relationship between maturity-weighted debt-to-GDP and longer-dated bond yields.

Krishnamurthy and Vissing-Jorgensen (2012) conduct an empirical analysis of the aggregate demand for treasury debt showing that changes in treasury supply have large effects on a variety of yield spreads, such as for safety and liquidity, due to preferred-habitat investors. Greenwood et al. (2014) argue that some types of, in particular, short-term government debt securities are cash-like due to safe-haven/liquidity characteristics and that the marginal holder of long-term government debt is a specialised fixed income investor, who demands compensation for bearing interest rate risk. These two papers underpin the notion of scarcity and supply effects, according to which changes in the supply behaviour of DMOs can have an effect on government bond yields.

Potential interactions between central banks' asset purchase programmes (APP) and government debt issuance have gained attention in the literature since the start of such programmes in the United States in 2008. Li and Wei (2013) and Eser et al. (2019) develop term structure models to estimate the effects of central banks' asset purchases in the United States and the euro area, respectively. Both papers consider bond supply and duration factors in their models. The results by Li and Wei (2013) imply that the Federal Reserve's QE programmes until 2011 in sum reduced the 10-year US Treasury yield by about 100 basis points. Eser et al. (2019) estimate that the ECB's APP has reduced the 10 year term premium in the euro area by 95 basis points. Greenwood et al. (2014) argue that while the FED's QE programme led to a sizeable reduction in 10-year US treasury yields of 137 basis points, the simultaneous impact of maturity extension by the US Treasury, counteracted this effect by 48 basis points. The paper does not assess the relationship between large-scale asset purchases and the funding behaviour of DMOs systematically using econometric methods, though. The quantification in this work is based on the growth in the total maturity of outstanding debt by the US Treasury during the QE implementation and point estimates for the 10-year yield impact of QE in other academic papers. Our paper shows that the weighted average maturity of newly issued government debt in

[6] Duration risk measures the sensitivity of the value of a fixed-income asset or portfolio to a change in interest rates.

the euro area reacts significantly to yield changes and central bank asset purchases. Using the approach by Greenwood et al. (2014), we find that in the euro area about 33% of the PSPP's term premium effect may have been counteracted by longer maturity issuance. The results from our paper could therefore be used to serve as an input to term structure models that estimate the effect and persistence of QE programmes.

A second strand of literature analyses the role of the maturity structure of debt as a tool for macroeconomic stabilisation policy. Leong (1999) and Wolswijk and de Haan (2005) note a discrepancy between the academic debate and practice when it comes to public debt management. While much of the scientific literature focuses on macroeconomic stabilisation goals, DMO practitioners take a more microeconomic approach by focusing on the cost-risk trade-off inherent in an upward-sloping yield curve. The macroeconomic literature often views public debt management from the perspective of a government optimisation problem, where DMO and government are one single entity. This approach ignores principal-agent problems that could arise, for example, due to potentially different planning horizons between governments searching for re-election and DMOs having a long-term perspective.

Tobin (1963) argues that governments should follow a countercyclical debt maturity policy for macroeconomic stabilisation purposes. He argues that governments should issue longer-dated maturities during economic expansions to drive up long-term interest rates, while the minimisation of financing costs is considered a secondary priority and risk minimisation is not considered. Friedman (1992) studies the proposition of Tobin (1963) empirically to quantify the impact of debt management policies on both interest rates and real economic activity. The simulations suggest, for a given budget deficit and therefore a given amount of debt to be issued, that long-term bond yields fall if a government issued short- rather than long-term securities. This in turn stimulates business investment, residential construction, and other interest-sensitive elements of aggregate spending. Angeletos (2002) studies the optimal maturity structure of public debt in a general equilibrium model. He shows that a broad range of Arrow-Debreu allocations are implementable when the government has the possibility of issuing debt at different maturities. Optimal policy consists of issuing long-term debt, which is used to invest into short-term debt as a reserve fund. The government can draw from this fund in bad times to stabilise the economy. Relatedly, Bhandari et al. (2017) derive prescriptions for optimal debt maturity in a dynamic macro model. They show that the government's optimal target debt level is negative when a Ramsey planner can control the maturity structure of a non-state-contingent debt portfolio.

Krause and Moyen (2016) formalise in a New Keynesian model that the capability of a central bank to reduce real debt levels by setting higher inflation targets increases with the average maturity of government debt. Missale and Blanchard (1994) delve into the same issue. They document that higher debt levels are related with lower average maturity of debt. They rationalise this finding in a reputation model, where the government decreases the maturity with rising debt levels, in order to keep its commitment to low inflation credible.

A further strand of literature analyses the behaviour of DMOs themselves, mainly using empirical methods. Greenwood et al. (2014) formalise an objective function of DMOs regarding the issuance of short- and long-term debt. This function captures the trade-off between the liquidity premium of short-term debt versus its higher refinancing risk compared to long-term debt, also considering the costliness of budget variability. Hoogduin et al. (2011) investigate DMOs' reaction functions in terms of long- versus short-dated issuance. They find that higher term spreads and higher long-term yield levels translate into a higher proportion of short-term debt in a panel of eleven euro area countries between 1990 and 2009. They document an increase in the proportion of short-term debt after 1999 and after the start of the global financial crisis in 2008, but the sample period does not allow them studying effects of QE.

Abbas et al. (2014) study the structure of public debt in a panel of 13 advanced economies between 1900 and 2011. Their results suggest that changes in the debt composition that increase exposure to crisis risk, such as a maturity shortening, can be related with subsequent financial crises. De Broeck and Guscina (2011) investigate crisis-related changes in government debt issuance in a panel of 16 European countries between 2007 and 2009. They find a shift away from fixed-interest rate instruments with longer maturities towards shorter-dated debt during the financial crisis. These works do not, however, consider the DMOs' response to changes in yields.

Beetsma et al. (2021) construct a theoretical model, where the public debt maturity choice depends on the liquidity services of short-term debt, roll-over risk, and credit risk. Using data for six euro area countries between 1999 and 2017 in a panel vector auto-regression framework, they find that higher risk aversion, credit risk, and demand for short-term liquid assets have negative effects on the maturity of newly issued debt. The paper does not discuss any separate effects of QE policies. Wolswijk (2020) finds that higher interest rate spreads are related with a rising share of short-term debt issuance in a panel of ten euro area countries between 1992 and 2017. This effect is found to be stronger in more vulnerable countries with higher debt levels. The paper also finds that growing debt levels imply more short-term financing, but that this effect vanishes after 2015 when the PSPP was introduced.

[Add Figure 1 here.]

3 An Illustrative Description of DMO Behaviour

Practitioners generally frame the government debt management problem in terms of a trade-off between cost and risk, as formalised, for example, by Greenwood et al. (2015). Former US Treasury Secretary Lawrence Summers summarised the considerations as follows: *I think the right theory is that one tries to [borrow] short to save money but not [so much as] to be imprudent with respect to rollover risk. Hence there is certain tolerance for [short-term] debt but marginal debt once [total] debt goes up has to be more long term* (cited after Greenwood et al., 2015).

Accordingly, DMOs optimise the maturity of its debt issuance intertemporally with regard to the funding cost (or interest expense) and to the refinancing risk, equating the marginal benefit of reducing refinancing risk with the marginal expense of higher funding costs. Figure 1 presents a stylised illustration of the cost-risk trade-off faced by DMOs in the spirit of the model by Greenwood et al. (2015).[7]

We assume that a DMO faces an objective to minimise both funding costs and refinancing risk, subject to their funding need and current market conditions.[8] The dashed lines in the figure represent indifference curves, which represent combinations of costs and refinancing risk that yield the same level to the objective function for the DMO.[9] Figure 1 shows indifference curves for two different DMOs, denoted as A and B. Reducing refinancing risk by funding via longer-term debt is associated with an acceptable increase in the funding cost captured by the slope of the DMO indifference curve. Depending on whether the DMO requires a large (or small) reduction in refinancing risk in order to accept an increase in funding costs, the slope of the line is flatter (or steeper). The steepness of the indifference curves may vary across DMOs and possibly also

[7]In practice DMOs employ a variety of indicators to measure portfolio risk, such as duration targets, average interest rate re-fixing period of the debt portfolio and other risk-adjusted cash flow based targets. See Jonasson and Papaioannou (2018) for a detailed report of such targets.

[8]For example, the Italian DMO states, *"Italy has focused on two principal risks: that posed by the interest rate [...] and that of refinancing, in order to distribute the maturities uniformly over time so that new debt may be placed with greater ease [...]. It is therefore crucial for Italy to set up an approach to debt management that places at the centre of its strategy risk control, and particularly those risks posed by rates and refinancing."* Dipartimento del Tesoro (2015), pp.5-6.

[9]For simplicity of the exposition we assume in the figure that costs and refinancing risk are perfectly substitutable against each other, resulting in linear curves. In a more general case with imperfect substitutability, the indifference curves would be concave, as both arguments of the objective, i.e. funding cost and refinancing risk, are "bads" that the DMO seeks to minimise.

over time. For example, some DMOs may have become more tilted towards risk-reduction in response to the European sovereign debt crisis.

A DMO can issue debt instruments with different tenors for funding its government's financing needs. The debt instruments issued will carry varying interest expenses, as the level of interest rates fluctuates in the market. The instruments will be associated with changing refinancing risk, since future demand for such bonds may shift. At each point in time, we assume that the government faces a market frontier in the cost-risk space reflecting market conditions, such as interest rates and term spreads, for a given funding need of the DMO. This market curve is depicted by the solid line in Figure 1. As the y-axis is given in percent and the risk depicted on the x-axis is inversely related with debt maturity, this market curve can also be thought of as a mirrored yield curve. A downward sloping market curve would then correspond to an upward sloping government bond yield curve: In an environment with an upward sloping yield curve, short-dated instruments (located at the lower-right part of the market curve) will be cheaper to issue but carry higher refinancing risk, while longer-dated instruments (located at the upper-left part of the market curve) will be more expensive but postpone refinancing risk further into the future.

The stylised representation in Figure 1 illustrates the optimal average maturity composition of government debt as the point where the slope of the DMO's indifference curve is equal to the slope of the market frontier. A steeper cost-risk trade-off translates into a portfolio optimum with a higher average maturity. This is reflected in the different portfolio optima for DMOs A and B in Figure 1. Through its liability management (e.g., in the form of new issuance, buybacks and exchanges) and by entering derivative agreements (such as interest rate swaps), a DMO can transform its average portfolio maturity toward the optimum level. A DMO may to some extent be able to influence the position of the market curve by consistently following a specific strategy across time, thus giving investors predictability and reducing the risk premia embedded in government yields.

The potential effect of the PSPP on DMOs' maturity funding behaviour is illustrated in Figure 2. Assuming that the yield curve for government debt declines and flattens due to central bank asset purchases, the market curve (black solid line) shifts down- and inwards. The market curve also becomes shorter at its upper-left end, as the cost for any long-term tenor is now lower than before. In this new environment, the DMO extends the average maturity of its debt from the portfolio "pre PSPP" to the portfolio "during PSPP", where it faces a generally better combination of cost and risk. Based on this simplified representation, we hypothesise that the PSPP, in addition to its effect of lowering yields and term spreads could lead to an overall reduction in refinancing risk for DMOs. In particular, it may have provided assurance that longer-dated bonds would be purchased by the market at an acceptable price for the duration of PSPP implementation.

[Add Figure 2 here.]

As with any model, there are limitations to the practical applicability of the illustrative funding trade-off depicted in Figures 1 and 2. In particular, it is not a comprehensive representation of funding choices. In practice, DMOs decide on the instruments issued, the issuance means and overall transparency, depending on the size of their funding requirements, the liquidity of their markets, their investor base, their risk tolerance and other internal and external drivers. A non-exhaustive overview of their decision space is provided in Table 1.

One limitation is that the illustrative model abstracts from the intertemporal nature of the DMO decision problem in the following sense. Only in rare circumstances will a DMO have to refinance the entire government debt in one period. In general, DMOs refinance around 10 to 20% of the outstanding government debt within one year. The overwhelming share of government debt has been "locked-in" by funding decisions taken in previous years. The relevant metric for capturing the outcome of a DMO's optimisation at a given point in time with regard to the maturity composition of the debt is, therefore, the weighted average maturity of the newly issued debt. This indicator will, accordingly, be the main variable of interest in our empirical analysis. The relation between WAM at issuance compared to the WAM of the overall debt portfolio outstanding (hereafter also denoted as WAM outstanding) is further described in Appendix A.

[Add Table 1 here.]

4 Data and Estimation Procedure

This section has three parts. The first part describes the data set. The second part analyses data properties, such as cross-sectional dependence and non-stationarity. The third part explains the econometric model employed in this paper and discusses issues of identification.

4.1 Data

The empirical analysis is based on a newly constructed panel data set of seven euro area countries over a monthly sample period of just under ten years from December 2009 to April 2019, thereby covering euro area sovereign debt crisis from 2010 to 2013 as well as the implementation of the full first period of net asset purchases under the PSPP from 2015 to 2018. The size of both panel dimensions is determined by data availability. This results in a balanced panel with 113 periods and 791 observations. The countries covered in our sample and the name of their respective DMO are summarised in Table 2. We collect data on DMO portfolios, government bond yields, and a set of control variables to account for the macroeconomic environment.

[Add Table 2 here.]

All data on DMO portfolios is taken from the European System of Central Banks' (ESCB) Centralised Securities Database (CSDB), which is the most comprehensive database for euro area sovereign debt securities. It consolidates security-level data from both ESCB-internal and commercial sources as of December 2009. The data undergoes extensive data quality testing within the ECB (European Central Bank, 2010). Monthly WAM outstanding, monthly nominal issuance and monthly nominal redemptions for euro area general government securities are publicly available on the ECB's website for Government Finance Statistics (GFS). For the purpose of this paper it is, however, important to obtain data specific to central, rather than general government issuers, i.e. excluding regional government issuers. These regional governments often have individual issuance strategies that may differ from the central government DMO strategy. Aggregating diverging strategies may impede the clear identification of DMO behaviour. In addition, monthly data on WAM issuance as opposed to WAM outstanding is required to directly measure changes in DMO behaviour as explained in Section 3. The data on central government debt is provided to us by ECB statistics.

