BANK OF ENGLAND

Staff Working Paper No. 624

QE: the story so far

Andrew G Haldane, Matt Roberts-Sklar, Tomasz Wieladek and Chris Young

October 2016

BANK OF ENGLAND

Staff Working Paper No. 624

QE: the story so far

Andrew G Haldane,[(1)] Matt Roberts-Sklar,[(2)]
Tomasz Wieladek[(3)] and Chris Young[(4)]

Abstract

In the past decade or so, a number of central banks have purchased assets financed by the creation of central bank reserves as a tool for loosening monetary policy – a policy often known as 'quantitative easing' or 'QE'. The first half of the paper reviews the international evidence on the impact on financial markets and economic activity of this policy. It finds that these central bank balance sheet expansions had a discernible and significant impact on financial markets and the economy. The second half of the paper provides new empirical analysis on the macroeconomic impact of central bank balance sheet expansions, across time and countries. It finds three key results. First, it is only when central bank balance sheet expansions are used as a monetary policy tool that they have a significant macro-economic impact. Second, there is evidence for the US that the effectiveness of QE may vary over time, depending on the state of the economy and liquidity of the financial system. And third, QE can have strong spill-over effects cross-border, acting mainly via financial channels. For example, the impact of US QE on UK economic activity may be as large as the impact on US economic activity.

Key words: Quantitative Easing, QE, unconventional monetary policy, central bank balance sheet.

JEL classification: E6, E43, E44, E52, E58.

(1) Bank of England. Email: andy.haldane @bankofengland.co.uk
(2) Bank of England. Email matt.roberts-sklar@bankofengland.co.uk
(3) Barclays Capital and CEPR. Email: tomaszwieladek@gmail.com
(4) Bank of England. Email: chris.young@bankofengland.co.uk

The views expressed in this paper are those of the authors, and not necessarily those of the Bank of England or its committees. Tomasz Wieladek's main analytical contribution to this paper was completed while employed by the Bank of England and does not represent the views of Barclays. The authors would like to thank Max Capel, Jenny Lam, Alison Schomberg and Mohammed Wazzi for their excellent research assistance. The authors would also like to thank Jeremy Franklin, Peter Gee, David Latto and Garry Young for input and helpful comments on this paper. The authors are grateful to Niall Ferguson, Andreas Schaab and Moritz Schularick for giving permission to use their historical data on central bank balance sheets.

Information on the Bank's working paper series can be found at
www.bankofengland.co.uk/research/Pages/workingpapers/default.aspx

Publications Team, Bank of England, Threadneedle Street, London, EC2R 8AH
Telephone +44 (0)20 7601 4030 Fax +44 (0)20 7601 3298 email publications@bankofengland.co.uk

ISSN 1749-9135 (on-line)

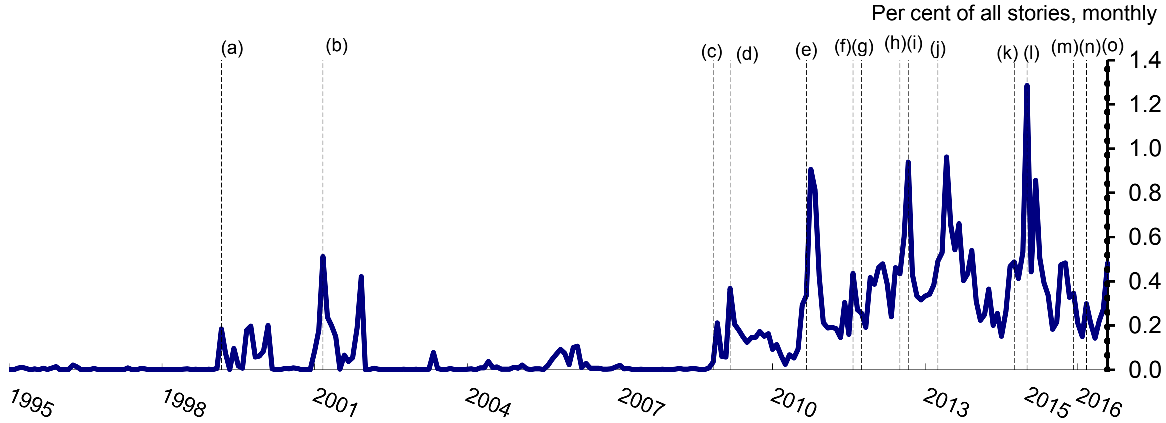
Section 1: Introduction

The modern history of Quantitative Easing (QE) starts in February 1999. With policy rates having approached the lower bound for nominal interest rates, one member of the Bank of Japan's (BoJ's) Policy Board expressed an opinion that the Bank of Japan should "implement a quantitative easing by targeting the monetary base". In 2001, Japan began down that road, purchasing government bonds financed by the creation of central bank reserves.

Outside Japan, QE was first adopted by the US Federal Reserve and the Bank of England in 2008 and 2009, as they neared the lower bound for nominal interest rates and sought to provide additional monetary stimulus. In 2015, these countries were joined by the euro-area, as the European Central Bank (ECB) began expanding its balance sheet as it neared the lower bound for interest rates. Three of these four central banks were continuing to expand their balance sheets in the second half of 2016.

These unconventional monetary policy interventions have steadily entered the public's consciousness. **Figure 1** provides one metric – the number of news stories containing the words QE or Quantitative Easing. This picked up after the global financial crisis and remains at elevated levels currently. Having not registered in news stories prior to this century, QE now appears to have entered the popular lexicon.

Figure 1: Bloomberg news stories containing "QE" or "Quantitative Easing"

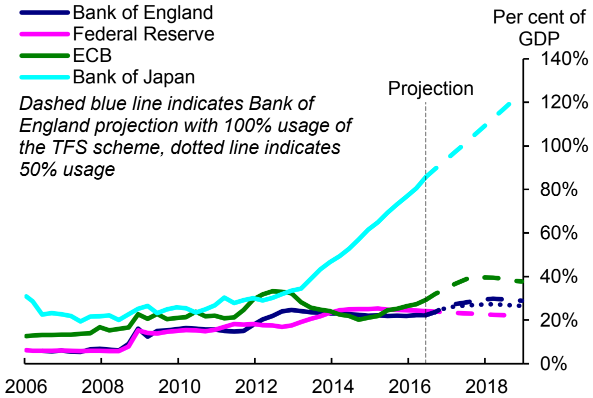


Monthly count of stories containing "QE" or "Quantitative Easing" as a percentage of all stories.
(a) Minutes of BoJ meeting show one member voting for "quantitative easing"; (b) BoJ announces QE; (c) Fed announces QE1; (d) BoE announces QE1; (e) Fed announces QE2; (f) Fed announces Maturity Extension Program; (g) BoE announces QE2; (h) BoE announces QE3; (i) Fed announces QE3; (j) BoJ announces QQE; (k) BoJ announces QQE2; (l) ECB announces QE (m) ECB extends QE (n) ECB increases and extends QE (o) BoE announces QE4. Sources: Bloomberg and Bank calculations.

This paper reviews the impact of central bank balance sheet expansions on financial markets and the economy. These expansions are, in one sense, nothing new. As Section 2 explores, significant expansions of central bank balance sheets have been going on for as long as we have had central banks. In previous centuries, however, these monetary injections tended to be associated with the financing of wars or the bail-out of banking systems, rather than operating as a monetary policy tool.

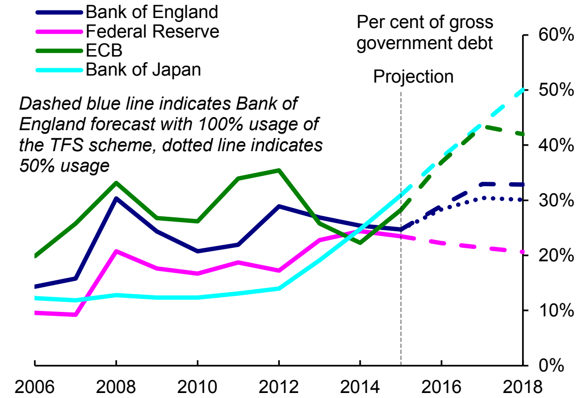
It is only during this century, and in particular since the global financial crisis, that we have seen central bank balance sheet expansions taking on an explicit monetary policy objective. Since 2007-8, as a number of countries approached the effective lower bound for official interest rates, central banks made outright purchases of securities funded by the creation of central bank reserves - Quantitative Easing or QE. This has led to a substantial increase in central banks' balance sheets, both relative to nominal GDP and to the stock of government debt outstanding (**Figures 2a and 2b**).

Figure 2a: Central bank balance sheet size relative to nominal GDP



Source: Bank of England, Federal Reserve, Bank of Japan, European Central Bank, Bloomberg, Thomson Reuters DataStream and Bank calculations.

Figure 2b: Central bank balance sheet size relative to government debt



Source: Bank of England, Federal Reserve, Bank of Japan, European Central Bank, Bloomberg, Thomson Reuters DataStream and Bank calculations.

With the Bank of Japan, Bank of England and European Central Bank continuing to expand their balance sheets, these monetary interventions are continuing to rise. They are already large in quantitative terms, at between 30-80% of each country's GDP and 20-40% of the government debt stock outstanding.

These central bank interventions, unprecedented in scale, are an important and topical area of study by central banks, academics and market practitioners alike. There have been a significant number of recent studies assessing the impact of QE. This paper provides a summary of these studies, while also offering some new empirical evidence on both the channels through which QE operates and its impact on financial markets and economic activity.

Section 2 provides a short historical perspective on QE. Section 3 explores the channels through which QE might, in practice, operate. As with any policy intervention, the effectiveness of QE depends on the extent of distortions or frictions in the functioning of various markets. Because these frictions may change over time, depending on the state of the economy and financial system, so too will the effectiveness of QE.

Section 4 begins to assess the effectiveness of QE, with a particular focus on its impact on financial markets. Looking across countries and episodes, there is reasonably clear evidence of QE announcements having lowered yields on long-term government debt. QE interventions have also tended to be associated with changes in other asset prices, such as equities, corporate bonds and exchange rates.

These "event studies" of the impact of QE on asset markets provide one means of assessing the wider macro-economic impact of unconventional monetary interventions. Existing event studies of asset price movements suggest that QE is likely to have had a material impact, providing a significant, if temporary, boost to growth and inflation. But as these studies use a particular approach to identifying the impact of QE, they leave a number of issues open.

By using a different approach to identifying the impact of QE, Sections 4 and 5 present some new empirical evidence on the macroeconomic impact of central bank balance sheet expansions, across time and countries. Our key findings include the following. First, it is only when central bank balance sheet expansions are used as a tool of monetary policy that they appear to have effects on the economy. QE is, in this sense, a different animal to other central bank balance sheet operations.

Second, there is evidence (at least for the US) that the effect of QE may vary over time, depending on the state of the economy and financial system, as theory would suggest. Specifically, the impact of QE is greater the weaker the economy and the more disturbed the state of financial markets. This state-dependency in the impact of QE is potentially important to our understanding of how QE has worked in the past and the circumstances in which it is likely to be effective in the future.

Third, QE appears to have strong spill-over effects to other advanced economies. Perhaps predictably, these spill-overs appear to operate largely through financial market channels. Indeed, these international spill-over effects of QE may, for some countries, be larger in their impact than equivalent-sized domestic monetary interventions. This finding is important when assessing the impact of overseas monetary interventions on domestic activity.

These are not the only issues that are topical and contentious when assessing the impact of QE. For example, there is clearly the potential for QE to have important distributional consequences – for example, on households' and financial intermediaries' assets and portfolio allocation decisions. These distributional issues are important and have been studied previously, including by the Bank of England (for example, Bank of England (2012)). This paper focuses on the *aggregate* impact of QE on financial markets and the macro-economy.

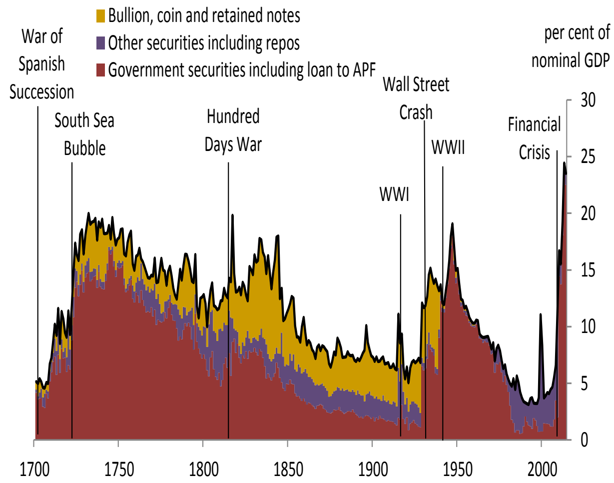
Section 2: A brief history of central bank balance sheet expansions

Central bank balance sheet expansions are, assuredly, not new. For example, the Bank of England's balance sheet was more than 10% of nominal GDP throughout most of the 18th and 19th centuries and into the first half of the 20th century (**Figure 3**). That compares with a balance sheet of a little over 5% of GDP just prior to the global financial crisis. In the period since, the Bank's balance sheet has since expanded to reach around its highest level relative to GDP since its inception in 1694.

Historical balance sheet expansions tended typically to be associated with the financing of wars and the management of financial crises. Although these interventions increased the stock of central bank money, they would not have been seen at the time as monetary policy, at least as it is currently conceived. Indeed, for much of the Bank of England's history, it played a dual role as both "a national and a profit-making bank" (Clapham (1958)). In that sense, its public policy role in setting monetary policy was at best vague and imperfect.