We obtain data on monthly PSPP purchases by jurisdiction from an internal database maintained by the ECB. This database contains security-level information, enabling the classification of issuer type, e.g., central government versus regional government and agencies.[10] The publicly available data does not allow for such a distinction. Additionally, the published data only discloses net as opposed to gross purchase values.

[10]EU supranational bonds are excluded from our analysis as well.

We use government bond yield data that is publicly available on the ECB's website. The choice of countries is restricted by the availability of monthly yield data in the 5- and 10-year maturity segments.[11] Furthermore, Ireland was excluded due to a series of floating rate bonds with a nominal value of EUR 25 billion, issued by the Irish government in connection with the Irish Bank Resolution Corporation Act 2013, with original maturities ranging from 25 to 40 years, of which more than 60% have been cancelled to date. This issuance leads to massive structural breaks in the time series for WAM indicators of Irish government bonds (National Treasury Management Agency, 2013). Austria is excluded for precautionary reasons as the presence of outliers could distort the results. If we include data on Austria into the sample, our results become even stronger.

We use HICP inflation and industrial production excluding construction from the ECB's website as additional macroeconomic control variables. Summary statistics for all variables over different sub samples are provided in Tables 10 and 11 in Appendix B. Table 12 provides bivariate correlations between all variables used in the analysis. The generally low correlations indicate that multicollinearity does not pose an issue in our regressions.

[Add Table 3 here.]

4.2 Cross-sectional Dependence and Non-stationarity

To determine the appropriate estimation method, we test the data for cross-sectional correlation and non-stationarity.

Table 3 presents average (absolute) cross-sectional correlation coefficients and results for the CD-test for cross-sectional dependence (Pesaran, 2004). The test statistic follows a standard normal distribution under the null hypothesis of cross-sectional independence. It is shown to be efficient even when the time dimension is relatively small. According to the CD-test, cross-sectional independence is rejected for all variables at the 1% level. Also the cross-sectional correlation coefficients indicate strong dependencies for several variables in the data set. Ignoring cross-sectional dependence would lead to inefficient standard errors and even biased coefficient estimates. Hence, we address it in our model.

Given the presence of strong cross-sectional correlation in the sample, we apply the CIPS test by

[11] Ten euro area jurisdictions did not have 5- and 10-year benchmark bonds outstanding throughout the sample period: Cyprus, Estonia, Finland, Greece, Latvia, Lithuania, Luxembourg, Malta, Slovakia and Slovenia.

Pesaran (2007), a second-generation panel unit root test, to analyse the stationarity properties of the data set.[12] The test is based on standard augmented Dickey–Fuller regressions, extended with the cross-section averages of lagged levels and first-differences of the individual series. Results for two versions of the CIPS test are presented in Table 4. The null hypothesis of the test assumes that the variable tested features a unit root. Autoregressive lags are included to control for autocorrelation, where the appropriate number of lags is determined by the Bayesian information criterion, searching between 0 and 4 lags. The presence of a unit root is rejected for all variables in the date set. Industrial production in levels features a unit root. Throughout the paper, it is therefore used as the 12 month-difference (denoted by Δ), for which non-stationarity can be rejected. Accordingly, it is not necessary to analyse the stationarity of regression residuals or to test for cointegration to rule out spurious regression results.

[Add Table 4 here.]

4.3 Econometric Model

To analyse the behaviour of DMOs before and during the PSPP period, we estimate the following econometric model

$$wam_{it}^{iss} = \alpha_i + \beta_1 yield_{it-1} + \beta_2 \left[\frac{PSPP}{issuance}\right]_{it-1} + \beta_3' X_{it-1} + \beta_4' M_{it-1} + u_{it}, \tag{1}$$

where the subindices denote DMO/country i and month t, α_i are DMO/country-fixed effects and u_{it} is an error term. The dependent variable wam_{it}^{iss} is a measure of DMO funding behaviour and denotes the weighted average maturity in years of securities issued by DMO i in month t.

To analyse the effect of the PSPP on DMOs' issuance behaviour, we regress WAM at issuance on the lagged 10-year sovereign bond yield, denoted by $yield_{it-1}$, and on a measure of lagged monthly central government bond purchases of country i by the ECB, scaled by monthly government debt issuance in that country, denoted $[PSPP/issuance]_{it-1}$. The coefficient β_1 captures how strongly DMOs adjust the maturity of their new issuance to changes in yields. One important driver of sovereign bond yields and term spreads in the euro area over the last years was the ECB's APP, which is therefore partially reflected in this coefficient.[13] The coefficient β_2 measures

[12] First generation unit-root tests, such as those by Im et al. (2003), Levin et al. (2002) and Maddala and Wu (1999), assume that variables are cross-sectionally independent and are therefore not appropriate for this data set.

[13] Naturally, yields are also directly affected by changes in private investor demand and in the funding needs of sovereigns themselves. Moreover, the PSPP effect on yields would also endogenously interact with the demand of

whether there are additional demand effects of the PSPP that drives DMO behaviour in addition to its impact on yields, which is captured by β_1.

When estimating these effects, some issues of endogeneity may potentially arise. A higher net supply of bonds (not included as a variable in our model) in a given tenor will ceteris paribus have a positive effect on the respective yield. Our variable of focus, WAM at issuance, is independent of the total amount issued. Nevertheless, it is still possible that a higher WAM of a *given* amount of newly issued debt can increase yield curve steepness and, thus, also the 10-year yield used in the model. We approach the issue of potential reversed causality in the following ways. In our regressions, we use lagged yields which are by definition exogenous to the current WAM at issuance. As yields are, however, highly correlated over time, this approach may not resolve the problem completely in practice. We, therefore, also consider a special case of exogenous variations in yields. To this end, we proxy monthly yield changes by monetary policy shocks that are identified using recent high-frequency identification methods (see, e.g., Gertler and Karadi, 2015 and Altavilla et al., 2019). We describe this alternative estimation approach in Section 5.2, where we find that the results of the regression approach described here are fully robust to this treatment of potential yield endogeneity.

Problems of reversed causality are less likely to occur between the monthly volume of PSPP purchases and DMO's WAM choices. In its press releases regarding the PSPP, the ECB announced the overall monthly purchase targets well in advance. Volumes by country are then determined according to the countries' share in the ECB capital. Publicly available data of the monthly purchases makes clear that any deviations from these announced purchase plans are not linked to yield movements or to the WAM of newly issued government debt.[14] From the perspective of the econometric model, the PSPP purchases can therefore be treated as an exogenous variable. As we scale the PSPP purchases by the debt issued in a given month, we also lag this ratio to rule out further endogeneity concerns.[15]

The regression model is augmented by a set of further control variables for DMO behaviour,

private investors. For example, Koijen et al. (2021) find that foreign investors had the most elastic demand for euro-denominated securities and sold considerable amounts of securities to the ECB after the PSPP's introduction. Boermans and Vermeulen (2018) find evidence that euro area investors instead acted as preferred habitat investors with no significant change in the coefficients of their bond demand function after 2015.

[14] See Hammermann et al. (2019) for a detailed description of the practical implementation of the PSPP.

[15] We also test for Granger causality between the variables of main interest, i.e. WAM at issuance, yields, and PSPP/issuance. Although Granger causality does not necessarily imply a "true" causal relationship, it can be used to analyse the explanatory power of these variables for each other. In line with our argumentation, we find evidence that yields and the scaled asset purchases Granger-cause WAM at issuance, but not the other way around.

summarised in the vector X_{it-1}. This set includes variables that control for portfolio redemption effects and the WAM of the total portfolio outstanding of DMO i. Since we want to quantify changes in DMO behaviour that occur as a response to changes in the external funding environment and the PSPP in particular, we control for deterministic portfolio effects that could affect wam_{it}^{iss} and are unrelated to the funding environment in month t.

The redemption variable is calculated as the logarithm of the total nominal value of all redemptions in the current and the previous month. Redemptions can affect the WAM at issuance because a high volume of redemptions may need to be replaced with issuances at relatively short maturities, as market demand and thus liquidity at the shorter end of the yield curve is often higher. We control for redemptions in the current and the previous month, since redemptions occur on a fixed date, while gross issuance is mainly implemented via the auction system in gradual steps.[16]

While controlling for redemptions captures most of the short-term portfolio legacy effects, we additionally control for WAM outstanding in levels to ensure that roll-down of debt is also captured across multiple periods. For example, DMOs that previously had a relatively low WAM outstanding could be more likely to issue at shorter maturities on average, independent of changes in external funding conditions.

The set of macro controls M_{it-1} includes lagged inflation and the lagged annual change of industrial production. These variables capture potential effects of the state of the business cycle on WAM at issuance, as governments may have incentives to borrow short-term during a recession to reduce funding costs. Moreover, larger funding requirements during a downturn could be easier to place at shorter maturities, where liquidity is typically higher.

The data set used is a macro panel with a relatively large time dimension and a small cross-sectional dimension ("large-T-small-N"), where cross-sectional dependence is found to be an issue. The Common Correlated Effects Pooled (CCEP) estimator by Pesaran (2006) is designed specifically for this type of data. Compared to, for example, the standard two-way fixed effects estimator well-suited for "large-N-small-T" micro panels, the CCEP estimator has several advantages. By assuming a multi-factorial structure as the data generating process, the estimator allows that each country in the panel can respond differently to common time effects in each variable of the model, while allowing for arbitrary degrees of auto- and cross-correlation among all variables.

These properties are particularly useful for the macro-financial variables in this data set. For example, euro area government bond yields can be considered to be driven by a number of

[16] The results are robust to using redemptions of the current month only.

common factors. These may include the common monetary policy as well as the global trends behind the low interest rate environment, e.g. demographics or the productivity slowdown. At the same time, the yields of each country may depend on these factors to a varying extent, besides further country-idiosyncratic factors. In comparison, the time fixed effects in the conventional two-way fixed effects estimator merely allow all countries to depend homogeneously on one single common time factor.[17]

The CCEP estimator is practically computed as an ordinary least squares regression, augmented with cross-sectional averages of the dependent and independent variables, which are interacted with the country dummies as additional regressors. As a robustness check, we also provide results using the two-way fixed effects estimator and the panel-corrected standard errors (PCSE) estimator by Beck and Katz (1995) that can account for heteroscedasticity, autocorrelation, and cross-sectional correlation in the regression errors.

5 Results

In the following, Section 5.1 presents and discusses all our main regression results. Section 5.2 shows the local projections to high-frequency yield shocks to explore potential endogeneity concerns about our main regressions. Section 5.3 provides a quantification of our findings' economic significance.

5.1 Yield and Demand Effect

Table 5 presents the main regression results for the whole sample of seven euro area countries from December 2009 to April 2019. The regressions are all based on the model in Equation (1), where WAM at issuance, measured in years, is regressed on different combinations of the independent variables. All regressions include DMO/country-fixed effects and use the CCEP estimator. Our two regressors of interest are yields and the demand variable, PSPP/issuance. The models in Columns (I) to (V) focus on the effect of the 10-year yield on WAM at issuance,

[17] Although non-stationarity could be rejected for the variables in our data set, Kapetanios et al. (2011) show that the CCEP estimator even remains consistent if the data is driven by unit root processes. This is a further advantage of this estimator in applications using macro-financial data. In a recent contribution Juodis et al. (2021) confirm the consistency of the CCEP estimator under very general conditions for the data generating process. Acknowledging the estimator's good small-sample performance, they show, however, that asymptotic normality no longer holds when the number of underlying common factors in the data is larger than the number of regressors in the model. As we will show in Section 5, the coefficient size of our main regressors of interest, β_1 and β_2, remains fairly stable when further control variables are added.

while the models in Columns (VI) to (X) additionally consider the effect of PSPP/issuance.

We find throughout all regressions that yields have a significant negative relationship with WAM at issuance. For instance, a one percentage point decrease in 10-year yields is related to an increase in the WAM of securities issued by 0.49 years in Column (V). The size of the coefficients remains relatively stable, ranging from -0.34 to -0.49, when different controls are added or removed. All effects are statistically significant at the 5% and in most cases even at the 1% level. This result indicates that DMOs change their weighted average maturity at issuance in response to changes in the yield environment. This finding is generally consistent with results in the literature. When regressing WAM at issuance on current, instead of lagged, yields, Beetsma et al. (2021) also finds a negative sign with somewhat larger coefficients than we do. Wolswijk (2020) and Hoogduin et al. (2011) use the share of short-term debt issuance as dependent variable. Consistent with us, they find that higher yields and term spreads are related with a higher share of short-term debt issuance.

In a next step, we add PSPP/issuance to the regression model, in order to test for additional effects of the PSPP on DMOs' behaviour due to the higher and stable demand by the ECB. We find that PSPP/issuance has a significant positive relationship with WAM at issuance in all our regressions. Specifically, a ten percentage point higher ratio of PSPP/issuance is related to an increase of WAM at issuance by 0.11 years in Column (X). The coefficients of the 10-year yield variable remain statistically significant and in the same order of magnitude with values ranging from -0.26 to -0.39 when PSPP/issuance is added.

The fact that both yields and PSPP/issuance enter the regressions significantly at the same time indicates the existence of an additional demand effect of the PSPP on WAM at issuance, which is not explained through the PSPP's effect on yields. An explanation is that the PSPP purchases by the ECB, as a relatively price-insensitive investor, enabled DMOs to issue additional longer-dated securities. When setting auction prices for new debt issuances, DMOs have to consider that primary dealer demand tends to be lower for high duration debt. Liquidity is typically higher at the shorter-end of the curve, meaning that dealers have a lower risk of not being able to offload their positions in the secondary market. Some of this risk is removed through the presence of the PSPP, as dealers can expect that the ECB will exert a significant secondary market demand for longer-dated maturities. The PSPP eligibility criteria prohibit purchases of securities with a residual maturity below one year and allow purchases at a yield to maturity below the deposit facility rate only to the extent necessary, thereby limiting shorter-maturity purchases. To the best of our knowledge, such QE-related demand effects have not been documented empirically before.[18]

The control variables in Table 5 generally have the expected sign or are insignificant. The effect of redemptions is negative, indicating that DMOs decrease their WAM at issuance in presence of higher redemption volumes. The redemptions variable is statistically significant in three out of eight cases. WAM outstanding also has a negative coefficient, but is found to be insignificant in all but one regression. The two macroeconomic controls, inflation and industrial production, enter the regressions with positive signs, which is in line with the notion that governments issue shorter in a downturn. None of the coefficients are statistically different from zero, though. This generally supports the notion that DMOs focus on funding costs and risks with alternative fiscal objectives playing a secondary role, if any.

In principle, yield levels and the amount of asset purchases are expected to correlate negatively. A high correlation would complicate the identification of separate yield and demand effects on WAM at issuance in our analysis. As Table 12 in Appendix B shows, however, the correlation between the 10-year yield and the PSPP/issuance variable that we employ in the regressions is rather moderate with a value of -0.40. Notably, the coefficients of PSPP/issuance and yields are robust to the exclusion of the respective other term compared to when they are added jointly. This can be seen by comparing Table 5 with Columns (VI) to (X) of Table 13 in Appendix C, indicating that the regressions can identify separate yield and demand effects on *WAM issuance*.

As a robustness check, we rerun Columns (I) to (V) of Table 5 with 5-year instead of 10-year yields. The results are displayed in Table 13 of Appendix C. The results are generally very close to each other, although the 5-year yields tend to have moderately smaller coefficients than 10-year yields. Adding yields at different maturities to the model simultaneously does not generate meaningful results given their very high levels of correlation. As one of the main objectives of the PSPP is term premium compression, we also test whether term spreads (i.e., the steepness of the curve) can play a role in determining WAM at issuance in addition to yield levels. Adding the 10 minus 2-year term spread to the regressions of Table 5 leaves all results unchanged.[19] The coefficient of the term spread itself is not found to be statistically significant. Yield levels and not curve steepness, therefore, appear to be the main driver of issuance maturity.

[18] Wolswijk (2020) finds that DMOs generally tend to issue more short-term when government debt is rising. The effect disappears after 2015, though. The paper hypothesises that this may be related to the presence of the ECB, as a predictable and relatively price-insensitive buyer, in sovereign bond markets.

[19] Results are available on request.

Our results also remain robust when using the two-way fixed effects estimator or an estimator with panel-corrected standard errors, as shown in Tables 14 to 17 in Appendix C. The signs of all coefficients as well as the patterns of significance remain broadly unchanged. With the two-way fixed effects estimator, the yield coefficients are somewhat larger, while the effects of PSPP/issuance are smaller and turn insignificant. As shown in Table 3, PSPP/issuance is among the variables in the data set with the largest degree of cross-sectional dependence. The insignificance of its coefficient is therefore likely a result of the more limited treatment of this issue under the two-way fixed effects estimator. Notably, when using the PCSE estimator, where standard errors are corrected for cross-sectional correlations, the effect of PSPP/issuance is again found to be significant. Also, the effect of the yield variable becomes a bit smaller and the effects of PSPP/issuance get larger when using this estimator.

[Add Table 5 here.]

[Add Table 6 here.]

Table 6 shows results of the regression model in Equation (1) for different sub-samples in the columns indicated with a superscript a. The table also analyses whether the responsiveness of DMOs to yields changed after the onset of the PSPP. The results for this are given in the columns with superscript b. We consider the following sub-samples: We study effects for the "Big 4" group, which consists of DE, FR, IT and ES. We also analyse whether effects are different for countries that were more and less affected during the European sovereign debt crisis of 2010-2012. Our "stressed" sample includes IT, ES and PT, while our "non-stressed" sample includes DE, FR and NL. The columns with superscript a in Table 6 compare the effects of yields and PSPP/issuance in the euro area sample (I^a), which is repeated here from Table 5 for convenience, with the different sub-samples. Overall, the negative effects of higher yields and the positive effect of higher PSPP/issuance prevails over all sub-samples considered. Notably, the effects of both variables are larger in the "Big 4" group (II^a) than in the overall sample.

The effects in the "Stressed" group (III^a) are found to be larger than those in the full sample and in the "Non-stressed" group (IV^a). For example, the effect of yields reads -0.58 for the stressed DMOs, while it is -0.39 in the full sample and insignificant for the non-stressed DMOs. The same holds true for the effect of PSPP/issuance with coefficients of 0.018 versus 0.011 and 0.014. Notably, the coefficients in the "Non-stressed" group are not statistically different from zero. This can be interpreted that these DMOs are less reactive to changes in their financing environment, but it may also be due to the relatively small sample size. Overall, these findings imply that DMOs that are more vulnerable to fiscal stress increase the maturity of their issuance relatively stronger in response to yield changes and PSPP purchases. Given the higher uncertainty and potentially higher roll-over risks these countries may have higher incentives to make use of a favourable market environment.[20]

Columns (I^b), (II^b), (III^b), and (IV^b) in Table 6 are augmented with an interaction term of the 10-yield yield and a binary PSPP-dummy variable that takes a value of one after the onset of the PSPP (as of March 2015) and is zero otherwise. When this interaction term is included to the model, the coefficient of the plain yield variable (hereafter denoted as Yield^b) captures the effect of yields on WAM at issuance before the PSPP. Meanwhile, the interaction coefficients represent any additional effect of 10-year yields on WAM at issuance during the PSPP, on top of the effect of 10-year yields before the start of the PSPP. Given the by construction high degree of correlation between the interaction term and the 10-year yield variable, their standard errors increase in some of the sub-samples, weighing down on their individual significance but not leading to biased estimates. The interaction term and the yield variable are, however, jointly significant for all groups except "Non-stressed", as presented in the first F-test at the bottom of the table, which tests the null hypothesis of joint significance. For convenience, we indicate joint significance of the yield and its interaction with a ‡ in the table.

The coefficients of the interaction term are insignificant in all of the sub-samples considered. Accordingly, DMOs did not change their responsiveness to yield changes after the onset of the PSPP. To analyse this further, we test whether there is a statistically significant difference in the effect of 10-year yields on WAM at issuance before and during the PSPP by means of another F-test. The null hypothesis of this test is that the pre-PSPP yield impact (denoted by Yield^b and taken from the columns with superscript b) is equal to the yield impact of the full sample period (denoted by Yield^a and taken from the columns with superscript a), i.e. that there is no additional yield effect during the PSPP ($\mathrm{Yield}^b = \mathrm{Yield}^a$). This null hypothesis cannot be rejected for any of the groups, which indicates that the effect of the 10-year yield on WAM issuance is not statistically different in the period before the PSPP (December 2009 to February 2015) and the full sample (December 2009 to April 2019). This indicates a continuation of the existing DMO behaviour before and after the PSPP. DMOs neither became more nor less

[20] Using a similar country-split, Wolswijk (2020) finds that the share of short-term debt issuance by vulnerable countries is more sensitive to yield spreads than it is for strong countries. Instead, Beetsma et al. (2021) find that the more vulnerable countries (Italy and Spain in their sample) react less, which would indicate that these countries favour lower costs over a reduction in roll-over risks.

responsive to yields than can be expected if they continued to act in line with their mandates. It is the intention of the PSPP to alleviate financing conditions and DMOs acted accordingly and endogenously in response to the changed conditions.

As a robustness check of Table 6, we repeat all regressions using 5-year yields in Table 18. All results remain fully robust.

5.2 Yield Shocks: A Special Case

To explore whether our results from the previous section are subject to issues of reversed causality between WAM at issuance and yields, we now focus on a special case of exogenous variation in government bond yields: monetary policy shocks. Arguably and given the statutory independence of the ECB's monetary policy from national fiscal policies, it can be assumed that monetary policy decisions of the ECB do not react in a systematic manner to changes in the WAM at issuance of euro area DMOs. To the contrary, monetary policy shocks can be expected to drive government bond yields and, thus, also exert effects on DMO issuance behaviour.

In this section, we therefore assess the direct effect of monetary policy-induced yield shocks on WAM at issuance. To this end, we estimate a dynamic version of Equation (1) using local projections methods as introduced by Jordà (2005). Impulse response functions (IRFs) are obtained following

$$Y_{i,t+h} = \alpha_{i,h} + \beta_h \sum_{p=1}^{P} Z_{i,t-p} + \gamma_h shock_{i,t}^{yld} + u_{i,t+h} \ , \tag{2}$$

where subindex h denotes the IRF horizon, while p gives the number of lags in the matrix of independent variables $Z_{i,t-p}$ and β_h is the corresponding matrix of coefficients. The vector of dependent variables is given by $Y_{i,t+h}$ and $shock_{i,t}^{yld}$ indicates an exogenous country-specific shock to the 10-year yield with coefficient γ_h.

The dependent variables are WAM at issuance and the 10-year yield. Yields are also used as dependent variable here to make sure that the monetary policy-induced yield shock has the expected effect on monthly yields. Finding a significant response here can be seen as a precondition for finding effects of the yield shock on the WAM at issuance. The list of independent variables can include all variables introduced in Section 4.3 as well as autoregressive terms $Y_{i,t-p}$.

To obtain an exogenous measure for the yield shocks, we use a high-frequency identification approach.[21] This approach employs the change of financial variables, e.g., government bond yields, in a small time window around monetary policy announcements. This allows to obtain the surprise effect of a monetary policy change on financial markets relative to market expectations before the announcement. The chosen time windows need to be sufficiently small to rule out confounding effects from other market-relevant news.

We use high-frequency intra-day data from the "Euro Area Monetary Policy Event-Study Database" by Altavilla et al. (2019). This data set contains the changes of a broad set of financial market variables in a narrow time window of monetary policy events on all monetary policy meetings of the ECB's Governing Council since January 1999. We use changes over the whole monetary event window that is calculated as the difference between the median quote from the time window 13:25-13:35 before the press release and the median quote from the time window 15:40-15:50 after the press conference. For our application, we use the intra-day changes in the 10-year government bond yields of France, Italy, Germany, and Spain. For the other countries of our sample, Belgium, the Netherlands and Portugal, no data is available in this database. We, therefore, use the one-day changes of the respective 10-year yields around the Governing Council dates that we obtain from Reuters. These high-frequency yield shocks correspond as closely as possible to the monthly 10-year yield series that we use in the regressions and the local projections. The shock measure includes the combined yield effect from all monetary policy instruments discussed at the respective dates, such as conventional interest rate changes, as well as forward guidance and asset purchases.

[Add Figure 3 here.]

Figure 3 shows our 10-year yield shock measure over time for all seven countries in the sample. While the mean value of the shock is close to zero, it features considerable variation within the cross-section and over time. The standard deviation reads 7 basis points (bps), while the min-max range spans from -44 to 54 bps.

[Add Figure 4 here.]

Figure 4 depicts IRFs of WAM at issuance and the 10-year yield to a one basis point high-frequency yield shock. The IRFs are based on Equation (2) and include all possible independent

[21] See, among many other papers, in particular Gürkaynak et al. (2005), Kuttner (2001), Gertler and Karadi (2015), and Jarociński and Karadi (2020). For a recent application in a macroeconomic panel analysis, see Holm-Hadulla and Thürwächter (2021).

variables, i.e. an autoregressive term, the 10-year yield, PSPP/issuance, redemptions, WAM outstanding, the change of industrial production, and inflation. The model features one lag for each variable. We find that a one basis point yield shock translates to an increase of the monthly 10-year yield by 0.6 bps after one month, growing further to slightly beyond 1 basis point after four months. The effect is highly statistically significant and persistent. This finding is decisive if we want to find a meaningful effect of the shock on WAM at issuance transmitted via the monthly yields. Consistent with the previous panel regression results, WAM at issuance is also found to react to the shock significantly. In the IRF the effect starts being statistically significant with a negative sign three months after the shock before reaching a peak response of -0.03 years five months after the shock.

While the panel regressions in Section 5.1 can be understood to provide long-run estimates on the effect of yields on WAM at issuance, the local projections also allow to study dynamic effects. The finding that WAM at issuance falls gradually corresponds to the gradual rise of the monthly yield to the shock. At the same time, this could also be rationalised economically by the fact that most DMOs plan and schedule the modalities of their issuance some months in advance.

In order to compare the local projection results with the long-run effects from Table 5, we calculate the average coefficient size over the first 12 months after the 1 basis point shock, which reads -0.0042 years. Scaling this up to a 1 percent yield shock, the average effect of -0.42 years lies very well in the range of yield coefficient estimates in Table 5, which are between -0.26 and -0.49 years. As the results of the panel regressions and the local projections are consistent with each other, we do not find an indication that the yield estimates in Section 5.1 are subject to reverse causality.

While Figure 4 shows results for the full model, the results continue to hold in more parsimonious specifications including yields and autoregressive terms only. Results are also robust to using more than one lag and when no lagged dependent variable is employed (see Figures 10, 11 and 12 in Appendix C).

5.3 Economic Significance of Maturity Extension and Duration Extraction

Our results support the hypothesis that the PSPP led to an overall lengthening of issuance maturities through its impact on euro area yields. We can now quantify this impact on the WAM at issuance based on results of Eser et al. (2019), who provide point estimates for the

PSPP's term premium compression in the 10-year segment for the Big 4 countries following APP announcements by the ECB Governing Council.[22] We use these point estimates in our model for the Big 4 countries from Column (II^a) in Table 6. The reaction of WAM at issuance to the PSPP-induced yield changes together with a 95% confidence band are shown in Figure 5. Our quantification shows that the mean monthly PSPP yield impact on WAM at issuance in the Big 4 countries after March 2015 is estimated to be 0.56 years (7 months).

[Add Figure 5 here.]

In a next step, we quantify the economic effect of the additional demand effect of the PSPP. Column (II^a) in Table 6 indicates that for the Big 4 countries a one percentage point increase in PSPP/issuance coincides with a 0.02 year increase in WAM at issuance. To gauge the economic significance of this effect, we convert this into an effect of nominal PSPP purchases in euro on WAM at issuance in Table 7. The average monthly issuance volume of the Big 4 countries across the full sample is EUR 30 billion per country. A one percent change therefore equals on average EUR 300 million. We can then calculate that a EUR 1 billion increase in monthly PSPP purchases results in a rise of WAM at issuance by 0.062 years (about one month) thereafter.