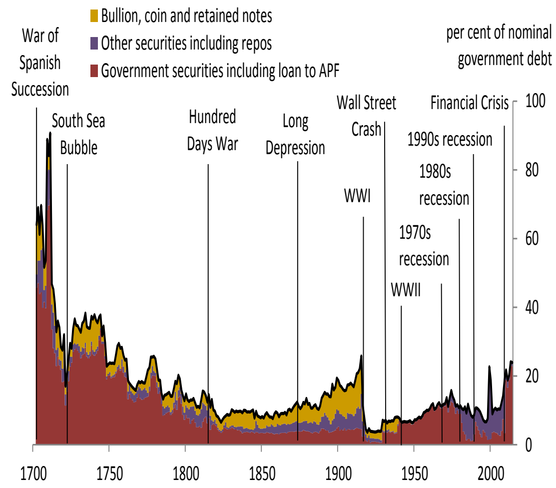
Reflecting its role as financier of war and other government activities, historical expansions of the Bank of England's balance sheet have tended to be backed by government securities. In some cases, these expansions were specifically designed to facilitate an increase in government debt. For example, in the early 18th century, the Bank ended up owning nearly all of UK government debt (**Figure 4**). This was in some ways a continuation of the Bank's original mandate in 1694, which was to raise funds to finance war with France (Clapham (1958)).

Figure 3: Composition of Bank of England Balance Sheet, scaled by nominal GDP (1700-2014)



Source: Hills, Thomas and Dimsdale (2015).

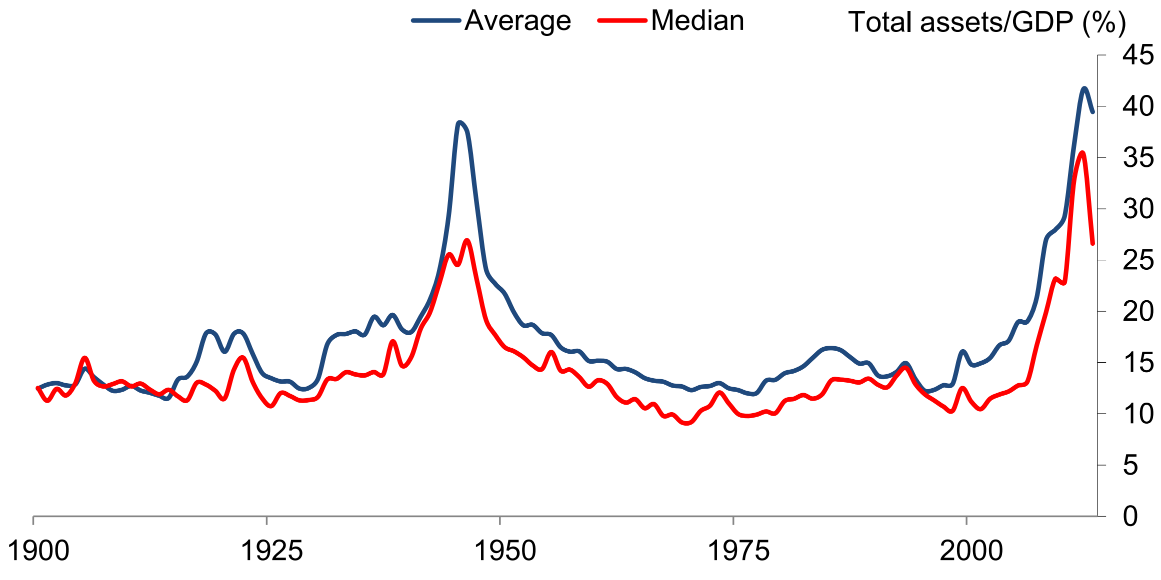
Figure 4: Composition of Bank of England Balance Sheet, scaled by nominal government debt (1700-2014)



Source: Hills, Thomas and Dimsdale (2015).

Nor were these historical central bank balance sheet expansions peculiar to the Bank of England. In their study of central bank balance sheets across sixteen countries since 1900, Ferguson, Schaab and Schularick (2015) find that historical expansions have also been mostly associated with geopolitical or financial crises. In particular, central bank balance sheets increased around the Second World War, at that stage approaching 40% of GDP in a range of countries (**Figure 5**).

Figure 5: Central Bank Balance Sheets (1900-2013)



Countries covered are: Australia, Belgium, Canada, Denmark, Finland, France, Germany, Japan, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, the United Kingdom and the United States.
Source: Ferguson, Schaab and Schularick (2015). We are grateful to Niall Ferguson, Andreas Schaab and Moritz Schularick for sharing these data with us.

Central bank balance sheet expansions during the course of this century have had a very different motivation. This has been to support economic activity, operating as a monetary policy measure augmenting the role of interest rates when they are close to their effective lower bound – hence Quantitative Easing or QE.

QE as a monetary policy tool first emerged in Japan in 1999. Japanese Consumer Prices Index inflation, excluding energy, fell below zero in early 1999. In response, the Bank of Japan continued to cut its policy rate, but found it was approaching the lower bound for nominal interest rates. In the minutes of the February 1999 Bank of Japan policy meeting, one member of the committee noted that the Bank of Japan should implement "a quantitative easing by targeting the monetary base" (Bank of Japan (1999)).

Yet it was not until March 2001 that such a "quantitative easing" policy was announced by the Bank of Japan. This involved using the quantity of central bank reserves as the operating policy target, injected via purchases of Japanese government bonds, with a commitment to maintaining the provision of liquidity until CPI inflation became zero or higher on a sustained basis (Ugahi (2007), Ueda (2011) and Ito (2014)). This program was expanded over the following five years, with the range of assets purchases extended to include equities and asset-backed securities.

Central bank balance sheet expansions for monetary policy purposes became more common after the global financial crisis. Around the world, central banks loosened monetary policy to offset the collapse in demand, with short-term interest rates cut to close to zero in the US, UK and euro area. Each of these central banks, as well as the Bank of Japan, subsequently significantly expanded their balance sheets. Until the Bank of Japan's quantitative and qualitative easing (QQE) announced in April 2013, these expansions were of a similar scale relative to nominal GDP, at around 20% (**Figure 2**). Relative to government debt, these balance sheet expansions were also similar (**Figure 3**).

Yet, in some respects, the differences in these balance sheet expansions have been as great as the similarities (Borio and Disyatat (2009), Lenza, Pill and Reichlin (2010), Kozicki et al (2011) and Fawley and Neeley (2013)). Some of the expansions reflected special liquidity operations, designed to liquefy bank balance sheets. In other words, they were not monetary policy interventions, but classic lender of last resort operations. In part reflecting that, the assets backing these expansions have often differed materially along three dimensions: repurchase agreements ("repo") versus outright purchases; public versus private sector assets; and longer versus shorter maturity assets.

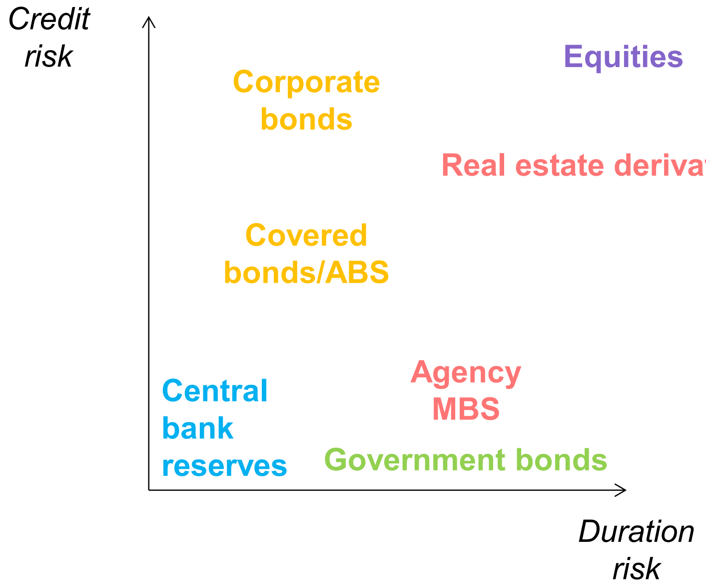
For example, the Federal Reserve (Fleming (2012)), Bank of England (Cross, Fisher and Weeken (2010)) and European Central Bank (Trichet (2010)) expanded their balance sheets using repo programmes at the start of the crisis. For the ECB, these repo operations remained its main source of balance sheet expansion until it started its asset purchase programme in 2015. In general, these large-scale repo operations were about providing liquidity support to the banking sector and, in the ECB's case, improving the functioning of the monetary policy transmission mechanism.

By contrast, when used as a tool of monetary policy, central bank balance sheet expansions have tended to take the form of outright asset purchases funded by the creation of central bank reserves.[1] They have involved the creation of central bank reserves – an essentially zero credit risk, zero duration risk instrument – by buying outright from the private sector assets that have either a longer duration and/or higher credit risk than the corresponding liability.

[1] Not all outright purchases were for monetary policy purposes. Market maker of last resort facilities were set up to improve functioning in key markets at the height of the crisis, such as the purchases of commercial paper and corporate bonds by the Bank of England (Fisher (2010)).

In the case of government debt purchases, the extent of this credit risk transfer is minimal since most government debt is perceived as low risk. But by purchasing long maturity government debt outright, QE operations can influence duration risk in the private sector. Moreover, many central banks have gone further along the credit risk spectrum by purchasing private sector assets – so-called "credit easing". In practice, a spectrum of options is possible (**Figure 6**). During the crisis, most points on this spectrum have been covered by QE operations at one time or another.

Figure 6: Stylised diagram of Quantitative Easing vs Credit Easing



Source: Authors

For example, the Bank of Japan's QE program in the early 2000s included a range of asset purchases. In their most recent quantitative and qualitative monetary easing (QQE) program, adopted in April 2013 and expanded in October 2014, the Bank of Japan has placed greater emphasis on longer-maturity government bonds and riskier assets, such as commercial paper, corporate bonds, equity exchange traded funds and real estate derivatives (Arslanalp and Botman (2015)). In September 2016, the Bank of Japan added "yield curve control" to their QQE program, explicitly targeting the 10-year yield (Bank of Japan (2016)).

In the US, the importance of the Agency MBS market for mortgage rates, and the size of this market, made it a natural candidate for the Federal Reserve's asset purchases, alongside US government bonds (Gagnon et al (2010)). MBS purchases comprised around 45% of the Federal Reserve's asset purchases during its QE programme.

In the euro area, the ECB's outright purchases have mainly comprised the bonds of 18 euro-area governments, purchased through a public sector purchase programme (PSPP) announced in January 2015 (Cœuré (2015)). This programme also includes bonds issued by recognised agencies, regional and local governments, international organisations and multilateral development banks located in the euro area. The ECB has also purchased small quantities of covered bonds, asset backed securities and corporate bonds.[2]

In the UK, the Bank of England has predominantly bought UK government bonds ("gilts") a part of its QE programme, as this is a large market and allows the purchases to be targeted at assets held by the non-bank sector (Fisher (2010)). Most recently the Bank of England has commenced a programme of corporate bond purchases (Bank of England (2016)), albeit on a relatively modest scale.

Even for government bond purchases, there has been a lot of heterogeneity in the maturity of bonds purchased. That partly reflects differences in government bond markets. For example, the maturity of the Bank of England's stock of asset purchases has been broadly in line with the stock of outstanding government debt. In some cases, such as the Fed's Maturity Extension Programme, there has been a specific focus on trying to buy longer duration assets (Ehlers (2012) and Meaning and Zhu (2012)). The design of the ECB's QE programme, announced in January 2015, took explicit account of the different sovereign bond markets in the euro area (Cœuré (2015)).

Section 3: How does QE work?

Ben Bernanke famously remarked in 2014: "The problem with QE is that it works in practice, but it doesn't work in theory."[3] In certain theoretical settings, Bernanke's observation is true. Even in models which admit some role for central bank balance sheet expansions, the channels through which QE works are still the subject of debate, academically and practically. In this section, we discuss these various channels and the factors which determine their quantitative significance.

Schematically, the transmission mechanism for QE can be thought to comprise two legs: an expansion of the central bank's balance sheet, creating new reserves to purchase short-term bills; and a maturity extension programme, swapping these bills for longer-term bonds. In many standard macroeconomic models, neither leg has an effect on economic activity. Expanding the supply of reserves has no economic impact if the opportunity cost of holding reserves is small.[4] And reallocating assets between private and public-sector balance sheets has no impact if these assets are only valued for their payoffs and there are no constraints on investors' portfolio positions other than their budget constraints (Woodford (2012)).