[Add Table 7 here.]

Figure 6 shows the PSPP "demand" effect implied by Column (II^a) in Table 6 on WAM at issuance over time. The average monthly PSPP impact on WAM at issuance amounts to 0.49 years (6 months) per country. As an illustration, we plot the average monthly PSPP purchases per country, i.e. the numerator of our demand variable, on the right axis of the figure.

[Add Figure 6 here.]

The findings suggest that the PSPP did have a significant positive impact on WAM at issuance through yields and demand, leading to an extension of issuance maturities by around 1.1 years on average. This is an economically meaningful number given that the WAM outstanding of the Big 4 countries at the onset of the PSPP was 6.4 years on average. During the PSPP implementation

[22] The point estimates correspond to the initial announcement of the APP in January 2015, with net purchases of EUR 60 billion per month from March 2015 to at least September 2016, and to subsequent changes to the purchase horizon and/or net purchase volumes.

phase, this average increased by almost one year to 7.2[23] and the calculations imply that the PSPP may explain a significant portion of the overall increase.

In a next step, we use our data and estimation results to calculate the change in the WAM outstanding that can be attributed to the yield and the demand effect as well as the offsetting effect these maturity extensions had on the term premium compression effect of the ECB's asset purchases. To this end, we follow the approach by Greenwood et al. (2014), who find that – depending on the reference period chosen – between 35% and 63% of the Federal Reserve QE's term premium compression effect was cancelled by higher maturity issuance of the US Treasury.

[Add Table 8 here.]

In the same vein, Table 8 compares the duration extraction through the ECB's PSPP with the injection of duration by DMOs for the euro area, the Big 4 countries, as well as our 'stressed' country sample.

To account for different maturities, we convert the total amount of the ECB's euro area sovereign debt holdings under the PSPP at the end of our sample in April 2019 into 10-year duration equivalents following

$$Debt_t^{10ye} = \frac{Debt_t \cdot Dur_t}{Dur_t^{10y}}, \tag{3}$$

where $Debt_t$ and Dur_t denote nominal debt amounts and average portfolio duration, respectively, while the superscript "$10ye$" indicates the 10-year equivalent. For example, using the nominal amount of the ECB's PSPP holdings of EUR 1929 billion and the average WAM outstanding of the ECB's portfolio of 7.27 years, we obtain ECB holdings in 10-year equivalents of EUR 1402 billion at the end of our sample period. Results by Eser et al. (2019) indicate a term premium compression of about 3.6 bps per EUR 100 billion of ECB asset purchases. The gross term premium compression until April 2019, accordingly, amounted to 51 bps.[24]

Greenwood et al. (2014) then decompose the change of total government debt outstanding in

[23] See Figure 8, Appendix B for the time series of the WAM of all debt outstanding for each country in our sample.

[24] This yield elasticity abstracts from the announcement effect of the PSPP on term premia, which Eser et al. (2019) estimate to be around 50bps, with the total effect, thus, being around 100bps at the end of our sample period.

10-year equivalents into pure debt expansion and maturity extension according to

$$\Delta\left(\frac{Debt_t \cdot Dur_t}{Dur_t^{10y}}\right) = \frac{1}{Dur_t^{10y}}\left(\underbrace{\Delta Debt_t \cdot Dur_{t-1}}_{\text{Debt Expansion}} + \underbrace{\Delta Dur_t \cdot Debt_t}_{\text{Maturity Extension}}\right). \tag{4}$$

We then calculate the maturity extension effect and the resulting term premium offset for two cases. In the first case (shown in Columns "Total" of Table 8), we use the total change of the WAM outstanding observed in the data between the start of the PSPP in February 2015 and the end of our sample period. In the second case (shown in Columns "Est."), we calculate an estimated change in WAM outstanding that can be directly attributed to the yield and demand effect. For this, we calculate the effect of the yield and demand effect on WAM at issuance using the regression model in Column (X) of Table 5. The estimated WAM at issuance is then transformed into WAM outstanding as described in Appendix A.

While the total observed change of WAM outstanding amounted to 0.85 years for the euro area, our estimation states that 0.57 years of this change are due to the response of the DMOs to the lower yields and the additional demand effect of the PSPP purchases. Calculating the maturity extension effect, we find that 33% of the PSPP's effect on term premia (17 out of 51 bps) may have been offset due the yield and the demand effect. As the total change of WAM outstanding was somewhat higher, even up to 49% of the PSPP's effect may have been cancelled due to behaviour of euro area DMOs. We find similar effect sizes for the Big 4 and the stressed countries. These numbers are within the range found for the US by Greenwood et al. (2014). This finding underlines the potentially large significance of our paper's empirical results on the effects and the transmission of QE policies.

6 Conclusion

The findings of this paper suggest that the impact of the PSPP on public funding maturities in the euro area is twofold. (i) The reduced yield level led to a lengthening of issuance maturities by about seven months, while (ii) increased demand for PSPP-eligible bonds led to a lengthening of issuance maturities by about 6 months on average. The overall monthly average effect of the PSPP on issuance maturities is, hence, estimated to be 1.1 years, which compares to the average maturity outstanding of Germany, France, Italy and Spain before the PSPP of about six years. We argue that the maturity extension by euro area governments represents a rational response to the altered cost-risk trade-off faced by DMOs, whereby overall funding costs, term spreads as well as refinancing risks are reduced. It is the intention of the PSPP to alleviate financing conditions for the whole economy and DMOs acted accordingly and endogenously in response to the changed conditions.

This paper represents a first assessment of an interaction between asset purchase programmes and DMO funding behaviour in the euro area. It contributes to the literature that examines such a relationship in the US (see in particular Greenwood et al., 2014).

The empirical literature to date does not investigate the real economic consequences of longer-dated maturity structures of public debt. This link is also not addressed in our paper. We do, however, provide empirical evidence of a link between QE effects and longer-dated public debt. The results of this paper are thereby a basis for further work on the economic impact of maturity extension by DMOs during the PSPP and its potential relevance for the transmission of monetary policy (see also Friedman, 1992).

Finally, our results imply that DMO reaction functions should be internalised where relevant in monetary policy research and not treated as an exogenous variable. This paper illustrates that DMO behaviour in response to yield changes and demand factors can to some extent be predicted. This opens the possibility to also treat DMO funding maturities as an endogenous factor in impact estimations of central bank purchase programmes.

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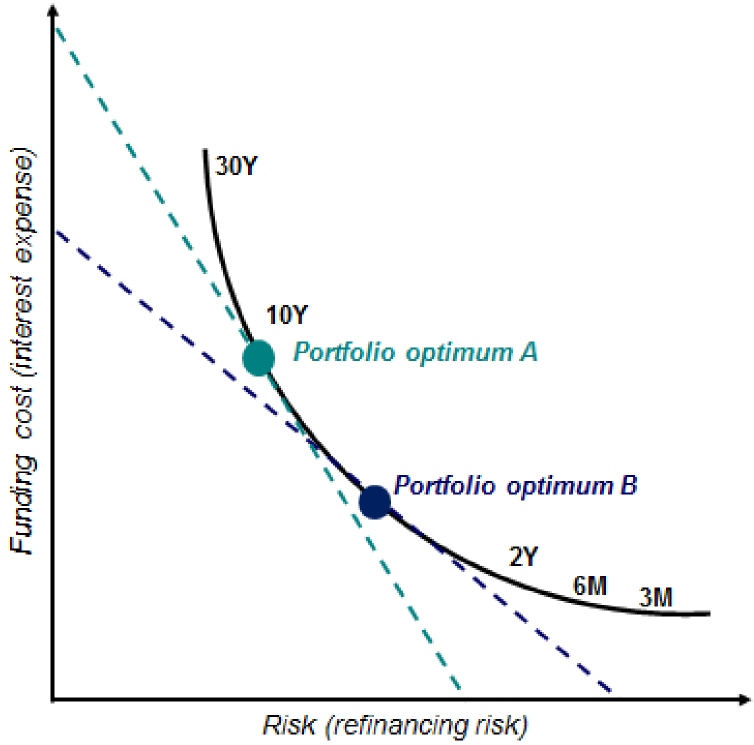
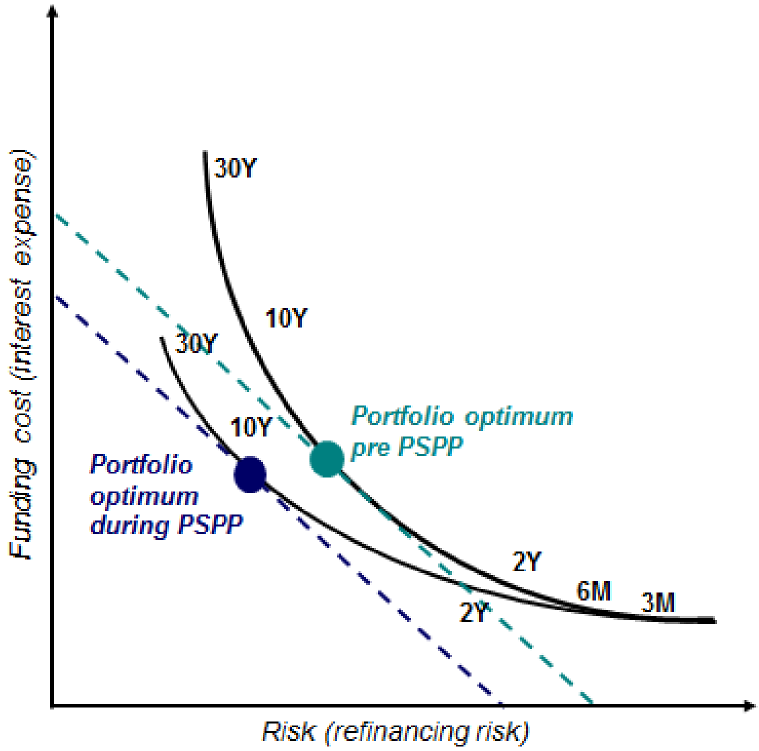
Figure 1: Illustrative maturity funding trade-off for DMOs



Note: Dashed lines represent indifference curves for DMOs A and B in the cost-risk space. Solid line depicts a market curve of debt at different maturities.

Figure 2: Effect of the PSPP on DMOs' funding trade-off



Note: Dashed lines represent DMO indifference curves in the cost-risk space. Solid lines depict market curves of debt at different maturities before and during the PSPP.

Table 1: Summary of DMO objectives, tools and drivers

Objectives	Tools	Drivers
• Minimise funding costs • Reduce risks, including: market risk, refinancing risk, liquidity risk, credit risk, settlement risk and operational risk • Develop and maintain an efficient market for government securities (depth, liquidity) • Reduce uncertainty for investors • Maintain a diverse investor base	• Issuance means: auction, syndication, buy-back, exchange, retention, private placements • Security types: e.g. floating vs. fixed, currency denomination, bond characteristics, green, derivatives (in particular swaps) • Maturity and size of issuance • Number/size of benchmarks • External communication: length of funding plans/ calendars, pre-auction announcements, communication of portfolio composition targets • Number of primary dealers	• Yield environment • Market access/ investor base • Market depth/ liquidity • Political considerations • Macroeconomic and financial sector policies • Perception of market cycle • Risk aversion/ targets set by finance ministry and cost of budget variability • Borrowing requirement • Sustainability of debt/ creditworthiness

Note: Market risk represents the risk of cost variability due to changes in market variables (such as interest or exchange rates), whereas refinancing risk (also known as roll-over risk) represents the risk that debt has to be refinanced at an unusually high cost, or cannot be rolled over at all. See Jonasson and Papaioannou (2018) for a comprehensive description of different types of risk faced by DMOs, including how they are managed and measured.

Table 2: Sample overview of countries and DMOs

Country	DMO
Belgium (BE)	Agence Fédérale de la Dette / Federaal Agentschap van de Schuld
France (FR)	Agence France Trésor
Germany (DE)	Bundesrepublik Deutschland – Finanzagentur GmbH
Italy (IT)	Dipartimento del Tesoro
the Netherlands (NL)	Agentschap van de Generale Thesaurie
Portugal (PT)	Agência de Gestão da Tesouraria e da Dívida Pública
Spain (ES)	Tesoro Público

Note: 791 usable observations between December 2009 and April 2019.

Table 3: Cross-sectional dependence tests

	CD_P	$avg.(r_{ij})$	$avg.(\|r_{ij}\|)$
WAM issuance	8.61***	0.177	0.179
PSPP/issuance	34.96***	0.770	0.770
5-year yield	37.52***	0.836	0.836
10-year yield	42.09***	0.864	0.864
Redemptions	6.65***	0.137	0.170
WAM outstanding	21.01***	0.431	0.512
Δ Industrial Production	11.15***	0.231	0.231
Inflation	23.93***	0.491	0.491

Note: CD_P denotes Pesaran (2004) cross-sectional dependence test statistic. Asterisks indicate rejection of the null hypothesis of cross-sectional independence at 10%(*), 5% (**) and 1% (***). $avg.(r_{ij})$ and $avg.(|r_{ij}|)$ denote average and average absolute cross-sectional correlation coefficients.

Table 4: Panel unit root tests

	CIPS without trend	CIPS with trend
WAM issuance	-12.935***	-12.942***
PSPP/issuance	-2.410***	-2.056**
5-year yield	-1.235*	-2.037**
10-year yield	-1.749**	-1.278*
Redemptions	-12.586***	-12.625***
WAM outstanding	-2.299***	-1.774**
Δ Industrial Production	-2.544***	-2.063***
Inflation	-3.597***	-2.648***

Note: Results of CIPS panel unit root test statistics (Pesaran, 2007). Asterisks indicate rejection of the null hypothesis of a unit root at 10%(*), 5% (**) and 1% (***). Optimal lag length determined by Akaike and Bayesian information criteria searching between 0 and 4 lags.