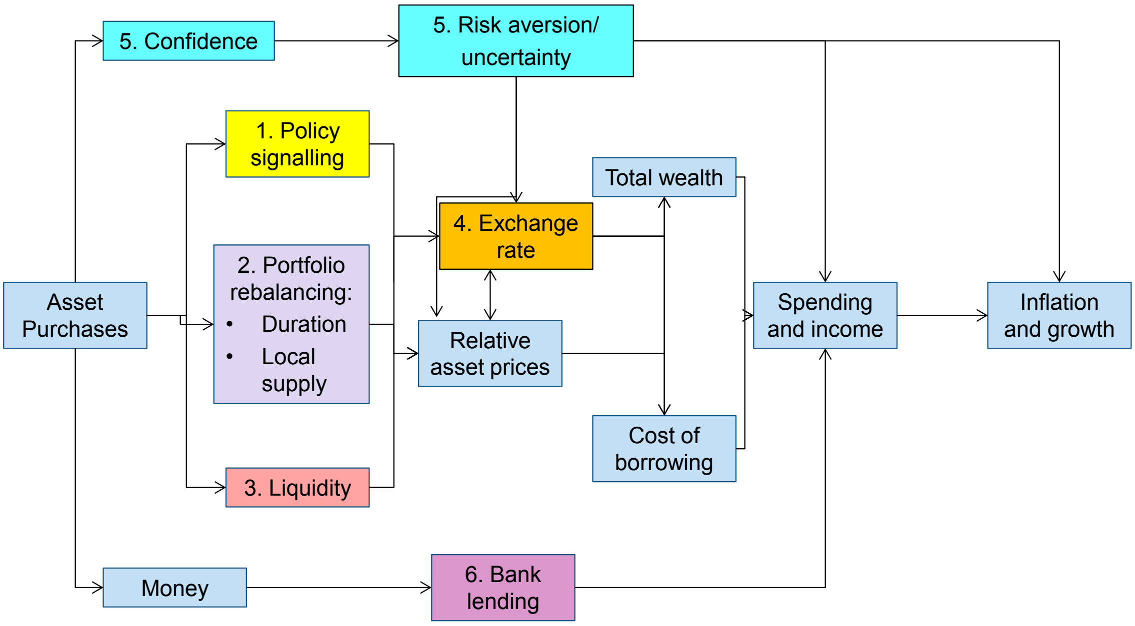
In order to understand how QE might work, we need to depart from these standard models by adding in various market frictions and distortions. Over the past few years, the ever-growing QE literature has identified a range of potential channels through which unconventional monetary policy might operate. These are shown schematically in **Figure 7**.

[2] The ECB purchased covered bonds from July 2009 to June 2010 ($60bn) and November 2011 to October 2012 (€16bn). As at October 2016, the ECB is undertaking purchases of covered bonds (programme started in October 2014), asset-backed securities (programme started in November 2014) and corporate bonds (programme started in June 2016) alongside its public sector purchase programme.

[3] Bernanke was speaking at the Brookings Institution "Central Banking after the Great Recession: lessons learned and challenges ahead" conference.

[4] However, Reis (2016) argues that the power of QE comes from interest-paying reserves being a special public asset, neither substitutable by currency nor by government debt. Christensen and Krogstrup (2016) also discuss a model whereby central bank reserve expansions can affect long-term bond prices.

Figure 7: Stylised transmission mechanism of QE



These channels include: *monetary policy signalling* – QE conveys extra information about the future path of short-term interest rates; *portfolio rebalancin*g – QE induces a switch into longer duration or higher risk assets; *liquidity effects* – QE squeezes the liquidity premium on various assets; *exchange rate* – QE lowers the price of domestic asset relative to overseas assets; *confidence/uncertainty* – QE reduces the amount of volatility in markets or uncertainty about the outlook; and *bank lending* – QE helps stimulate a rise in lending by banks .

Some of these are standard channels of monetary policy transmission, recast for the unconventional era. For example, the monetary policy signalling and exchange rate channels also operate when using conventional interest rate instruments. But some channels are more distinctively associated with QE. For example, the portfolio balance and liquidity channels are specific, if not unique, to QE.

To be effective, all of these channels rely, to greater or lesser extent, on the existence of various frictions or imperfections in the functioning of financial markets. Without these frictions, the effects on asset prices of asset purchases would be expected to be small or non-existent. **Table 1** provides a taxonomy of these market frictions and identifies the key papers to date which have explored these channels of QE transmission.

Generally speaking, these frictions can be grouped two ways:

- Information frictions: These might arise from private agents having less than perfect information either about the future monetary policy reaction function of the authorities and/or about the future course of the macro-economy (Eggertsson and Woodford (2003) and Rudebusch and Williams (2008)). This friction underlines the signalling, exchange rate and uncertainty channels of QE.

- Market frictions: These might arise from imperfect degrees of substitutability between different classes of asset, from investors having a preferred habitat for bonds of a particular duration or credit risks, or from limits to arbitrage between certain assets (Vayonas and Vila (2009)). This friction underlies the portfolio balance, liquidity and bank lending channels of QE.

The importance and effectiveness of these different channels will depend jointly on the type of assets bought, the design of the asset purchase programme, and the structure of the economy and financial system. Conventional monetary policy relies for its effectiveness on a particular market friction - inertia in labour and goods prices. This price or wage stickiness gives conventional monetary policy its potency. Because this friction is structural and slow-moving, the effectiveness of conventional monetary policy is itself expected to be reasonably inertial and state-invariant.

Unconventional monetary policy relies for its effectiveness on a different set of frictions - portfolio allocation decisions by financial intermediaries. Because these frictions in financial markets are likely to be faster-moving and more transient, the effectiveness of unconventional monetary policy would itself be expected to vary over time and across states of nature. For example, QE may have a bigger effect when the financial system is impaired (Miles and Schanz (2014)). Below, we consider the empirical evidence on the potential state-dependency of QE.

Section 4: Evidence on the impact of QE

The first stage of the transmission mechanism from asset purchases to the real economy occurs through their impact on financial market prices. A number of empirical studies have looked quantitatively at the impact of QE on a range of asset prices: government bond yields; exchange rates; equity prices; volatility; and corporate bond spreads. Borio and Zabai (2016) summarise various previous empirical studies in Table 4 of their paper.

4.1: The impact of QE on government bond yields

Because financial markets are forward looking, the main impact of asset purchases on government bond yields is likely to occur when expectations of purchases are formed rather than when purchases are made. A number of papers assess the impact of asset purchases by applying an "event study" approach, looking at the immediate reaction of government bond yields to announcements about QE.

Gagnon et al (2011) and Krishnamurthy and Vissing-Jorgensen (2011) analyse the market reaction to the Federal Open Market Committee's (FOMC's) large-scale asset purchase (LSAP) announcements. Williams (2014) summarises the evidence, noting that $600bn of LSAP purchases have tended, on average, to lower the yield on 10-year Treasury bonds by 15-25 basis points. This is roughly the same-sized move in longer-term yields as would be expected from a 0.75-1 percentage point cut in the Federal Funds rate.

Joyce et al (2011) estimate that the Bank of England's first wave of asset purchases from March 2009 to January 2010, which involved purchasing a cumulative £200 billion of medium- to long-term UK government bonds, led to an average fall in 5 to 25-year gilt yields of about 100 basis points.

Table 1 – Channels of QE and what you have to believe for them to work

Channel	Description	What do you have to believe for this channel to work? (what frictions?)	References
1. Policy signalling	Anything economic agents learn about the path of future monetary policy.	Information frictions - need for the central bank to "put money where your mouth is".	Clouse et al (2003); Eggertsson and Woodford (2003); Bauer and Rudebusch (2012); Farmer (2012)
2. Portfolio balance • Duration • Local supply	Pushing up price of assets bought and also the price of other assets. Investors rebalance their allocation of different assets and money.	Preferred-habitat demand – preferences for bonds of specific maturities. Limits to arbitrage. Some investors do not view bonds of different maturities as perfect substitutes.	Tobin (1961, 1963 and 1969); Modigliani and Sutch (1967); Brunner and Meltzer (1973); Friedman (1978); McCallum (2000); Bernanke, Reinhart and Sack (2004); Andrés et al (2004); Vayonas and Vila (2009); Krishnamurthy and Vissing-Jorgensen (2011); Harrison (2012)
3. Market liquidity premia	If financial markets are dysfunctional, central bank asset purchases can improve liquidity by encouraging trading, reducing liquidity premia.	Markets dysfunctional. Transaction costs.	Krishnamurthy and Vissing-Jorgensen (2011)
4. Exchange Rate	Impact on the exchange rate, through changing interest rate differentials and/or risk premia and long-term exchange rate expectations		Glick and Ledu (2013)
5. Confidence/risk aversion/uncertainty	QE improves the economic outlook/reduces risk of bad outcomes (via any mechanism)	People need to believe QE will improve the economic outlook	
6. Bank lending	Increased deposits expand banks' balance sheets.	Bank lending is not constrained. Agents cannot perfectly substitute other forms of lending.	Bridges and Thomas (2012); Butt et al (2014); Bowman et al (2015)

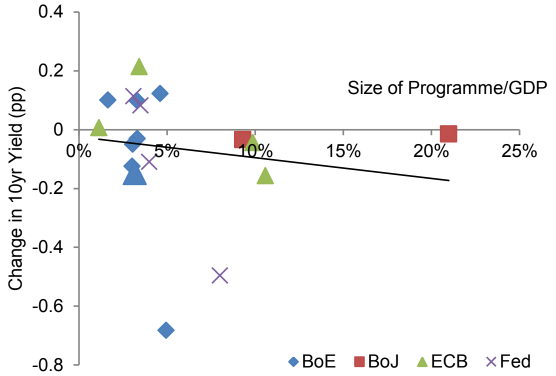
Looking across the first £375bn of Bank of England QE, Meaning and Warren (2015) estimate that QE reduced yields by around 25bps. As discussed below, the Bank's monetary policy package announced in August 2016 also had a significant impact on longer-term government bond yields.

The ECB's asset purchase programme was announced in January 2015. Looking at news events around ECB QE, Altavilla, Carboni and Molto (2015) find that euro-area sovereign 10-year bond yields fell by 30 to 50 basis points. Middeldorp (2015) uses the relative frequency of Bloomberg news articles containing "QE" or "Quantitative Easing" and finds a significant effect across a variety of asset classes, not only in the euro-area but in the US and UK too. Andrade et al (2016) also find that the ECB's asset purchase programme had a significant and persistent impact on long-term yields. Finally, for the Bank of Japan's asset purchases, Ito (2014) finds that QE lowered long-term interest rates and flattened the yield curve, significantly and persistently.

Consistent with those studies, **Figure 8** shows the impact of QE announcements by the Bank of England (up to and including the August 2016 policy package), the Federal Reserve, the European Central Bank and the Bank of Japan on long-term interest rates. It also shows a line of best fit. While individual country experiences have clearly differed, and the pattern is by no means uniform, in general QE interventions have tended to be associated with a fall in long-term government bond yields, as we would expect.

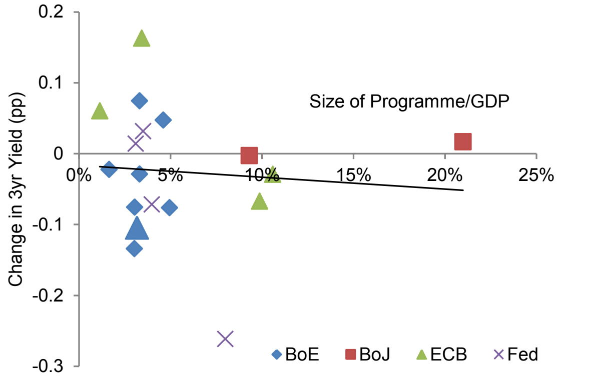
Figure 9 shows the impact of these same interventions on *short-term* interest rates. These would be expected to capture any monetary policy signalling impact, to the extent QE is interpreted as offering a signal about a lower-than-previously-expected path for future short-term interest rates. Consistent with the signalling hypothesis, short-term interest rates fell in the majority of cases, although the degree of cross-country variation in responses is again considerable.

Figure 8: Change in long rates around selected QE announcements



Source: Bloomberg and Bank calculations.
Note: Change in 10-year spot government bond yields (German yields used for ECB QE events) over two-day windows around QE events[5], against size of announcement relative to that economy's GDP at the time. Does not control for expectations of QE announcements or other news during two-day window.

Figure 9: Change in short rates around QE announcements



Source: Bloomberg and Bank calculations.
Note: Change in 3-year spot market interest rates (OIS for UK, US and euro area, government bond yield for Japan) over two-day windows around QE events, against size of announcement relative to that economy's GDP at the time. Does not control for expectations of QE announcements or other news during two-day window.

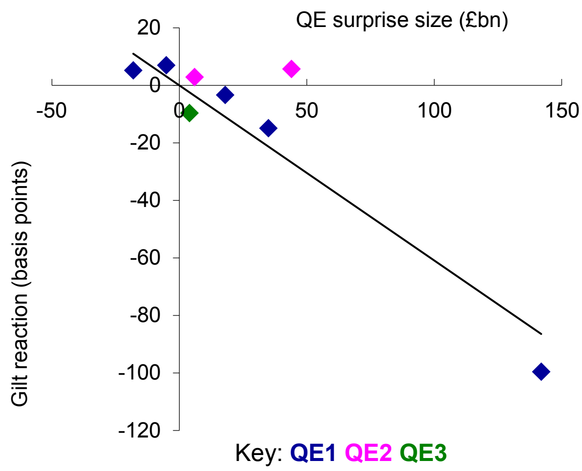
[5] The QE events considered in Figures 8-9 and 14-17 are: BoE (5 March 2009, 7 May 2009, 6 August 2009, 5 November 2009, 6 October 2011, 9 February 2012, 5 July 2012, 4 August 2016), Federal Reserve (25 November 2008, 18 March 2009, 3 November 2919, 13 September 2012 and 12 December 2012), ECB (4 September 2014 and 22 January 2015) and BoJ (4 April 2013 and 31 October 2014).

Looking at **Figures 8 and 9**, it is clear that there is considerable variation across time and across countries in the impact of QE on the yield curve. In the UK, the largest fall in gilt yields was in response to the March 2009 announcement that the Bank of England would begin a programme of asset purchases. As shown in **Figure 10,** the reaction to subsequent QE announcements has been more muted.

The Bank of England's MPC conducted £200bn of asset purchases between March 2009 and January 2010. In October 2011, growing concerns about the competitiveness and macroeconomic imbalances of some euro-area economies led to the MPC resuming its asset purchases. Between October 2011 and May 2012 the Bank purchased an additional £125 billion of gilts ('QE2'). As shown in Joyce et al (2012), the absolute size of the impact on gilt yields was smaller in this case. In July 2012, the MPC announced a £50bn extension of their programme (QE3), taking the stock to £375bn, again with little reaction from gilt yields.

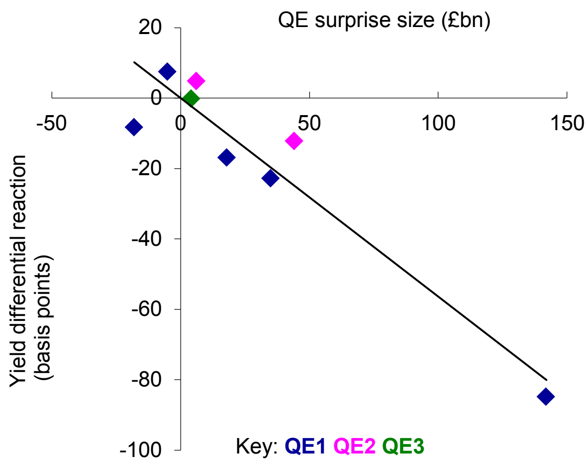
One explanation for this more muted effect is that the market had begun to anticipate the use of QE. For the October 2011 and July 2012 announcements, a resumption of asset purchases may have been expected because of earlier MPC communications, including the minutes of the September MPC meeting and the flow of adverse economic news. According to a Reuters survey of economists, the October 2011 announcement contained significant news about expected asset purchases.

Figure 10: QE in the United Kingdom, Size of surprise and average 5-25 gilt yield reaction[(a)]



Source: Bloomberg, Reuters, and Bank calculations

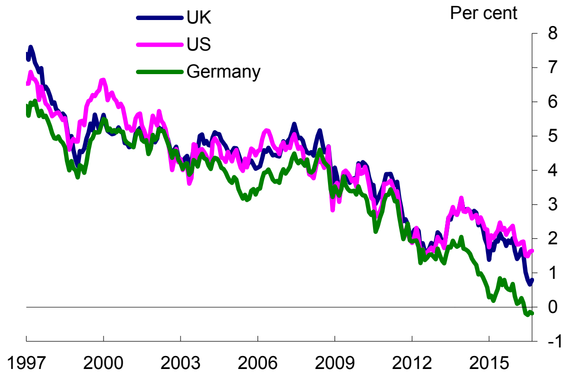
Figure 11: QE in the United Kingdom, Size of surprise and average 5-25 reaction in spread of gilts to US treasuries



Source: Bloomberg, Reuters, and Bank calculations

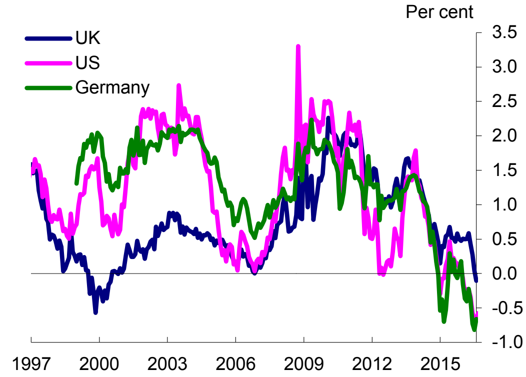
Another possible factor may have been the significant stream of other, in particular international, economic news during this period that may have affected gilt yields within our event window. If so, then looking at the reaction of gilt yields relative to German and US government bond yields may provide a better indication of the impact of QE on gilt yields. **Figure 11** replicates **Figure 10** using the spread between 10-year gilt yields and 10-year US government bond yields and suggests more of an effect.

Figure 12: UK, US and German 10-year spot yields



Source: Bloomberg, and Bank calculations. January 1997 to September 2016.

Figure 13: Estimated 10-year term premia



Sources: Bloomberg, Federal Reserve Bank of New York and Bank calculations. UK estimate is derived using the model described in Malik and Meldrum (2016). The German series is a preliminary estimate based on the same methodology as the UK estimate. US estimates are available from www.newyorkfed.org/research/data_indicators/term_premia.html.

While event studies can be used to estimate the initial impact of QE on gilt yields, they are less well-suited to capture persistent effects. In theory, we would expect the impact of QE to be temporary – for example, because of temporary flow effects on liquidity premia. One practical reason to doubt that UK QE had a large persistent impact on gilt yields is the very close correlation between yields (**Figure 12**) and estimates of term premia (**Figure 13**) in the UK and US in recent years.

One interpretation of this high correlation is that international factors may be more important determinants of gilt term premia than domestic factors, including QE (Kaminska, Meldrum and Young (2015), Roberts-Sklar (2015)). The reaction of UK yields to the US 'taper tantrum' in 2013 is an interesting case study in this respect. Section 5 assesses the evidence on international spill-overs from QE.[6]

<u>4.2: The impact of QE on other financial markets</u>

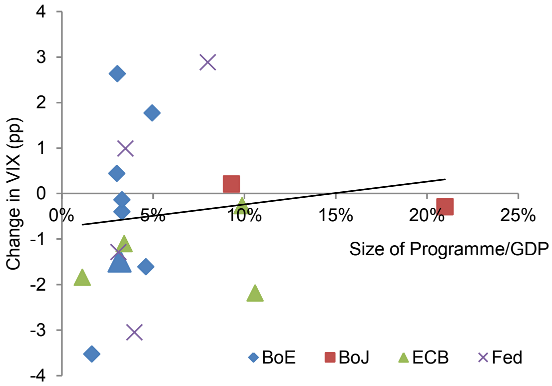
Insofar as investors regard other assets – such as corporate bonds and equities – as closer substitutes for government bonds than money, we might expect them to re-balance their portfolio towards these assets if their money holdings are boosted by temporary bond purchases (Benford et al (2009)). This would tend to put upward pressure on the prices of those assets and downward pressure on the exchange rate. Changes in government bond yields may also affect the rate at which investors discount future cash flows on these assets, also boosting their price.

Announcements about QE may contain information about the future course of monetary policy or the economy, with implications for future corporate earnings and the uncertainty around them. This effect could either push up or depress the prices of these assets depending on how QE affects

[6] Looking at the persistence of the impact in the US, Wright (2012) uses a structural VAR to estimate the effect of monetary policy shocks during the crisis (although he looks at all FOMC-related news, not only those regarding LSAPs). Despite finding a significant effect on 10-year Treasury yields on announcement, this impact effect fades within a month.

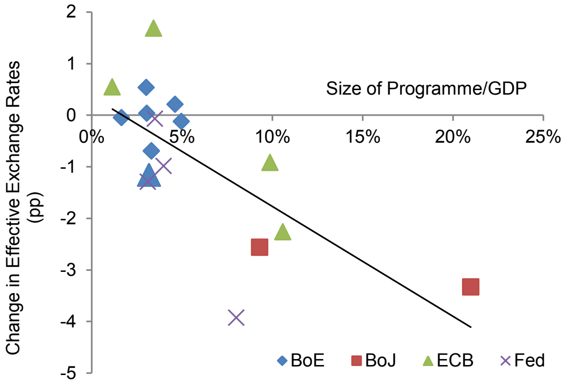
agents' risk perceptions. This means that, although we would expect QE eventually to push up riskier asset prices, their short-term impact may in some cases be ambiguous.

Figure 14: Change in VIX around selected QE announcements



Source: Bloomberg and Bank calculations. Note: Change in VIX over two-day windows around QE events, against size of announcement relative to that economy's GDP at the time. Does not control for expectations of QE announcements or other news during two-day window.

Figure 15: Change in effective exchange rates around selected QE announcements



Source: Bloomberg and Bank calculations. Note: Change in effective exchange rates over two-day windows around QE events, against size of announcement relative to that economy's GDP at the time. Does not control for expectations of QE announcements or other news during two-day window.

As shown in **Figure 14**, there is evidence of some asset purchase programmes having dampened measures of uncertainty, proxied here by the VIX index of US equity implied volatility (Bollerslev, Tauchen and Zhou (2009)). This pattern is far from uniform, however. Moreover, there is some evidence of the announcement of large QE programmes having generated a *rise* in financial market uncertainty, at least in the short term, perhaps because these interventions coincided with periods of significant financial market stress.

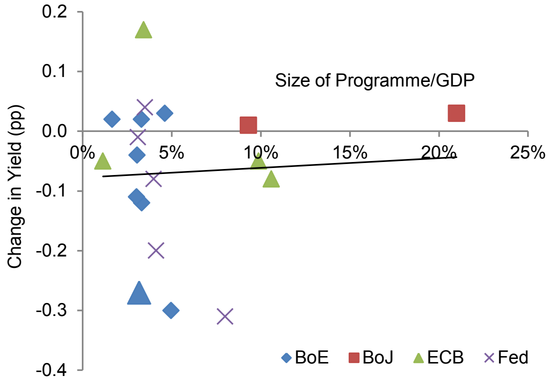
As for the exchange rate, **Figure 15** shows that most of QE announcements led to a depreciation. This is consistent with QE loosening financial conditions in the domestic economy, with larger loosenings imparting greater downward pressure on the exchange rate. Section 5 considers the impact of QE on the exchange rate in the context of international spill-overs.

Figure 16 shows the impact on corporate bond yields of QE interventions. In the UK, there were substantial falls in corporate bond yields following QE announcements. Sterling investment-grade corporate bond yields fell by a similar amount to gilt yields, leaving spreads to gilts unchanged.[7] Sterling high-yield corporate bond yields fell more sharply, on average by 150 basis points over the six QE announcements, with spreads narrowing by 70 basis points. The narrowing in spreads is consistent with QE reducing both longer-term safe rates of interest and the default risk for firms.

QE announcements are, in general, associated with higher equity prices (**Figure 17**). The reaction is, however, far from uniform across different QE interventions. For example, in the UK the FTSE index rose following the May, August and November 2009 QE announcements, but fell after the February and March 2009 events. Summing across all events, the FTSE index on average *fell* by 3%. It is possible any significant positive impact on equity prices may have taken longer to feed through.

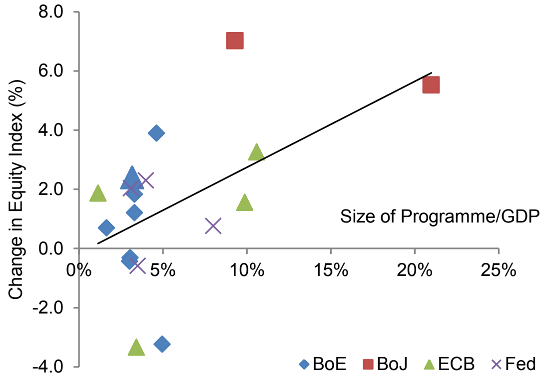
[7] The average maturity of corporate bonds is lower than gilts. Once this difference is taken into account, both sterling investment-grade corporate bond and gilt yields both fell by around 70 basis points following the announcements.

Figure 16: Change in corporate bond yields around selected QE announcements



Source: Bloomberg and Bank calculations.
Note: Change in investment grade corporate bond spreads over two-day windows around QE events, against size of announcement relative to that economy's GDP at the time. Does not control for expectations of QE announcements or other news during two-day window.

Figure 17: Change in equities around selected QE announcements



Source: Bloomberg and Bank calculations.
Note: Change in equity indices (FTSE All Share (UK), S&P 500 (US), Euro Stoxx 300 (euro area) and Topix (Japan)) over two-day windows around QE events, against size of announcement relative to that economy's GDP at the time. Does not control for expectations of QE announcements or other news during two-day window.

Overall, these event studies suggest evidence of a reaction in asset prices, other than government securities, to QE announcements. These effects are, on average, smaller and more volatile than for government bond yields, however. It is possible the event window used in these studies is too short to capture these asset price channels fully, with portfolio rebalancing taking time to have its full effect.

To assess the impact of QE over a longer period, the third column in **Table 2** reports the change in asset prices over the full period during which UK QE1 purchases were being made, from 4 March 2009 (the day before the programme was announced) to 22 January 2010 (the day of the last QE1 auction). Over this period, asset prices movements were much more pronounced. Sterling corporate bond spreads narrowed dramatically, for both investment and non-investment grade bonds. And there was a sustained rise in the FTSE index of around 50%. It would be heroic to attribute all of these gains to QE, but it seems plausible it made some contribution.

Some further insight into the portfolio re-balancing process can be found by looking directly at the portfolio allocation decisions of financial intermediaries. In the UK, policymakers explicitly structured their QE purchases with the aim of buying primarily from the domestic non-bank financial sector, such as life insurance companies and pension funds (ICPFs). They are traditionally the largest holders of long-term gilts (Bank of England (2009)).

Joyce, Liu and Tonks (2014) look at the impact of QE on the behaviour of insurance companies and pension funds, using sectoral and micro-level data. Using counterfactual analysis of what would have happened to investors' asset allocations in the absence of QE, they report ex-ante and ex-post measures of the impact of QE on insurance companies' and pension funds' investment behaviour (**Figure 18**).[8] They find that there was some portfolio rebalancing behaviour by institutional

[8] The ex-ante impact is measured by taking the difference between the model predictions for net investment with and without QE and the ex-post measure is based on comparing the actual (i.e., ex-post) out-turn with what would have been expected by using the model estimated over the pre-crisis period to predict net investment over the QE period.