Table 5: The effect of yields and the PSPP on WAM at issuance – euro area

Dependent variable: WAM issuance	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)	(IX)	(X)
PSPP/issuance						0.014***	0.011**	0.011**	0.011**	0.011**
						(0.0032)	(0.0040)	(0.0044)	(0.0041)	(0.0044)
10-year yield	-0.34***	-0.35***	-0.38**	-0.38***	-0.49***	-0.26**	-0.28**	-0.31*	-0.29**	-0.39**
	(0.075)	(0.075)	(0.10)	(0.089)	(0.12)	(0.097)	(0.10)	(0.14)	(0.098)	(0.11)
Redemptions		-0.54*	-0.58*	-0.51	-0.63**		-0.49	-0.49	-0.42	-0.54*
		(0.24)	(0.24)	(0.27)	(0.25)		(0.26)	(0.26)	(0.28)	(0.24)
WAM outstanding			-0.25	-0.48	-0.70*			-0.10	-0.41	-0.62
			(0.21)	(0.33)	(0.29)			(0.29)	(0.42)	(0.37)
Δ Industrial production				0.021	0.017				0.031	0.027
				(0.040)	(0.038)				(0.034)	(0.033)
Inflation					0.42					0.38
					(0.31)					(0.30)
Observations	784	784	784	784	784	784	784	784	784	784
Adjusted R^2	0.366	0.371	0.369	0.372	0.373	0.371	0.373	0.371	0.374	0.374

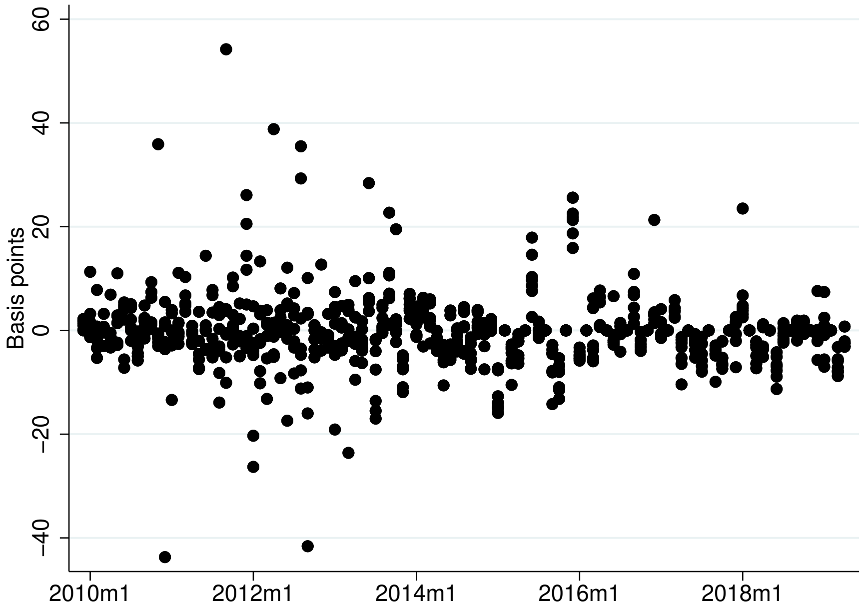
Note: Robust standard errors presented in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. CCEP estimator is used for all regressions. All models include country fixed effects. Dependent variable: WAM at issuance in years. PSPP/issuance are monthly PSPP purchases per country divided by the monthly issuance volume of debt securities in the country. All independent variables except for redemptions are lagged by one month. The sample includes BE, DE, FR, ES, IT, NL and PT over the period December 2009 to April 2019.

Table 6: The effect of 10-year yields and the PSPP on WAM at issuance over different sub-samples

	EA		Big 4		Stressed		Non-Stressed	
Dependent variable: WAM issuance	(I^a)	(I^b)	(II^a)	(II^b)	(III^a)	(III^b)	(IV^a)	(IV^b)
PSPP/issuance	0.011**	0.011**	0.019**	0.019**	0.018*	0.018*	0.014	0.014
	(0.0044)	(0.0039)	(0.0051)	(0.0047)	(0.0053)	(0.0047)	(0.0062)	(0.0064)
10-year yield	-0.39**	-0.32**‡	-0.69**	-0.66**‡	-0.58*	-0.52‡	-1.15	-1.15
	(0.11)	(0.11)	(0.21)	(0.17)	(0.16)	(0.22)	(1.05)	(1.03)
10-year yield x PSPP-dummy		-0.43‡		-0.20‡		-0.15‡		0.064
		(0.32)		(0.33)		(0.15)		(0.41)
Redemption effect	-0.54*	-0.56**	-1.01**	-1.02**	-0.27*	-0.30**	-1.70**	-1.70**
	(0.24)	(0.22)	(0.28)	(0.26)	(0.089)	(0.065)	(0.23)	(0.23)
WAM outstanding	-0.62	-0.57	-1.54	-1.55	-0.18	-0.15	-0.86	-0.87
	(0.37)	(0.39)	(1.40)	(1.38)	(0.19)	(0.26)	(0.59)	(0.61)
Δ Industrial production	0.027	0.030	0.0041	0.0047	0.036	0.038	-0.072	-0.072
	(0.033)	(0.027)	(0.049)	(0.052)	(0.031)	(0.040)	(0.030)	(0.030)
Inflation	0.38	0.35	0.14	0.12	0.74**	0.72***	-0.092	-0.091
	(0.30)	(0.28)	(0.24)	(0.26)	(0.087)	(0.064)	(0.26)	(0.27)
Observations	784	784	448	448	336	336	336	336
Adjusted R^2	0.374	0.376	0.522	0.521	0.596	0.596	0.453	0.451
F($Yield^b$, Interaction = 0)		6.95**		11.17**		294.3***		8.15
F($Yield^b = Yield^a$)		0.42		0.03		0.06		0.00

Note: Robust standard errors presented in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. CCEP estimator is used for all regressions. All models include country fixed effects. Dependent variable: WAM at issuance in years. PSPP/issuance are monthly PSPP purchases per country divided by the monthly issuance volume of debt securities in the country. PSPP-dummy is 1 as of March 2015, otherwise 0. All independent variables except for redemptions are lagged by one month. ‡ denotes joint significance of the yield and the interaction term of yield*PSPP-dummy in the first F-test presented below the table. When the null hypothesis of the second F-test, $Yield^b = Yield^a$, cannot be rejected, the effect of 10-year yield on WAM issuance is not statistically different over the whole sample period (December 2009 to April 2019) and before the the PSPP (until February 2015). Big 4 includes: DE, FR, IT and ES. Stressed includes: ES, IT and PT. Non-Stressed includes: DE, FR and NL.

Figure 3: High-frequency yield shocks over time



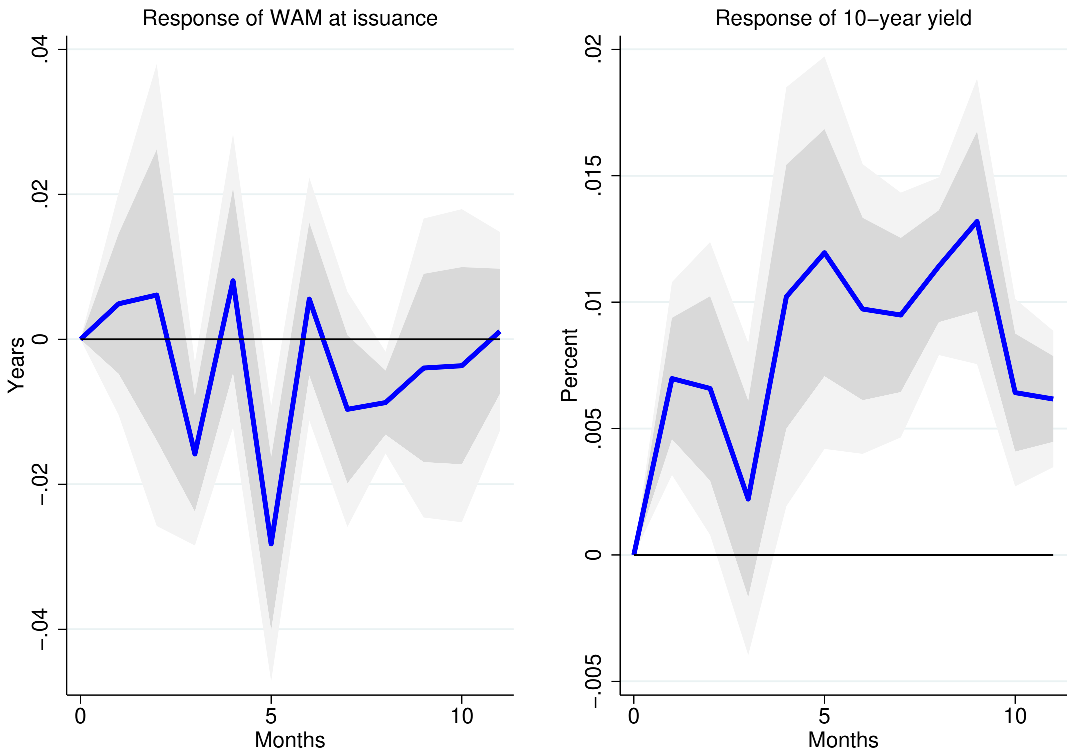
Note: Dots show intra-day/end-of-day changes of the 10-year yield of all countries in the sample on all ECB Governing Council meeting dates between December 2009 and April 2019.

Table 7: PSPP "Demand" effect impact quantification

(EUR million unless stated differently)	
μ issuance (per country)	30,661
Implied value of a 1 pct. change in PSPP/issuance	307
μ WAM issuance impact of a EUR 1 bn. increase in monthly PSPP (years):	
1000/307 x 0.019 (coefficient)	0.062

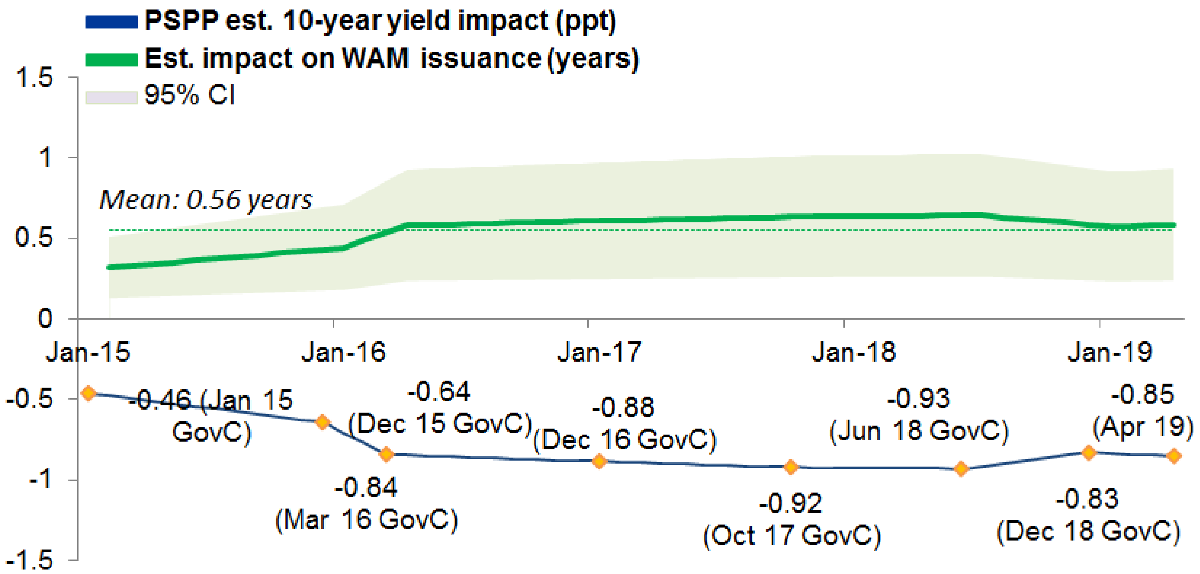
Note: Calculation based on data for DE, FR, ES, IT from March 2015 to April 2019.

Figure 4: Impulse responses to 1 basis point yield shock



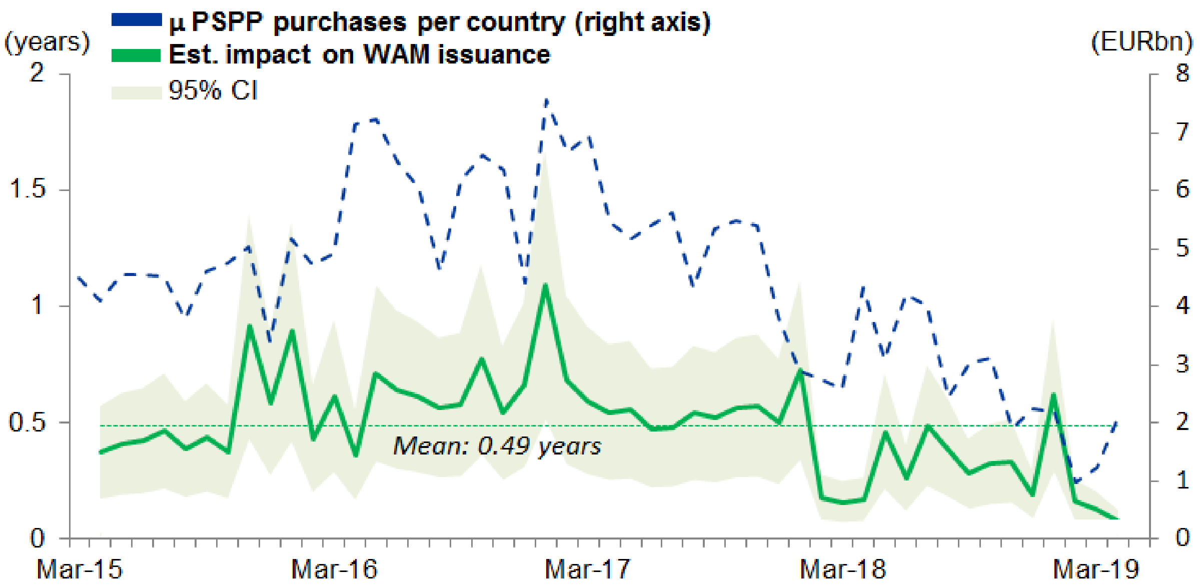
Note: Impulse response functions to a 1 basis point high-frequency yield shock based on local projections as defined in Equation (2). Control variables include an autoregressive term, the 10-year yield, PSPP/issuance, redemptions, WAM outstanding, the change of industrial production, and inflation. Models include one lag for each variable. Robust standard errors are clustered by country. Dark (light) grey-shaded areas indicate 68% and 90% confidence intervals.