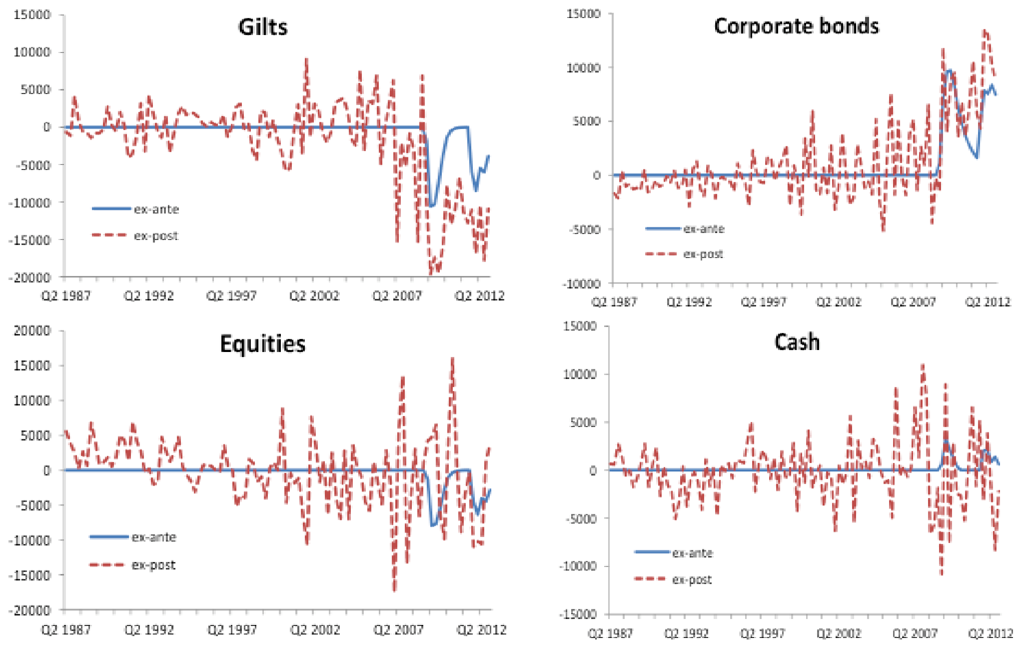
investors as they reduced their allocations to gilts and increased their allocations to corporate bonds. By contrast, institutional investors moved out of equities during the period of QE purchases.

Table 2: Summary of asset price movements around BoE QE 1,2 and 3 (basis points, unless specified)

	QE1: total of £200 billion purchases		**QE2**: total of £125 billion purchases		**QE3:** total of £50 billion purchases	
Asset	**Change around QE1 announcements** (Feb 09, Mar 09, May 09, Aug 09, Nov 09, Feb 10).	**Change 4 March 2009 – 22 Jan 2010**	**Change around QE2 announcements** (Oct 11, Feb 12, May 12)	**Change 5 October 2011 – 2 May 2012**	**Change around QE3 announcement (July 2012)**	**Change 4 July 2012 – 8 Nov 2012**
Gilts (5-25 year average)	-104 (o/w -90 gilt-OIS spread)	-6 (o/w -41 gilt-OIS spread)	+14	-18	-10	-3
Corporate yields (investment-grade)	-70	-387	+5	-85	-11	-85
Corporate yields (high-yield)	-150	-1944	-5	-215	-5	-189
FTSE All-Share	-3%	+47%	+5%	+14%	0%	+2%
Sterling ERI	-4%	+3%	0%	+5%	+1%	+1%

Source: Bank of America/Merrill Lynch, Bloomberg and Bank calculations

Figure 18: Impact of QE on UK insurance companies and pension funds, ex-ante and ex-post QE effects, £ million



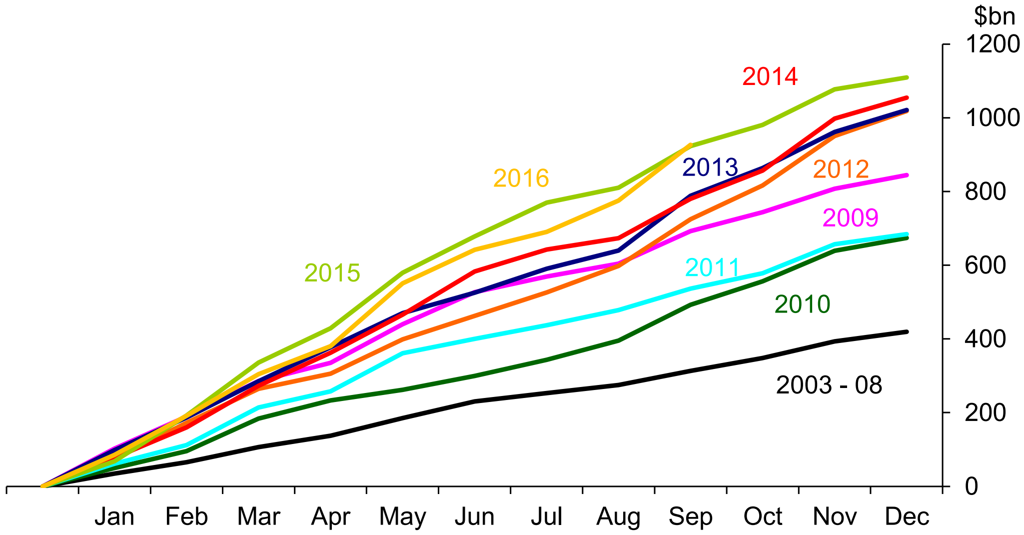
Source: Joyce, Liu and Tonks (2015)

If QE successfully raised equity and corporate bond prices, we might expect firms to respond by making more use of capital markets to raise funds. In other words, there would be a positive effect of QE on the quantity of debt and equity raised, as well as its price. The evidence is consistent with such an effect.

Net equity issuance by UK private non-financial corporations was particularly strong in 2009, reversing the negative annual average net issuance observed over 2003-08. And gross corporate bond issuance by UK private non-financial corporations in 2009 was also stronger than annual average issuance over the 2003-08 period (**Figure 19**). It is impossible to know what would have happened in the absence of QE. But the Bank of England's market contacts suggest a strong institutional investor demand for corporate bonds during the second half of 2009 (see Joyce, Tong and Woods (2011)), consistent with a portfolio rebalancing channel.

A final portfolio rebalancing channel might operate through banks', rather than non-banks', portfolio allocation decisions. In particular, increases in banks' deposit funding caused by asset purchases might lead banks to increase their lending - the 'bank lending channel' of QE. For the UK, Butt, Churm and McMahon (2015) find no evidence to suggest QE boosted bank lending. International evidence suggests possibly more of an effect. For example, in their study of the impact of the Bank of Japan's 2001-2006 QE programme, Bowman et al (2015) find a positive and statistically significant impact of bank liquidity on lending, especially for weaker banks.

Figure 19: Cumulative gross issuance of bonds by UK, US and EA19 PNFCs



Source: Dealogic and Bank calculations. 2016 line is to end September.
(a) Issuance by UK, US and EA19 private non-financial corporations (PNFCs) or their financial vehicles. Includes investment grade and non-investment grade bonds. Data are subject to revisions. 2003-08 is an average over the period.

4.3: Case Study - the Bank of England's monetary policy package in August 2016

On 4 August 2016, the Bank of England's MPC voted to introduce a package of measures to support growth and achieve a sustainable return of inflation to the target (Bank of England (2016)). The package comprised: a 25bp cut in Bank Rate to 0.25%; a new Term Funding Scheme to reinforce the pass-through of the cut in Bank Rate; the purchase of up to £10bn of UK corporate bonds, financed by the creation of central bank reserves; and an expansion of UK government bond purchases by £60bn to £435bn, also financed by the creation of central bank reserves.

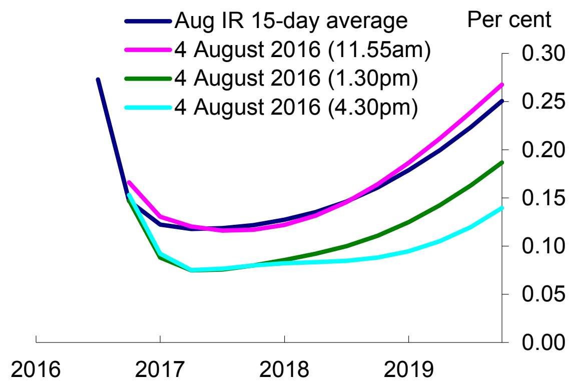
The announcement of this package provides an interesting case study of the asset price channels of QE. While a 25bp cut in Bank Rate had been widely expected by market participants, the breadth and size of the accompanying package of measures was a surprise to many in the market. As a result, there was a significant impact across a range of asset prices, both on the day of announcement and immediately afterwards (**Table 3**).

Table 3: Summary of asset price moves following 4 August 2016 MPC decision

	1 day reaction (3-4 August)	2 day reaction (3-5 August)
UK 3-year forward overnight index swap rate	-8bps	-5bps
10-year gilt yield	-17bps	-15bps
£ ERI	-1.3%	-1.4%
FTSE All Share	+1.5%	+2.4%
Sterling PNFC IG corporate bond spreads	-10bps	-18bps
Sterling PNFC HY corporate bond spreads	-8bps	-22bps

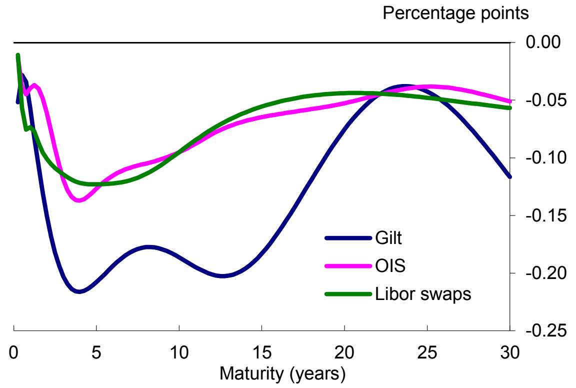
As a 25bp cut in Bank Rate was fully priced in, there was little reaction at the very short end of UK yield curves to the package announcement. Further out, however, the market-implied path for Bank Rate fell and the yield curve flattened (**Figure 20**). The gilt forward curve fell by 10-20bps across all maturities, with largest falls in the 5-15yr sector (**Figure 21**). The UK OIS and Libor swap curves also fell across all maturities, albeit by less than the gilt curve.

Figure 20: Market profile for Bank Rate before and after the August 2016 MPC announcement



Source: Bloomberg and Bank calculations

Figure 21: Changes in UK forward curves between 11:55 and 16:30, 4 August 2016

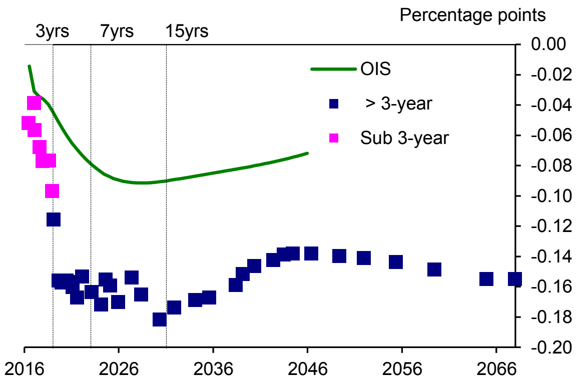


Source: Bloomberg and Bank calculations

Looking at changes in gilt yields-to-maturity (rather than smoothed zero-coupon curves), it is possible to see some evidence of local supply effects (**Figure 22**). For example, the Bank of England announced that – in line with its previous purchases – it would not be buying bonds of maturity less than three years, or those where the Bank of England holds more than 70% of the "free float". The sub 3-year maturity bond yields fell by much less than neighbouring maturities following the MPC announcement. Moreover, the yield on the September 2019 gilt – which was only eligible for the first five weeks of the purchase programme – fell by 4 basis points less than longer maturity gilts.

Given the different components of the August package, it is difficult to isolate the impact of QE and compare it with previous QE episodes. To try and identify the impact of QE, we can look at changes in the spread between gilt yields and OIS rates. This spread only captures the gilt-specific component of term premia, so will not tell us about the channels of QE that also affect OIS rates, such as policy signalling and reductions in compensation for interest rate risk.[9] The gilt-OIS spread fell by an average of 8bps across 5-25 year maturities on 4 August.

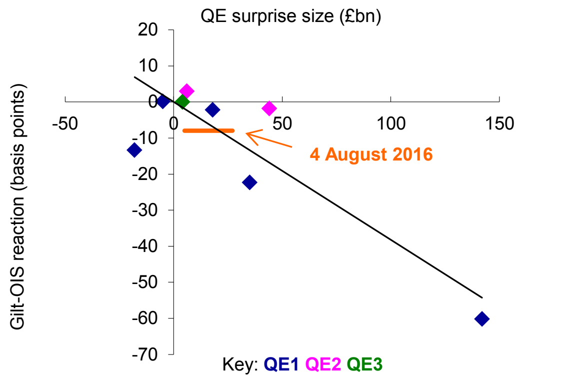
Chart 22: Change in gilt yields-to-maturity and OIS curve on 4 August 2016



Note: The Bank of England does not buy gilts with maturity below 3-years.