Figure 5: PSPP "yield" impact on *WAM issuance*



Note: The figure shows the estimated effect of PSPP-induced changes in 10-year yields on WAM at issuance for DE, FR, ES, IT, based on regression results in Column (II^a), Table 6. Point-estimates for the PSPP's 10-year yield term premium compression are taken from Eser et al. (2019). The point estimates correspond to the initial announcement of the APP by the ECB Governing Council (GovC) in January 2015 with net purchases of EUR 60 billion per month from March 2015 to at least September 2016, and to subsequent changes to the purchase horizon and/or net purchase volumes. Estimates shown together with 95% confidence interval.

Figure 6: PSPP "demand" impact on *WAM issuance*



Note: The figure shows the estimated effect of PSPP/issuance on WAM at issuance for DE, FR, ES, IT, based on regression results in Column (II^a), Table 6. Estimates shown together with 95% confidence interval. Gross PSPP purchases per country for central government issuers in EUR billion shown on right axis.

Table 8: Term premium compression offset due to DMO maturity extension

	EA		Big 4		Stressed	
	Total	Est.	Total	Est.	Total	Est.
ECB						
PSPP holdings Apr 2019 (EUR bn)	1929		1374		590	
WAM outstanding Apr 2019 (years)	7.27		7.13		7.72	
Term premium compression (bps)	50.49		35.25		16.39	
DMOs						
Sovereign debt Feb 2015	7580		6084		2845	
Sovereign debt Apr 2019	8193		6604		3225	
WAM outstanding Feb 2015	6.52	6.52	6.43	6.43	6.29	6.29
WAM outstanding Apr 2019	7.37	6.80	7.23	6.69	6.98	6.62
Δ WAM outstanding	0.85	0.57	0.80	0.54	0.69	0.35
Maturity extension effect (EUR bn)	692	463	528	357	222	114
Term premium offset (bps)	24.93	16.67	19.02	12.87	7.98	4.09
- in percent	49%	33%	54%	37%	49%	25%

Note: Table shows the offset of the PSPP term premium compression effect due to maturity extension of euro area DMOs for two cases. 1. Columns "Total": The offset effect under the total change of WAM outstanding actually observed between the start of the PSPP (Feb 2015) and the end of the sample (Apr 2019). 2. Columns "Est.": The offset effect due to changes in WAM outstanding that can be attributed to the yield and demand effect from the regression models (Table 5, Column X). Sensitivity of term premia to asset purchases taken from Eser et al. (2019). Maturity extension effect as defined in Equation (4). PSPP holdings and sovereign debt oustanding are given in nominal amounts.

Appendix

A Decomposition of WAM Outstanding

The total outstanding amount of a DMO debt portfolio, denoted by out_t, evolves according to

$$out_t = out_{t-1} + iss_t - red_t, \tag{5}$$

where iss_t denotes the nominal amount of newly issued debt and red_t is the nominal amount of outstanding debt that is redeemed in period t (called redemptions hereafter), consisting both of regularly maturing securities and of active buybacks by the DMO.

The weighted average maturity of the outstanding debt portfolio, WAM_t^{out}, changes over time according to the following identity:

$$\begin{aligned} WAM_t^{out} \quad = \quad & (WAM_{t-1}^{out} - a) && \text{(6a)} \\ & + \frac{iss_t}{out_t} \left[WAM_t^{iss} - (WAM_{t-1}^{out} - a)\right] && \text{(6b)} \\ & + \frac{red_t}{out_t} \left[WAM_t^{red} - (WAM_{t-1}^{out} - a)\right], && \text{(6c)} \end{aligned}$$

where WAM_t^{iss} represents the weighted average (residual) maturity of newly issued securities and WAM_t^{red} is the weighted average (residual) maturity of redemptions at the time of their redemption. In the absence of any DMO buybacks and subsequent cancellations, $WAM_t^{red} = 0$.

The first component of the identity, given by a on the right-hand-side of (6a), captures the roll-down of all outstanding maturities by one period every period. This deterministic reduction is termed the *aging effect*. Component (6b), termed the *issuance effect*, covers the effect of newly issued debt on WAM_t^{out}. Whenever the WAM of the newly issued debt is higher than last period's WAM of the outstanding debt minus aging, the WAM outstanding will increase in the current period. The closer WAM_t^{iss} is to WAM_t^{out}, the smaller the overall impact of new issuances will be. Similarly, Component (6c), termed the *redemption effect*, covers the effect of debt redemptions on WAM_t^{out}. As redemptions generally have low or zero maturities, the weighted average maturity of the outstanding portfolio increases after redemptions. While the issuance effect depends on the DMOs' funding decisions in the given period, the aging and redemption effects on WAM outstanding are a consequence of historical portfolio legacy effects

Table 9: Decomposed cumulative change of WAM oustanding

Cumulative total Jan-10 to Apr-19 (years)	DE	FR	IT	ES
Aging effect	-9.3	-9.3	-9.3	-9.3
Redemption effect	15.4	23.1	13.7	11.1
Issuance effect	-5.7	-12.5	-4.7	-0.4
Other (currency conversion/accounting)	0.2	0.2	0.1	-0.3
WAM outstanding change period	0.6	1.5	-0.3	1
WAM outstanding start	5.9	6.6	7	6.5
WAM outstanding end	6.6	8	6.8	7.6
average WAM outstanding	6	7.2	6.7	6.5
average WAM issuance	4	3.8	4.7	5.6

Note: All numbers are measured in years. The cumulative change in each component of WAM_t^{out} as shown in (6a) to (6c) is presented in upper part of this table.

(except for buyback events).

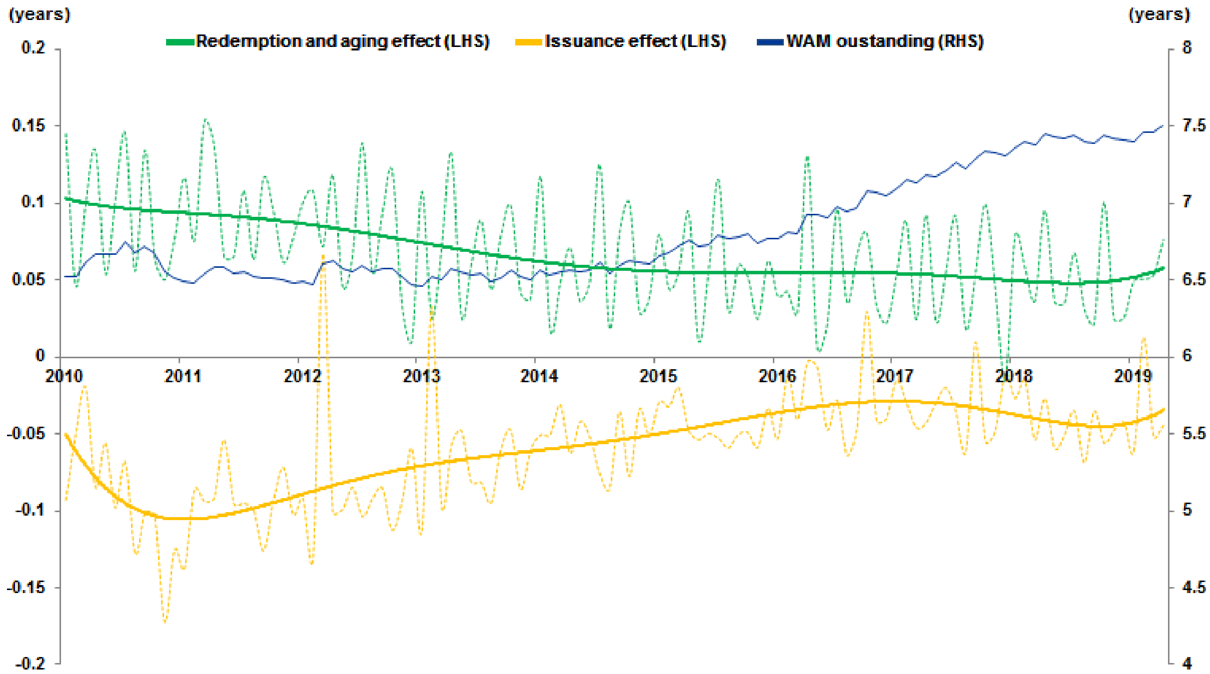
In order to illustrate the working of Equation (6), we quantify the relative contribution of issuance compared to aging and redemptions in determining changes in WAM_t^{out} in our data set for the largest four euro area countries (DE, FR, IT, ES). To this end, Table 9 summarises the cumulative sum of the *aging effect*, the *issuance effect* and the *redemption effect* over the whole sample period of 9.3 years.

In line with the description given above, the WAM of the outstanding portfolio increases significantly following redemptions. New issuances contribute less than both redemptions and aging to the total change in WAM outstanding. In fact, new issuances are found to have a negative cumulative impact although they inject duration into the market. All four jurisdictions have active bill markets (with maturities of less than one year), which make up a relatively high contribution of total bonds outstanding and which roll over on a regular basis due to their relatively low maturity at issuance. The negative effect of new issuance on the WAM outstanding is comparably large for France, which can be explained by the relatively high volume of bills in the AFT's portfolio.[25] Overall, the effect of redemptions net of aging is larger than the effect of newly issued debt, implying that portfolio legacy effects contribute more to changes in WAM_t^{out} than current portfolio decisions. The WAM of the outstanding debt is therefore a poor behavioural indicator for current DMO funding decisions.

Figure 7 shows the components of WAM outstanding across the sample period for the euro area, where the redemption and the constant aging effect have been summed. The component

[25] See, for example, the ECB Government Finance Statistics on this. France has a relatively large number of money market funds, which contribute to the active bill market.

Figure 7: WAM components: euro area



Note: Euro area changing composition based on CSDB data. WAM outstanding denotes the weighted average maturity of the outstanding debt portfolio. The issuance, redemption and aging effects are calculated as shown in Equations (6a) to (6c). The aging effect represents the roll-down of outstanding maturities by one period every period. Redemption and aging effects are summed. Trend lines are added for illustrative purposes and are derived from a 6th-order polynomial for all indicators.

indicators fluctuate and broadly counterbalance each other, thereby generally stabilising the WAM of outstanding debt. It can be seen that WAM_t^{out} remained relatively stable until the middle of 2014, after which it increased by more than one year.

B Summary and Descriptive Statistics

Table 10: Summary statistics for the euro area

	N	Unit	Mean	SD	Min	Max
EA: During PSPP (March 2015-April 2019)						
WAM issuance	350	Years	4.77	2.52	0.14	18.27
PSPP/issuance	350	Pct	24.1	17.25	0.68	134.62
10-year yield	350	Pct	1.19	0.88	-0.09	4.06
5-year yield	350	Pct	0.29	0.65	-0.55	2.65
Redemptions	350	EURm	19,048	15,355	0	67,651
WAM outstanding	350	Years	7.13	0.9	6.05	10
Δ Industrial Production	350	Index	1.51	2.73	-7.2	10.5
Inflation	350	Pct change	1.1	0.89	-1.2	3.3
EA: Before PSPP (December 2009-February 2015)						
WAM issuance	441	Years	3.69	2.39	0.16	13.85
PSPP/issuance	441	Pct	0	0	0	0
10-year yield	441	Pct	3.63	2.23	0.35	14.09
5-year yield	441	Pct	2.72	2.7	-0.06	17.5
Redemptions	441	EURm	22,837	16,949	9	73,505
WAM outstanding	441	Years	6.36	0.61	4.97	7.8
Δ Industrial Production	441	Index	0.53	4.49	-12.3	14
Inflation	441	Pct change	1.67	1.19	-1.5	4
EA: Full sample (December 2009-April 2019)						
WAM issuance	791	Years	4.17	2.51	0.14	18.27
PSPP/issuance	791	Pct	10.66	16.58	0	134.62
10-year yield	791	Pct	2.55	2.14	-0.09	14.09
5-year yield	791	Pct	1.64	2.39	-0.55	17.5
Redemptions	791	EURm	21,160	16,362	0	73,505
WAM outstanding	791	Years	6.7	0.84	4.97	10
Δ Industrial Production	791	Index	0.96	3.84	-12.3	14
Inflation	791	Pct change	1.41	1.1	-1.5	4

Note: Euro area includes BE, DE, FR, ES, IT, NL and PT. Issuance and PSPP are monthly nominal values. PSPP is based on gross purchases. Industrial production index is excluding construction and calculated as annual rate of change. Inflation is based on annual rate of change of Eurostat HICP Index, neither seasonally nor working day adjusted.

Table 11: Summary statistics for the Big 4 countries

	N	Unit	Mean	SD	Min	Max
Big 4: During PSPP (March 2015-April 2019)						
WAM issuance	200	Years	5.17	1.89	0.66	12.76
PSPP/issuance	200	Pct	25.53	17.24	2.18	134.62
10-year yield	200	Pct	1.15	0.75	-0.09	3.48
5-year yield	200	Pct	0.28	0.57	-0.55	2.65
Redemptions	200	EURm	27,974	14,335	2,068	67,651
WAM outstanding	200	Years	6.84	0.55	6.07	8.04
Δ Industrial Production	200	Index	1.56	2.34	-6.4	7.2
Inflation	200	Pct change	0.96	0.92	-1.2	3
Big 4: Before PSPP (December 2009-February 2015)						
WAM issuance	252	Years	4.01	2	0.37	11.9
PSPP/issuance	252	Pct	0	0	0	0
10-year yield	252	Pct	3.31	1.5	0.35	6.86
5-year yield	252	Pct	2.28	1.53	-0.06	6.88
Redemptions	252	EURm	32,606	15,552	5,856	73,505
WAM outstanding	252	Years	6.42	0.55	5.24	7.21
Δ Industrial Production	252	Index	0.37	4.43	-9.1	13.8
Inflation	252	Pct change	1.63	1.08	-1.5	3.8
Big 4: Full sample (December 2009-April 2019)						
WAM issuance	452	Years	4.52	2.03	0.37	12.76
PSPP/issuance	452	Pct	11.3	17.09	0	134.62
10-year yield	452	Pct	2.36	1.63	-0.09	6.86
5-year yield	452	Pct	1.4	1.56	-0.55	6.88
Redemptions	452	EURm	30,556	15,185	2,068	73,505
WAM outstanding	452	Years	6.61	0.58	5.24	8.04
Δ Industrial Production	452	Index	0.9	3.7	-9.1	13.8
Inflation	452	Pct change	1.33	1.07	-1.5	3.8

Note: Big 4 countries includes DE, FR, IT and ES. Issuance and PSPP are monthly nominal values. PSPP is based on gross purchases. Industrial production index is excluding construction and calculated as annual rate of change. Inflation is based on annual rate of change of Eurostat HICP Index, neither seasonally nor working day adjusted.

Figure 8: WAM outstanding by country

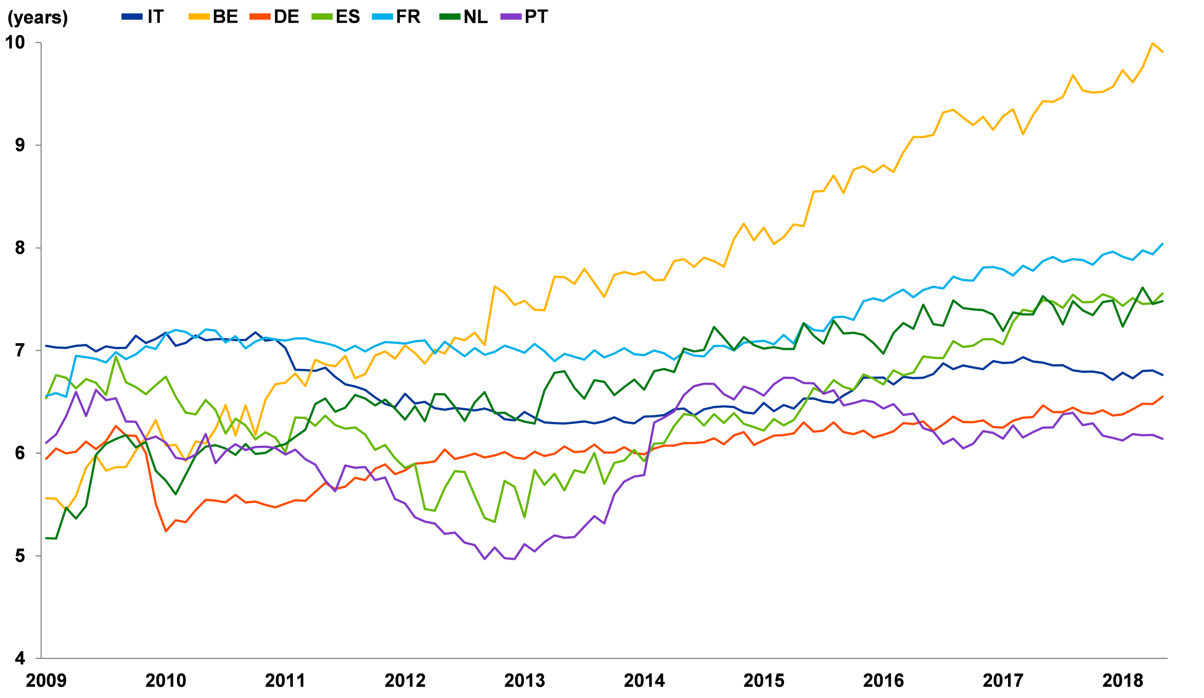


Figure 9: WAM at issuance by country

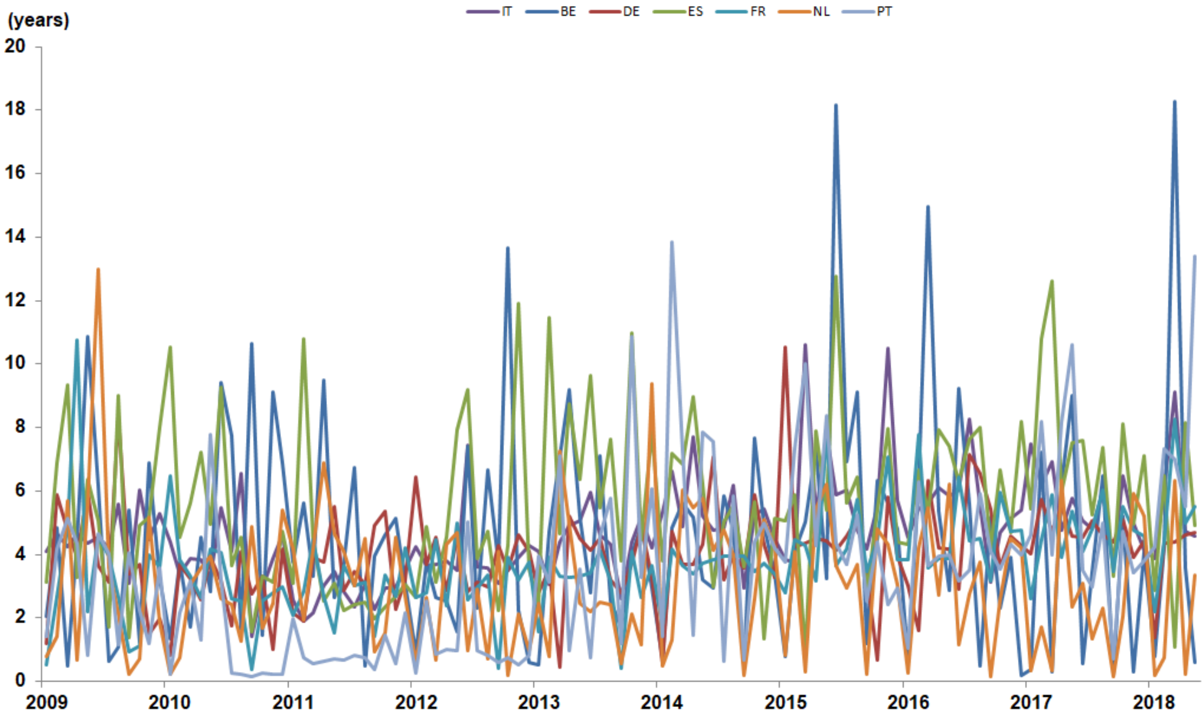


Table 12: Bivariate correlation coefficients

	wam^{iss}	PSPP/iss.	$yield^{5y}$	$yield^{10y}$	Redem.	wam^{out}	ΔIP	Infl.
WAM issuance	1.00							
PSPP/issuance	0.08	1.00						
5-year yield	-0.22	-0.36	1.00					
10-year yield	-0.20	-0.40	0.98	1.00				
Redemptions	-0.05	-0.11	-0.25	-0.26	1.00			
WAM outstanding	0.13	0.16	-0.38	-0.42	0.07	1.00		
Δ Ind. Prod.	0.12	0.13	-0.24	-0.22	0.05	0.02	1.00	
Inflation	-0.17	-0.30	0.42	0.41	0.01	0.08	-0.12	1.00

C Robustness Checks

Table 13: The effect of 5-year yields and the PSPP on WAM at issuance – euro area

Dependent variable: WAM issuance	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)	(IX)	(X)
PSPP/issuance						0.012**	0.010**	0.012**	0.012*	0.012**
						(0.0034)	(0.0033)	(0.0044)	(0.0052)	(0.0045)
5-year yield	-0.23**	-0.24**	-0.28**	-0.30***	-0.46***					
	(0.076)	(0.081)	(0.096)	(0.078)	(0.100)					
Redemptions		-0.55*	-0.57*	-0.48	-0.63**		-0.37	-0.38	-0.41	-0.51*
		(0.25)	(0.26)	(0.28)	(0.23)		(0.23)	(0.27)	(0.31)	(0.26)
WAM outstanding			-0.16	-0.37	-0.70**			-0.60**	-0.96**	-0.63*
			(0.16)	(0.29)	(0.24)			(0.18)	(0.37)	(0.31)
Δ Industrial production				0.029	0.026				0.064*	0.040
				(0.035)	(0.035)				(0.029)	(0.031)
Inflation					0.35					0.23
					(0.28)					(0.22)
Observations	784	784	784	784	784	784	784	784	784	784
Adjusted R^2	0.366	0.371	0.370	0.372	0.376	0.308	0.311	0.332	0.348	0.373

Note: Robust standard errors presented in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. CCEP estimator is used for all regressions. All models include country fixed effects. Dependent variable: WAM at issuance in years. PSPP/issuance are monthly PSPP purchases per country divided by the monthly issuance volume of debt securities in the country. All independent variables except for redemptions are lagged by one month. The sample includes BE, DE, FR, ES, IT, NL and PT over the period December 2009 to April 2019.

Table 14: The effect of 10-year yields and the PSPP on WAM at issuance – euro area, two-way fixed effects estimator

Dependent variable: WAM issuance	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)	(IX)	(X)
PSPP/issuance						0.0074	0.0063	0.0035	0.0035	0.0050
						(0.0082)	(0.0085)	(0.0085)	(0.0085)	(0.0083)
10-year yield	-0.49***	-0.50***	-0.50***	-0.48***	-0.53***	-0.49***	-0.50***	-0.50***	-0.48***	-0.53***
	(0.065)	(0.065)	(0.065)	(0.074)	(0.079)	(0.065)	(0.065)	(0.065)	(0.074)	(0.079)
Redemption effect		-0.24	-0.35	-0.36	-0.37		-0.21	-0.34	-0.34	-0.35
		(0.28)	(0.29)	(0.29)	(0.29)		(0.29)	(0.29)	(0.29)	(0.29)
WAM outstanding			-0.65***	-0.63***	-0.73***			-0.64***	-0.62***	-0.73***
			(0.23)	(0.23)	(0.24)			(0.22)	(0.23)	(0.24)
Δ Industrial production				0.021	0.024				0.021	0.024
				(0.037)	(0.037)				(0.037)	(0.037)
Inflation					0.36**					0.36**
					(0.18)					(0.18)
Observations	784	784	784	784	784	784	784	784	784	784
R^2	0.371	0.371	0.385	0.386	0.390	0.371	0.372	0.385	0.386	0.391

Note: Robust standard errors presented in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Fixed effects estimator is used for all regressions. All models include country and time fixed effects. Dependent variable: WAM at issuance in years. PSPP/issuance are monthly PSPP purchases per country divided by the monthly issuance volume of debt securities in the country. All independent variables except for redemptions are lagged by one month. The sample includes BE, DE, FR, ES, IT, NL and PT over the period December 2009 to April 2019.

Table 15: The effect of 5-year yields and the PSPP on WAM at issuance – euro area, two-way fixed effects estimator

Dependent variable: WAM issuance	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)	(IX)	(X)
PSPP/issuance						0.0078	0.0072	0.0044	0.0045	0.0052
						(0.0085)	(0.0087)	(0.0088)	(0.0087)	(0.0086)
5-year yield	-0.34***	-0.34***	-0.33***	-0.32***	-0.35***					
	(0.045)	(0.045)	(0.045)	(0.051)	(0.054)					
Redemption effect		-0.19	-0.29	-0.30	-0.31		-0.11	-0.23	-0.27	-0.27
		(0.28)	(0.29)	(0.29)	(0.29)		(0.30)	(0.30)	(0.30)	(0.30)
WAM outstanding			-0.60***	-0.58**	-0.68***			-0.64***	-0.56**	-0.60**
			(0.22)	(0.23)	(0.24)			(0.23)	(0.23)	(0.24)
Δ Industrial production				0.024	0.026				0.072**	0.075**
				(0.036)	(0.036)				(0.034)	(0.034)
Inflation					0.35*					0.15
					(0.18)					(0.18)
Observations	784	784	784	784	784	784	784	784	784	784
R^2	0.369	0.370	0.382	0.382	0.387	0.338	0.339	0.352	0.357	0.358

Note: Robust standard errors presented in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Fixed effects estimator is used for all regressions. All models include country and time fixed effects. Dependent variable: WAM at issuance in years. PSPP/issuance are monthly PSPP purchases per country divided by the monthly issuance volume of debt securities in the country. All independent variables except for redemptions are lagged by one month. The sample includes BE, DE, FR, ES, IT, NL and PT over the period December 2009 to April 2019.

Table 16: The effect of 10-year yields and the PSPP on WAM at issuance – euro area, PCSE estimator

Dependent variable: WAM issuance	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)	(IX)	(X)
PSPP/issuance						0.018***	0.018***	0.018***	0.017***	0.017**
						(0.0064)	(0.0067)	(0.0067)	(0.0067)	(0.0066)
10-year yield	-0.27***	-0.28***	-0.32***	-0.29***	-0.24***	-0.21***	-0.21***	-0.24***	-0.22***	-0.18***
	(0.051)	(0.056)	(0.057)	(0.058)	(0.062)	(0.054)	(0.061)	(0.062)	(0.063)	(0.065)
Redemptions		-0.093	-0.10	-0.090	-0.041		-0.0065	-0.018	-0.0068	0.029
		(0.10)	(0.10)	(0.10)	(0.10)		(0.11)	(0.11)	(0.11)	(0.11)
WAM outstanding			-0.17	-0.15	-0.072			-0.15	-0.13	-0.063
			(0.15)	(0.15)	(0.15)			(0.15)	(0.15)	(0.15)
Δ Industrial production				0.055*	0.056*				0.053*	0.054*
				(0.030)	(0.029)				(0.029)	(0.028)
Inflation					-0.14					-0.12
					(0.12)					(0.12)
Observations	784	784	784	784	784	784	784	784	784	784
R^2	0.079	0.080	0.082	0.087	0.078	0.081	0.079	0.081	0.086	0.082

Note: Panel-corrected standard errors presented in parentheses, using panel-specific AR(1) autocorrelation structure. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. PCSE estimator is used for all regressions. All models include country fixed effects. Dependent variable: WAM at issuance in years. PSPP/issuance are monthly PSPP purchases per country divided by the monthly issuance volume of debt securities in the country. All independent variables except for redemptions are lagged by one month. The sample includes BE, DE, FR, ES, IT, NL and PT over the period December 2009 to April 2019.