Source: Bloomberg and Bank calculations

Chart 23: Average 5-25 year reaction in gilt-OIS spreads following UK QE surprises



Note: Range of QE surprise for 4 August 2016 based on Reuters poll expectations of £33bn of QE for August and £65bn by end 2017, and announcement of £60-£70bn. Surprises for previous QE episodes based on changes in terminal QE expectations from Reuters polls.
Source: Reuters, Bloomberg and Bank calculations.

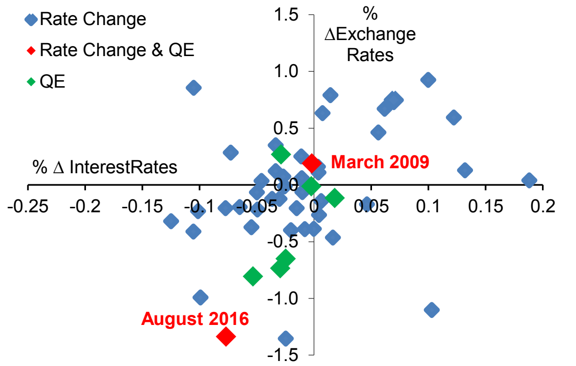
Although we do not know for sure how much QE was priced in ahead of the announcement, the flat orange line in **Figure 23** illustrates a range of estimated QE surprises, based on Reuters poll of economists' expectations of £33bn additional purchases in August MPC and £65bn by end 2017. The reaction was broadly similar to QE1 and slightly stronger than following QE2 and QE3.[10] That perhaps reflects the breadth of the August policy package.

There was also a broad-based sterling depreciation following the MPC's announcement, with the exchange rate index down 1.3% on the day. As is often the case, the fall in sterling was larger than that implied by changes in relative interest rates (**Figure 24**). Over a one-day window, sterling's depreciation was larger than other UK QE announcements and only surpassed by reactions following the QE announcements by the Bank of Japan in 2013 and 2016, the Fed in 2009 and the ECB in 2015.

Although the possibility of corporate bond purchases had been discussed by some market contacts ahead of the August MPC meeting, the announced purchase programme came largely as a surprise. Sterling non-financial investment grade spreads fell by 10bps on the day, while dollar and euro investment grade spreads remained broadly flat (**Figure 25**). There was a smaller fall in the ineligible sterling non-financial high-yield spreads. There was also a compression of bond spreads for financial firms, perhaps influenced by the introduction of the Term Funding Scheme.

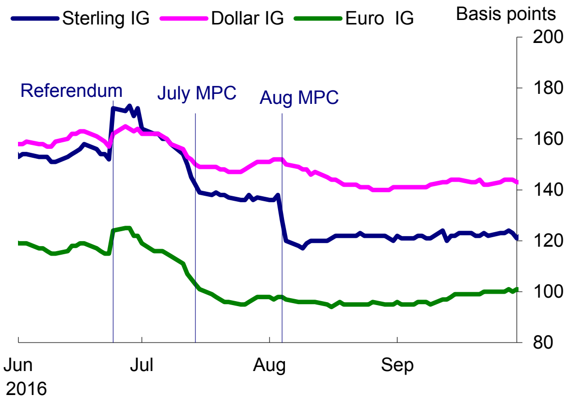
[9] Both gilt yields and OIS rates reflect the expected path for Bank Rate and the component of term premia that compensates for interest rate risk.
[10] This result also holds for changes in gilt yields spreads and changes in the spread between gilts and US Treasury yields.

Figure 24: 1-day change in sterling exchange rate index vs change in UK 2-year interest rates relative to US and German interest rates around UK monetary policy changes



Source: Bloomberg and Bank calculations. June 1997 to August 2016.

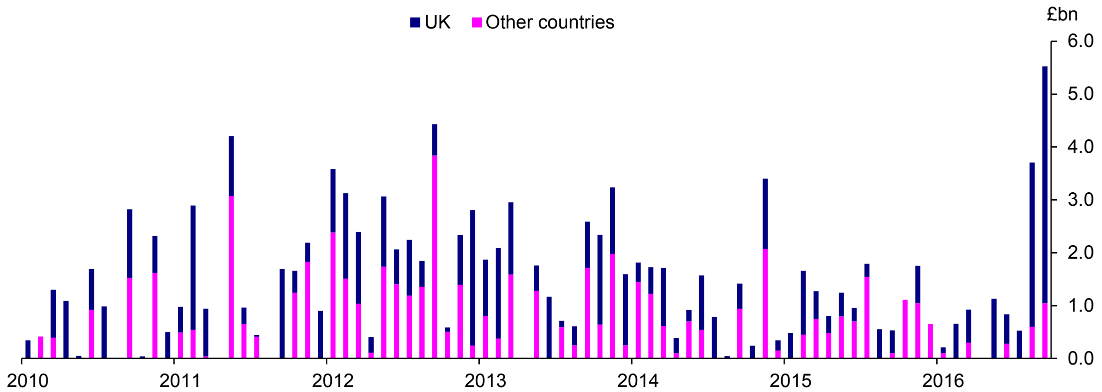
Figure 25: Non-financial corporate investment grade spreads, June-September2016



Sources: Bank of America Merrill Lynch and Bank calculations.

The announcement of the Corporate Bond Purchase Scheme, and fall in sterling corporate bond spreads, appears to have also had some impact on the issuance market. Corporate bond issuance by investment grade UK non-financial corporates picked up sharply following the announcement. The total sterling issuance of investment grade non-financial corporates was around £3.4bn in August and £4.5bn in September, with around 80% being issued by UK firms (**Chart 26**).

Figure 26: Monthly sterling non-financial corporate investment grade issuance



Sources: Bloomberg, Dealogic and Bank calculations

UK equity indices rose on 4 August, with the FTSE 100, 250, and All-Share all closing around 1.5% higher. The rise in the FTSE All-Share was broad-based across sectors. An index of UK-focused equity prices rose 1.2%. FTSE 100 option-implied volatility also fell significantly on the day. Indeed, it was the second largest one-day fall across in volatility for all QE announcement days. The skew of the option-implied distribution increased sharply as the weight attached to large falls in the FTSE decreased. This perhaps reflected expectations that the policy package had reduced tail macro risk.

Overall, the MPC's August 4 policy package provides a clean case study of the impact QE might have on financial markets and the various asset market channels in operation. The effects on the yield curve, equity prices, corporate bond spreads and the exchange rate were all large and significant, consistent with a material loosening of credit conditions.

4.5: The impact of QE on the economy

The evidence suggests that QE has often had a significant impact on financial markets, albeit one whose scale has varied over time and across countries. What ultimately matters for monetary policy, however, is the impact of these asset purchases on the economy. There is some existing empirical evidence of a macroeconomic effect of QE. In general, however, estimates are quite uncertain. For example, Williams (2013) estimates that the degree of uncertainty surrounding the macroeconomic effects of asset purchases is at least twice as large as that for conventional monetary policy.

Bank of England estimates suggest that the initial £200bn of QE may have pushed up on the level of GDP by a peak of 1½-2% and on inflation by ¾-1½% (Joyce, Tong and Woods (2011)). Estimates for the US are generally found to lie in a similar ballpark. For example, Chung et al (2011) use an extension of the FRB/US model and estimate a positive peak effect of LSAPs 1 and 2 on US GDP in the range of 1%-3%.

These effects are often estimated via a two-step procedure: first assessing the impact of QE on asset prices using event study analysis, and then putting these asset price changes through a macroeconomic model to determine their impact on economic activity and inflation. This procedure is far from perfect. For example, it takes only a snap-shot measure of the impact of QE interventions on asset markets, whereas in practice these effects play out over an extended period. These models are also often estimated with data before the introduction of the QE policy, making any inference subject to structural break issues.

One alternative approach is provided by Weale and Wieladek (2016). They introduce asset purchase announcements by the Bank of England and Federal Reserve directly into a Structural Vector Auto-Regression (SVAR), using economic theory to impose restrictions which enable the impact of QE to be identified. Due to lack of consensus in identifying QE shocks, they use four different identification schemes, each of which leaves the reaction of output and prices unrestricted. Using this methodology, they find that both the US and UK's QE programmes may have pushed up GDP materially, with peak effects that are higher than most other estimates.

Here, we expand the analysis in Weale and Wieladek (2016) by examining central bank balance sheet expansions in a broader set of countries and across a broader span of time. As a robustness check, and following the approach in Weale and Wieladek (2016), we use four different VAR identification schemes. The methodology and identifying restrictions are set out in Appendix A.

The central bank balance expansions analysed here can be split into two categories: the Bank of England, the Federal Reserve and the Bank of Japan purchased assets mostly in the form of long-term government debt and some private sector debt to stimulate their economies. The Bank of Canada and – until recently – the ECB and Riksbank engaged in liquidity operations to stabilise conditions in short-term bank funding markets, as part of their lender of last resort role.[11]

[11] In 2015, the ECB and the Swedish Riksbank both introduced explicit asset purchase programs of sovereign debt to stimulate their economies. But given how recent this was, we are only able to evaluate the impact of liquidity driven balance sheet expansions in this paper. See Garcia Pascual and Wieladek (2016) for an initial assessment of the impact of the ECB's QE on euro area real GDP and core CPI using a similar methodology to this paper. Using a stylised

The availability of historical data for the Bank of England (Hills, Thomas and Dimsdale, 2015) also allows us to analyse the impact on the economy of historical balance sheet operations during past periods of financial crises and wars. The historical data for the UK cover the period 1719 to 1822, when the Bank of England's "Bank Rate" was fixed at 5%.

We identify QE and other shocks based on their likely sign of impact on other variables in the model. All of the four proposed identification schemes leave the reaction of output and prices unrestricted (Appendix A provides more detail). We estimate separate models for each country. For Japan, we separate the sample into two periods: the first phase of QE from April 2001 to July 2008, the second phase from August 2008 to February 2015. For all of the other countries, the data start in March 2009, when these countries hit their effective zero lower bound, and finishes in February 2015. In other words, the sample does not cover the most recent asset purchase programmes initiated by the ECB and the Bank of England, and only covers part of the Bank of Japan's QQE programme.

A more detailed description of the data sources can be found in Appendix D. The results are summarised in **Table 4**. This shows the peak effect of a 1% of nominal GDP central bank balance sheet expansion on output and prices for each of the identification schemes. Only statistically significant results are shown. The results are reasonably consistent across the identification schemes.

Graphs of impulse response functions are shown in Appendix B. In general, the pattern of responses accords with expectations: an increase in asset purchases generally pushes down on long-term interest rates and up on real equity prices, as well as pushing up on real GDP and consumer prices.

Table 4: Impact of Central Bank Balance sheet Expansion programme on Real GDP and CPI

Country/ Programme	Identification Scheme 1		Identification Scheme 2		Identification Scheme 3		Identification Scheme 4		Average	
	Real GDP	CPI	Real GDP	CPI	Real GDP	CPI	Real GDP	CPI	Real GDP	CPI
Canada										
ECB			0.15							
Japan – QE1	0.36									
Japan – QE2	0.12	0.087		0.091	0.15	0.11	0.13	0.084	0.13	0.093
Sweden										
UK –QE	0.11		0.34	0.49	0.27	0.32	0.22	0.22	0.24	0.34
US – QE	0.33	0.33	0.83	0.85	0.88	0.80	0.51	0.54	0.63	0.63
UK - Historical										

Note: The Table shows the sign, magnitude and significance of the impact of a central bank balance sheet program on output and prices. The numbers reported in the individual cells correspond to the peak impact of output and prices in response to a 1% central bank balance sheet expansion in terms of nominal GDP. Where possible (for the UK and US), we use asset purchase announcements, as economic theory dictates that announcements rather than actual purchases should affect the actual macroeconomy. Due to the absence of such a measure for Japan, we use actual asset purchases for that country. For the Canada, the euro area and Sweden, we use the total size of the balance sheet. Effects are only reported if they are statistically significant, as indicated by 68% quantiles.

macroeconomic model, Andrade et al (2016) find that the macroeconomic impact of the ECB's asset purchase programme can be expected to be sizeable.

Table 4 suggests a number of interesting conclusions when it comes to assessing the impact of central bank balance sheet expansions on economic activity and inflation:

- First, there is clear evidence that not all central bank balance sheet expansions are created equally, at least in terms of their impact on activity and growth. There is a clear split here between those countries whose central bank balance sheet expansions were for reasons of liquidity provision (in this sample, Canada, the ECB and Sweden) and those where the purpose has been a loosening of monetary policy (Japan, UK and US). Only in the latter cases do central bank balance sheet expansions appear to have had a significant impact on activity and prices. In other words, it is not balance sheet expansions per se, but their purpose and, prospectively, method of execution that matters for determining their impact on nominal spending. Only interventions badged as monetary policy – or QE – appear to have reliably boosted activity and prices. This suggests that the expectational effects of QE - for example, operating through the signalling and uncertainty channels - may be particularly potent.

- Consistent with that hypothesis, historical evidence on the impact of central bank balance sheet expansions in the UK suggests no statistically significant impact on prices and output over the period 1719 to 1822. All of the variation in central bank money supply over this period was to meet the needs of government debt financing or financial stability, rather than monetary policy. This is consistent with the evidence in Ferguson, Schaab and Schularick (2015).

- Even for QE interventions with an explicit monetary policy objective, evidence on their effectiveness is not fixed, either across time or countries. For example, in Japan there is at best very weak evidence of the initial QE interventions (QE1) having had much impact on output and prices. QE2 in Japan appears, by contrast, to have had a significant impact on money spending.

- QE in the US and UK appears to have had both a correctly-signed and significant impact on activity and inflation. For example, consistent with Weale and Wieladek (2016), evidence in the US (Figure B1.7 in Appendix B) suggests that a 10% of GDP central bank balance sheet expansion has a peak impact on output of around 6% after three years and a peak impact on CPI of around 6% after around seven quarters. This impact of US QE is broadly similar to most other studies (Chung et al (2011) and Baumeister and Benati (2013)). But, as in Weale and Wieladek (2016), the estimated impact of UK QE on UK CPI is larger than in other studies.

Section 5: State-Dependency and Spill-overs from QE

So far we have focussed on the average impact of QE on domestic financial markets and the domestic economy. In practice, there are good reasons to expect the effectiveness of QE to vary over time and across countries depending on the state of the economy and financial markets. The impact of QE interventions may also spill-over across national borders – for example, through demand and financial market channels. In this section, we explore empirically these two effects.

5.1: The state-dependence of QE

The portfolio balance and market liquidity channels of QE would predict that central bank balance sheet expansions are likely to have a larger impact when frictions in financial markets are high and stresses great. In other words, the impact of QE on activity and prices depends importantly on the state of financial markets.

To explore the state-dependence of QE, we augment our model to assess whether episodes of financial market stress amplify the quantitative impact of QE. Specifically, we augment model (1) from Appendix A by assuming that $\boldsymbol{\Sigma_t} = \boldsymbol{A_t}'\boldsymbol{A_t}$, where

$$\boldsymbol{A_t} = \boldsymbol{K} + \boldsymbol{C} * \boldsymbol{R_t}$$

where $\boldsymbol{R_t}$ is a variable that indicates whether the economy is in a high financial stress regime or not, taking a value of one when this is the case and zero otherwise.[12] To identify $\boldsymbol{R_t}$, we focus on an indicator of frictions in the government bond market, since this is the market most directly affected by central bank asset purchases.

The indicator of financial stress is the mean squared fitting errors from the government bond yield curves estimated by the Bank of England. In distressed markets, distortions in particular bond yields relative to a fitted curve are likely to be greater and, perhaps, more persistent.[13] In the previous section we found that among all balance sheet expansions, only QE had an impact on output and prices, and only for the US and UK for the whole sample. We therefore examine whether QE was state-dependent in these two countries.

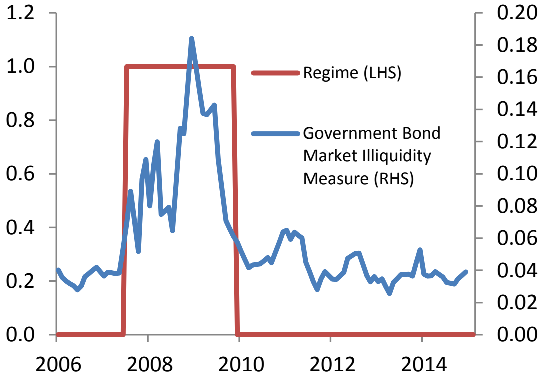
This model allows us to generate two different sets of VAR impulse responses, by evaluating $\boldsymbol{R_t}$ at the values of one and zero, respectively: $\boldsymbol{R_t} = \boldsymbol{1}$ or 'Regime 1' is the higher financial stress regime, and $\boldsymbol{R_t} = \boldsymbol{0}$ or 'Regime 2' is the less financially stressed or 'normal times' regime. We apply all of the four identification schemes to each of these sets of VAR coefficients.

Figures 27a and 27b show the data and our classification scheme for the two regimes. These clearly show that, for both the US and the UK, frictions in government bond markets started in 2007, well before the height of the global financial crisis of 2008/2009, and then persisted until the start of 2010. Our classification scheme for financial frictions uses this chronology of the regimes, as shown in Figure 28.

[12] To estimate this model it is necessary to estimate $\boldsymbol{A_t}$ directly rather than recovering it from the variance-covariance matrix. This can be achieved by assuming that $\boldsymbol{A_t}$ **is** lower triangular, which means that each equation of the VAR will now be different. Specifically, no contemporaneous terms enter the first equation. The first endogenous variable enters the second equation contemporaneously. The first and second endogenous variables enter the third equation and so forth. These contemporaneous terms are then interacted with each equation independently**.** Evaluating $\boldsymbol{R_t}$ at the value of one then yields the Choleski matrix $\boldsymbol{A_t}$ for when financial frictions are high. Evaluating $\boldsymbol{R_t}$ at the value of zero yields the choleski matrix $\boldsymbol{A_t}$ for when times are normal. All of the identification schemes are then applied to $\boldsymbol{A_t}$ to assess if asset purchases have an impact on output and prices in either state of the world.

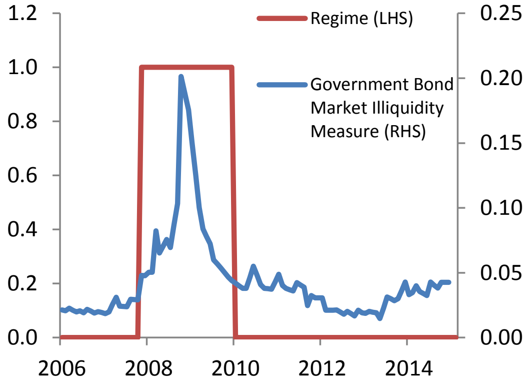
[13] Local supply effects from QE could also cause more distortions in government bond markets if, for example, certain maturities of bonds are bought in greater quantity. As we are only trying to identify high and low financial stress regimes, this should be less of an issue for our analysis.

Figure 27a: UK Market Liquidity Measure and Regime



Source: Bloomberg, Bank and authors calculation.

Figure 27b: US Market Liquidity Measure and Regime



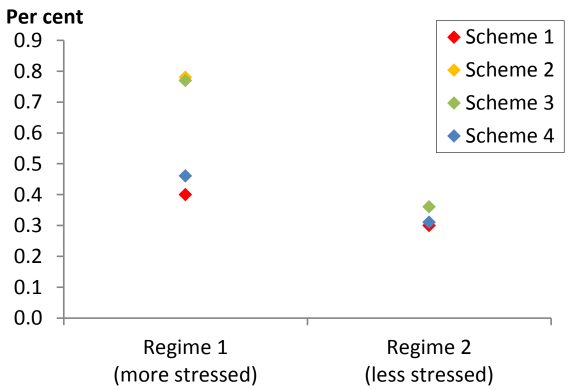
Source: Bloomberg, Bank and authors calculation.

Table 5: The State dependence of Balance sheet Expansions based on measures of illiquidity

Country/ Programme	Identification Scheme 1		Identification Scheme 2		Identification Scheme 3		Identification Scheme 4		Average	
	Real GDP	CPI	Real GDP	CPI	Real GDP	CPI	Real GDP	CPI	Real GDP	CPI
UK – Regime 1	0.097		0.34	0.63	0.27	0.66			0.24	0.645
UK – Regime 2	0.096		0.32	0.48		0.67			0.14	0.48
US – Regime 1	0.40	0.32	0.78	0.95	0.77	0.95	0.46	0.70	0.60	0.73
US – Regime 2	0.30	0.26			0.36		0.31	0.71	0.32	0.485

Note: The Table shows the sign, magnitude and significance of the impact of a central bank balance sheet program on output and prices for two different regimes. Regime 1 is a regime with a high degree of frictions in the market where asset were purchased. Regime 2 is a regime with a low degree of frictions. For the UK and the US, the measure of frictions is the deviation of government bond yields from those predicted by a standard yield curve model. The numbers reported in the individual cells correspond to the peak impact of output and prices in response to a 1% central bank balance sheet expansion in terms of nominal GDP. We use asset purchase announcements, as economic theory dictates that announcements rather than actual purchases should affect the actual macroeconomy. Effects are only reported if they are statistically significant, as indicated by 68% quantiles.

Figure 28: State dependency of peak impact on real GDP of a 1% change in US Federal Reserve balance sheet



Note: Different identification schemes shown in different colours. Identification scheme 2 is omitted from regime 2 as it is not statistically significant.

Table 5 shows the peak impact on output and prices in response to a 1% central bank balance sheet shock in two different regimes, where regime one (two) indicates the high (low) financial frictions regime. Again, only statistically significant results are shown. The results suggest that, for the US at least, there is some evidence that the impact of QE was larger in more stressed markets. For example, the average output impact of QE is around twice as large in a regime of high financial frictions **(Figure 28)**. The US results are consistent with the portfolio balance and market illiquidity channels being more potent in the presence of financial frictions and market illiquidity. QE is state-dependent in its impact. For the UK, there is less evidence of the impact being different across the two regimes.

5.2: International spill-overs of QE to foreign financial markets

As discussed in Chen et al (2011), we would expect QE to have international spill-overs effects, especially when conducted by a large country. For example, the portfolio rebalancing channel should work internationally as well as domestically. This might be particularly true of US QE, as the US dollar is the dominant reserve currency. The uncertainty channel is also likely to operate through international financial markets, with QE in one country reducing the risk of bad macro outcomes elsewhere. Again, we would expect those effects to be especially potent for large countries. To the extent that QE affects the exchange rate, it will have direct spill-over effects, although in this case these would tend to depress the economic outlook in other countries.

Bernanke (2015) argues that, conceptually, US QE can affect other countries through three different channels. First, to the extent that QE leads to a deprecation of the currency, the adjustment in the trade balance will raise US output at the expense of its trading partners. But if US demand rises in response to QE, this can more than offset the impact from the exchange rate, and lead to a rise in output both at home and abroad. Finally, US QE might lower both the global risk-free rate and risk premia.

The majority of the literature on international spill-overs of QE has focussed on the impact of the Federal Reserve's large scale asset purchases on other countries' asset prices. For example, Neely (2015) finds that the Federal Reserve's unconventional monetary policy in 2008-09 reduced long-term bond yields across advanced economies and depreciated the dollar versus the currencies of those countries.

Fratzscher et al (2013) find that US QE1 lowered long-term yields in the US and elsewhere and supported equity prices. But they also find that US QE1 triggered a strong rebalancing of investor portfolios out of emerging markets and into US equity and bond funds. Rogers, Scotti and Wright (2016) find that a US monetary policy shock at the lower bound affects UK and German term premia by a little over half as much it affects US term premia.

The spill-overs from US QE to global financial markets were shown in sharp relief during the so-called "taper-tantrum" in 2013, with long-term bond yields rising across advanced and emerging economies (Fischer (2015)) and leading to large capital flows (Sahay et al (2014) and Barroso, Pereira and Sales (2016)). As noted by Rogers, Scotti and Wright (2014), cross-country spill-overs from US QE also appear to be asymmetric, with the impact of US QE on non-US yields being larger than the other way round. The anticipation of asset purchases by the ECB in late 2014, and their subsequent announcement in January 2015, appeared to lower not only euro area government bond yields but also those in the US and other advanced economies (Middeldorp (2015)).

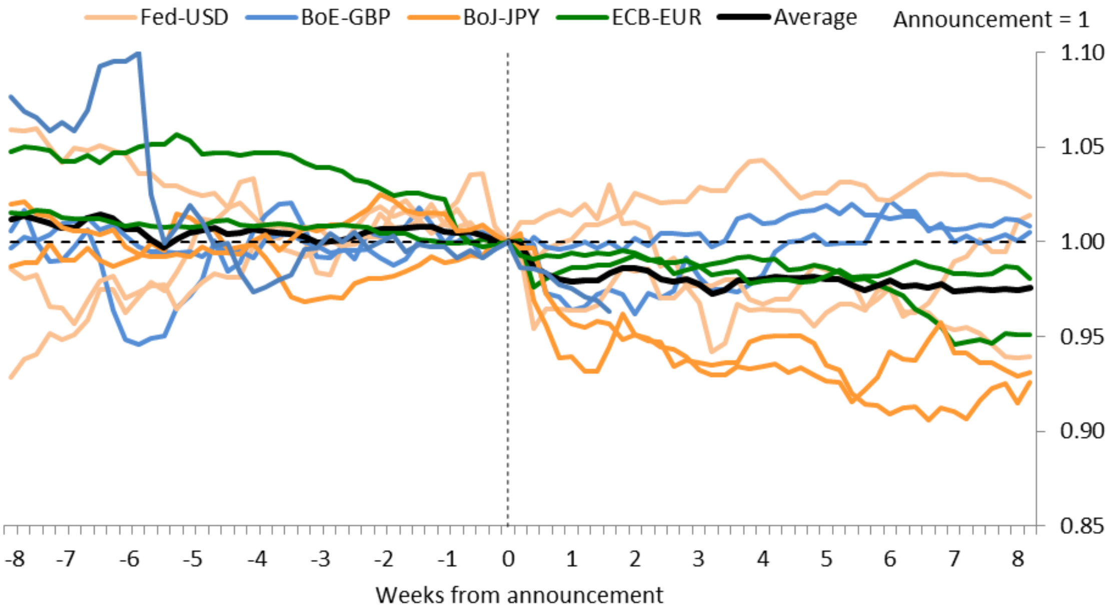
Understanding these international spill-overs is important when identifying the impact of domestic QE. For example, any study of the impact of UK QE on the exchange rate needs to take into account the impact of US QE, which was largely happening at the same time. Goodhart and Ashworth (2012) estimate that the sterling exchange rate might have been up to 5 per cent higher if the Bank of England had not undertaken the first round of QE but was in practice little changed because of simultaneous QE policies in the US.