Table 17: The effect of 5-year yields and the PSPP on WAM at issuance – euro area, PCSE estimator

Dependent variable: WAM issuance	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)	(IX)	(X)
PSPP/issuance						0.026***	0.027***	0.026***	0.025***	0.022***
						(0.0061)	(0.0062)	(0.0061)	(0.0062)	(0.0062)
5-year yield	-0.26***	-0.26***	-0.28***	-0.26***	-0.23***					
	(0.043)	(0.047)	(0.047)	(0.049)	(0.052)					
Redemptions		-0.083	-0.086	-0.074	-0.040		0.11	0.11	0.11	0.14
		(0.10)	(0.10)	(0.10)	(0.10)		(0.11)	(0.11)	(0.10)	(0.100)
WAM outstanding			-0.12	-0.11	-0.058			0.052	0.055	0.10
			(0.14)	(0.14)	(0.15)			(0.14)	(0.14)	(0.14)
Δ Industrial production				0.051*	0.052*				0.062**	0.061**
				(0.030)	(0.029)				(0.029)	(0.028)
Inflation					-0.12					-0.23**
					(0.12)					(0.11)
Observations	784	784	784	784	784	784	784	784	784	784
R^2	0.086	0.087	0.088	0.092	0.085	0.076	0.066	0.068	0.070	0.075

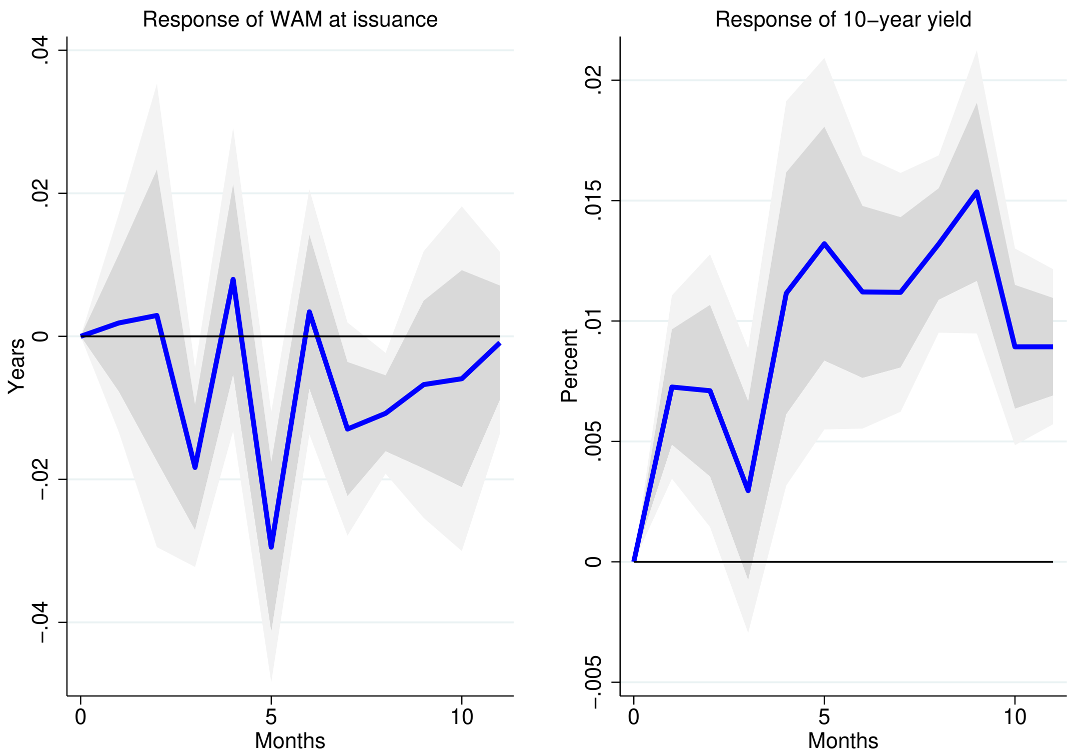
Note: Panel-corrected standard errors presented in parentheses, using panel-specific AR(1) autocorrelation structure. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. PCSE estimator is used for all regressions. All models include country fixed effects. Dependent variable: WAM at issuance in years. PSPP/issuance are monthly PSPP purchases per country divided by the monthly issuance volume of debt securities in the country. All independent variables except for redemptions are lagged by one month. The sample includes BE, DE, FR, ES, IT, NL and PT over the period December 2009 to April 2019.

Table 18: The effect of 5-year yields and the PSPP on WAM at issuance over different sub-samples

	EA		Big 4		Stressed		Non-Stressed	
Dependent variable: WAM issuance	(I^a)	(I^b)	(II^a)	(II^b)	(III^a)	(III^b)	(IV^a)	(IV^b)
PSPP/issuance	0.010*	0.0094*	0.018**	0.018**	0.020*	0.018**	0.013	0.013
	(0.0044)	(0.0043)	(0.0049)	(0.0045)	(0.0047)	(0.0039)	(0.0062)	(0.0070)
5-year yield	-0.38***	-0.30**‡	-0.55**	-0.53**‡	-0.27	-0.18‡	0.100	0.054
	(0.088)	(0.11)	(0.17)	(0.14)	(0.12)	(0.18)	(1.17)	(1.04)
5-year yield x PSPP-dummy		-0.68‡		-0.18‡		-0.49‡		0.42
		(0.56)		(0.36)		(0.43)		(1.11)
Redemption effect	-0.55*	-0.57**	-0.99**	-1.01**	-0.23	-0.29**	-1.73**	-1.73**
	(0.24)	(0.22)	(0.29)	(0.28)	(0.11)	(0.066)	(0.23)	(0.23)
WAM outstanding	-0.64*	-0.56	-1.66	-1.69	-0.39	-0.26	-0.71	-0.71
	(0.33)	(0.36)	(1.51)	(1.54)	(0.31)	(0.50)	(0.52)	(0.58)
Δ Industrial production	0.035	0.036	0.011	0.011	0.037	0.037	-0.071	-0.071
	(0.032)	(0.028)	(0.052)	(0.053)	(0.024)	(0.038)	(0.032)	(0.030)
Inflation	0.31	0.29	0.12	0.098	0.66**	0.64**	-0.18	-0.17
	(0.28)	(0.27)	(0.25)	(0.26)	(0.14)	(0.093)	(0.25)	(0.25)
Observations	784	784	448	448	336	336	336	336
Adjusted R^2	0.377	0.379	0.519	0.518	0.589	0.591	0.446	0.445
F(Yield^b, Interaction = 0)		10.07***		13.01**		173.5***		5.94
F($\text{Yield}^b = \text{Yield}^a$)		0.45		0.02		0.21		0.00

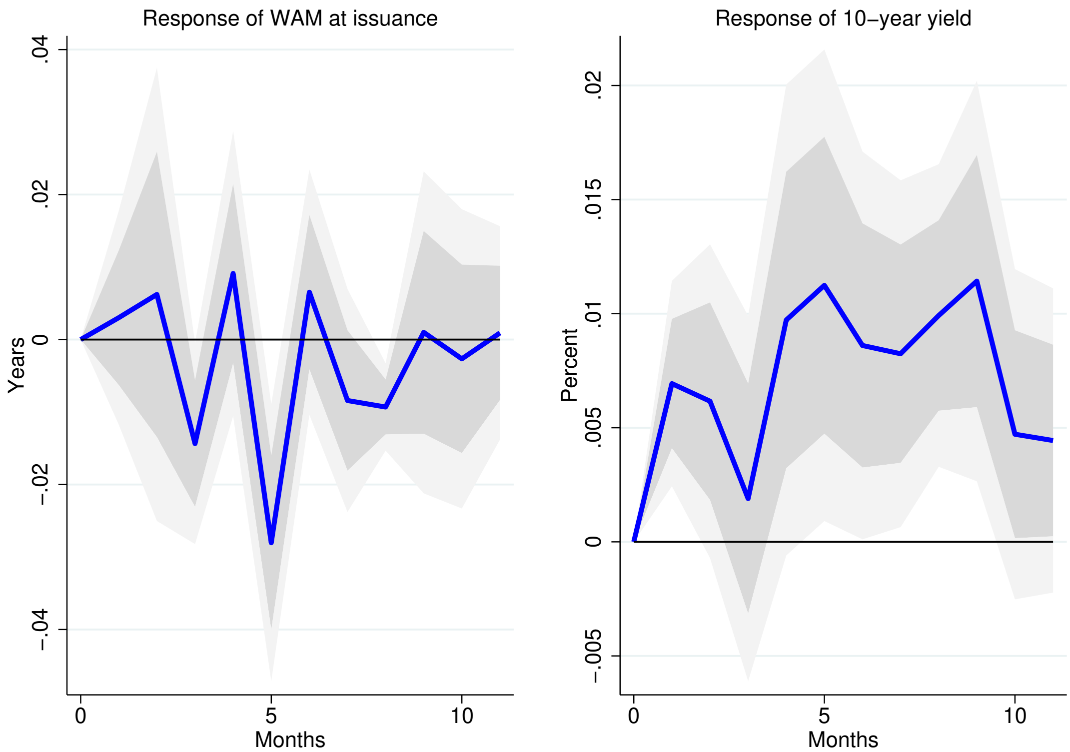
Note: Robust standard errors presented in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. CCEP estimator is used for all regressions. All models include country fixed effects. Dependent variable: WAM at issuance in years. PSPP/issuance are monthly PSPP purchases per country divided by the monthly issuance volume of debt securities in the country. PSPP-dummy is 1 as of March 2015, otherwise 0. All independent variables except for redemptions are lagged by one month. ‡ denotes joint significance of the yield and the interaction term of yield*PSPP-dummy in the first F-test presented below the table. When the null hypothesis of the second F-test, $\text{Yield}^b = \text{Yield}^a$, cannot be rejected, the effect of 10-year yield on WAM issuance is not statistically different over the whole sample period (December 2009 to April 2019) and before the the PSPP (until February 2015). Big 4 includes: DE, FR, IT and ES. Stressed includes: ES, IT and PT. Non-Stressed includes: DE, FR and NL.

Figure 10: Impulse responses to 1 basis point yield shock – parsimonious specification



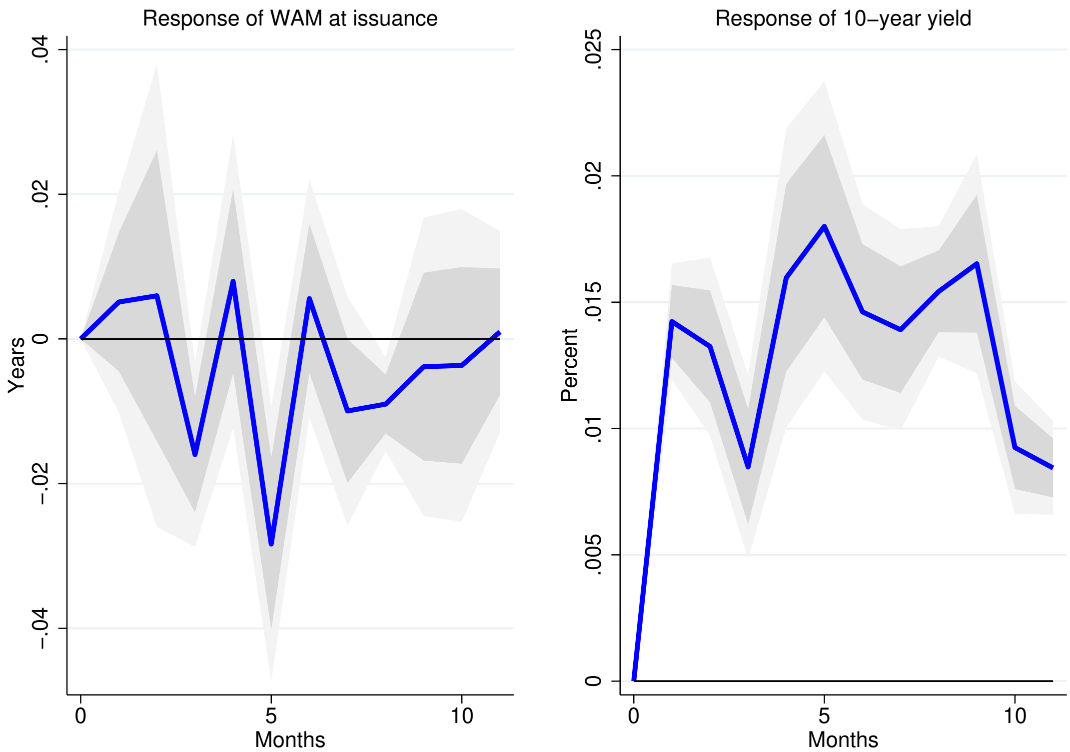
Note: Impulse response functions to a 1 basis point high-frequency yield shock based on local projections as defined in Equation (2). Control variables in regressions for WAM at issuance include an autoregressive term and the 10-year yield. The yield regression includes an autoregressive term only. Models include one lag for each variable. Robust standard errors are clustered by country. Dark (light) grey-shaded areas indicate 68% and 90% confidence intervals.

Figure 11: Impulse responses to 1 basis point yield shock - model with two lags



Note: Impulse response functions to a 1 basis point high-frequency yield shock based on local projections as defined in Equation (2). Control variables include an autoregressive term, the 10-year yield, PSPP/issuance, redemptions, WAM outstanding, the change of industrial production, and inflation. Models include two lags for each variable. Robust standard errors are clustered by country. Dark (light) grey-shaded areas indicate 68% and 90% confidence intervals.

Figure 12: Impulse responses to 1 basis point yield shock – no lagged dependent variables



Note: Impulse response functions to a 1 basis point high-frequency yield shock based on local projections as defined in Equation (2). Control variables include the 10-year yield, PSPP/issuance, redemptions, WAM outstanding, the change of industrial production, and inflation, but no autoregressive lagged dependent variables. Models include one lag for each variable. Robust standard errors are clustered by country. Dark (light) grey-shaded areas indicate 68% and 90% confidence intervals.

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