The impact of QE on the exchange rate is relatively unexplored in the literature. Looking across a range of QE announcements, there does appear to be evidence of QE generating a depreciation in the domestic exchange rate (**Figure 29**). This is consistent with Glick and Leduc (2013) who find that US QE surprises tended to be followed by a sharp depreciation of the US dollar versus a range of currencies. This effect was comparable to the impact of conventional monetary policy surprises on the US dollar.

The evidence in Figure 29 suggests that movements in relative interest rates are not the only channel through which QE affects the exchange rate. Of all the currency depreciations, only around half were associated with a fall in relative interest rates. QE may affect long-term exchange rate expectations – for example, the foreign exchange risk premium may fall through an uncertainty channel. Consistent with this, Rogers, Scotti and Wright (2016) estimate a structural VAR and find that US monetary policy easing shocks leads to a dollar deprecation and lower FX risk premia.

While there has been some work assessing the impact of central bank balance sheet expansions in advanced economies on asset prices and capital flows in emerging market economies,[14] few have explored international transmission of balance sheet expansions among advanced economies. Bluwstein and Canova (2015) examine the impact of ECB unconventional monetary policy on small open economies in the EU. They find that while unconventional monetary policy shocks had an impact on euro area inflation as well as economic activity and asset prices in the rest of the EU, there was no statistically significant impact on euro area output.

Figure 29: Intraday reaction of exchange rates on QE announcement days



Sources: Bank of England, ECB, Federal Reserve, Bloomberg, Bank of Japan, Bank calculations.

Chen et al (2016) use a global vector error-correcting model to look at the impact of a shock to the US term spread (which they use as a proxy for QE) on a range of advanced and emerging economy asset prices and real variables. They find little evidence of lower US yields leading to rapid credit growth in other advanced economies, at least in the immediate aftermath of the crisis. But the

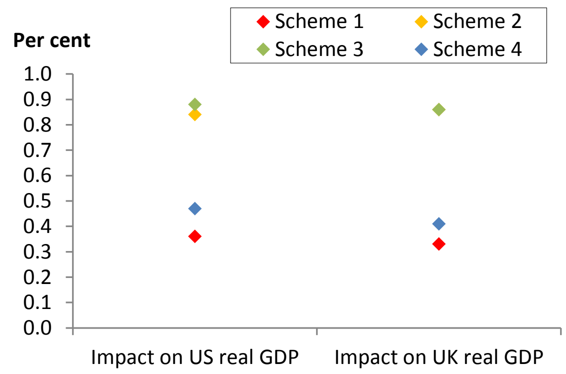
[14] Lo Duca, Fratzscher and Straub (2014) document a significant impact of US QE implementation on capital flows to emerging market economies.

impact on emerging economies was generally larger than on other advanced economies. For example, they find that the expansionary impact of US QE was significant in Hong Kong and Brazil, with rapid credit growth, strong capital inflow, currency appreciation and inflationary pressures.

Rather than proxying QE with the term spread, it would be preferable to use a more direct measure of QE which allows us to pick up other (than yield curve) effects of balance sheet expansions. Focussing on advanced economies, we extend the SVAR analysis from Section 4 to explore international spill-overs from central bank balance sheet expansions. Specifically, we focus on the transmission of US asset purchase shocks to the euro area, Japan and the UK. As before, we use four different identification schemes, all of which leave the responses of output and prices unrestricted. We also allow for feedback to the US from these economies and examine whether unconventional monetary policy originating in those countries had an impact on the US.

We again experiment with a range of identification schemes, discussed further in Appendix A. We report the peak impact on output and prices of US QE in **Table 6**, with impulse response functions shown in Appendix B3. This shows that US asset purchases appear to have had a strong impact on output and prices in both the US and the UK. Indeed, their effect on the UK is almost as large as the impact of US asset purchases on the US (**Figure 30**). Once we control for the spill-over effect of US QE to the UK, the impact on UK output and prices of UK asset purchases is no longer statistically significant (bottom row of Table 6, Panel A).

Figure 30: Peak impact on US and UK real GDP of a 1% change in US Federal Reserve QE announcement



Note: Different identification schemes shown in different colours. Schemes 2 and 3 result in the same impact on UK real GDP.

For Japan, US asset purchase announcements seem to have mostly affected Japanese CPI, though the effect of Japanese asset purchases on Japanese CPI appears somewhat larger (Table 6, Panel B). For the euro area, the evidence suggests US QE had powerful spill-overs effects, with a peak output and price impact in the euro area that is a little larger than the impact of US asset purchases on the US economy (Table 6, Panel C).

Overall, these transmission effects are significantly larger than those implied by previous research on the international transmission of conventional monetary policy across countries. At first sight this finding seems surprising, since the US dollar always depreciates in response to US asset purchase announcement shocks. However, as can be seen from the peak impacts in **Table 7,** this is more than offset by the boost to foreign asset prices resulting from US QE. Specifically, an increase in US QE leads to a significant increase in equity prices and a fall in long-term interest rates in the UK, Japan and euro area. Indeed, the reaction of foreign equity prices is typically somewhat larger than the reaction of US stock prices. This is consistent with a powerful international portfolio rebalancing channel or uncertainty effect at work.

Table 6: International transmission of QE shocks – Real Economy Variables

Panel A – US/UK

Country/ Programme		Identification Scheme 1		Identification Scheme 2		Identification Scheme 3		Identification Scheme 4	
Response of	**To Asset Purchases in**	**Real GDP**	**CPI**	**Real GDP**	**CPI**	**Real GDP**	**CPI**	**Real GDP**	**CPI**
US	**US**	0.36	0.39	0.84	1.07	0.88	0.91	0.47	0.63
UK	**US**	0.33	0.34	0.86	0.93	0.86	0.81	0.41	0.55
US	**UK**	0.17	0.15	0.70					
UK	**UK**			0.86	0.67				

Panel B – US/Japan

Country/ Programme		Identification Scheme 1		Identification Scheme 2		Identification Scheme 3		Identification Scheme 4	
Response of	**To Asset Purchases in**	**Real GDP**	**CPI**	**Real GDP**	**CPI**	**Real GDP**	**CPI**	**Real GDP**	**CPI**
US	**US**	0.21	0.16	1.11	1.05	0.95	0.98	0.48	0.57
Japan	**US**	0.41	0.33		1.74		1.38		
US	**Japan**	0.60	0.50	0.53				0.63	0.54
Japan	**Japan**		1.30		1.30		2.55		1.19

Panel C – US/Euro area

Country/ Programme		Identification Scheme 1		Identification Scheme 2		Identification Scheme 3		Identification Scheme 4	
Response of	**To Asset Purchases in**	Real GDP	CPI	Real GDP	CPI	Real GDP	CPI	Real GDP	CPI
US	**US**	0.28	0.36	0.73	0.88	1.06	1.08	0.64	0.68
Euro Area	**US**		0.46	1.32	0.91	1.19	1.12	0.56	0.72
US	**Euro Area**	0.16			0.21				
Euro Area	**Euro Area**	0.15							

Note: The Table shows the sign, magnitude and significance of the impact of a central bank balance sheet program on output and prices in the country of origin and abroad. The numbers reported in the individual cells correspond to the peak impact of output and prices in response to a 1% central bank balance sheet expansion in terms of nominal GDP. The first column shows which country the variables are responding in, while the second column shows the origin of the shock. Where possible (for the UK and US), we use asset purchase announcements, as economic theory dictates that announcements rather than actual purchases should affect the actual macroeconomy. Due to the absence of such a measure for Japan, we use actual asset purchases for that country. For the euro area, we use the total size of the balance sheet. Effects are only reported if they are statistically significant, as indicated by 68% quantiles.

To investigate these international spill-over channels further, we include indices of equity implied volatility (the VIX for the US) in our model as an additional variable (Appendix B, Figures B3.7 and B3.8), as a proxy for uncertainty and risk aversion. This suggests that US asset purchase announcements push down on the VIX with almost one-for-one transmission to other countries' implied volatilities. This is consistent with the strong co-movement of implied volatility across countries, which may reflect global risk aversion (Kaminska and Roberts-Sklar (2015)).[15]

[15] The block exogeneity assumption might not be the right assumption to make if asset purchases are transmitted mainly through financial channels across borders. In that case imposing block exogeneity on the contemporaneous feedback in the VAR may lead to biased inference. We can also relax this assumption in identification schemes II and III by imposing restrictions on the exchange rate. Specifically, we will need to assume that central bank balance sheet shocks identified in

Table 7: International transmission of QE shocks – Financial Variables

Panel A – US/UK

Country/ Programme		Identification Scheme 1		Identification Scheme 2		Identification Scheme 3		Identification Scheme 4	
Response of	**To Asset Purchases in**	**Stock Prices**	**Long Rate**	**Stock Prices**	**Long Rate**	**Stock Prices**	**Long Rate**	**Stock Prices**	**Long Rate**
US	**US**	0.46	-0.54	0.96	-1.31	1.02	-1.25	0.44	-0.88
UK	**US**	0.67	-0.54	1.44	-1.33	1.62	-1.27	0.55	-0.90
US	**UK**		-0.55	0.83	-1.32	0.22			-0.93
UK	**UK**	0.26		1.34	-1.33	0.95			-0.61

Panel B – US/Japan

Country/ Programme		Identification Scheme 1		Identification Scheme 2		Identification Scheme 3		Identification Scheme 4	
Response of	**To Asset Purchases in**	**Stock Prices**	**Long Rate**	**Stock Prices**	**Long Rate**	**Stock Prices**	**Long Rate**	**Stock Prices**	**Long Rate**
US	**US**	0.38		1.35	-0.88	1.08		0.45	
Japan	**US**	0.52	-0.25	1.68	-1.17	1.34	-1.11	0.56	-0.46
US	**Japan**	0.67		0.78	-0.56	0.85		0.77	
Japan	**Japan**	0.98	-0.61	1.30	-0.82	2.49		1.04	-0.63

Panel C – US/Euro area

Country/ Programme		Identification Scheme 1		Identification Scheme 2		Identification Scheme 3		Identification Scheme 4	
Response of	**To Asset Purchases in**	**Stock Prices**	**Long Rate**	**Stock Prices**	**Long Rate**	**Stock Prices**	**Long Rate**	**Stock Prices**	**Long Rate**
US	**US**	0.36	-0.39	0.91	-0.91	1.11	-1.02	0.60	-0.52
Euro Area	**US**	0.98	-0.37	0.96	-0.81	1.77		1.19	-0.53
US	**Euro Area**		-0.70		-0.80				-0.65
Euro Area	**Euro Area**		-0.70	1.50	-1.35	1.53			-0.74

Note: The Table shows the sign, magnitude and significance of the impact of a central bank balance sheet program on real stock prices and the long-term interest rate (yield on 10-year government debt) in the country of origin and abroad. The numbers reported in the individual cells correspond to the peak impact of output and prices in response to a 1% central bank balance sheet expansion in terms of nominal GDP. The first column shows which country the variables are responding in, while the second column shows the origin of the shock. Where possible (for the UK and US), we use asset purchase announcements, as economic theory dictates that announcements rather than actual purchases should affect the actual macroeconomy. Due to the absence of such a measure for Japan, we use actual asset purchases for that country. For the euro area, we use the total size of the balance sheet. Effects are only reported if they are statistically significant, as indicated by 68% quantiles.

either country 1 or country 2 lead to a corresponding depreciation of the exchange rate. With this assumption, it is possible to drop the block exogeneity assumption. The results from this exercise are presented in figures A3.9 – A3.15. The results for the impact of US asset purchase announcement shocks on real activity and financial markets in other countries are as strong as before. But now the UK's asset purchase announcement shocks and Japanese asset purchase announcements also have a strong impact on real activity and financial markets in the US. The fact that the cross-country impacts get stronger when we relax the block exogeneity assumption is consistent with a strong role for QE transmission through financial markets.

Section 6: Conclusion

In the past decade or so, central bank balance sheet expansions have been used as a tool for loosening monetary policy. This paper has gathered together empirical evidence on the effectiveness of these policies on financial markets and the wider economy. It finds reasonably strong evidence of QE having had a material impact on financial markets, generating a significant loosening in credit conditions. There is also evidence of QE having served to boost temporarily output and prices, in a way not associated with other central bank balance sheet expansions.

The effectiveness of QE policies does vary, however, both across countries and time. For example, there is some evidence of QE interventions being more effective when financial markets are disturbed. There is also evidence of strong positive international spill-over effects of QE from one country to another. This paper has focussed on the aggregate impact of central bank balance sheet expansions. This leaves to future research important issues such as the impact of a reversal in QE policies and the distributional consequences of QE.

References

Altavilla, C., Carboni, G,. and Moot, R. (2015). “Asset purchase programmes and financial markets: lessons from the euro area”. ECB Working Paper 1864.

Andrade, P., Breckenfelder, J., De Fiore, F., Karadi, P., and Tristani, O. (2016). “The ECB’s asset purchase programme: an early assessment”. ECB Working Paper 1956.

Andrés, J., López-Salido, J. D., and Nelson, E. (2004). “Tobin’s Imperfect Asset Substitution in Optimizing General Equilibrium”, Journal of Money, Credit and Banking, 36(4), 665–90.

Arias, J., Rubio-Ramirez, J. and Waggoner, D. (2014). “Inference Based on SVARs with Sign and Zero Restrictions: Theory and Applications”, Working Paper, Duke University.

Arslanalp, S. and Botman, D. (2015). “Portfolio Rebalancing in Japan: Constraints and Implications for Quantitative Easing”. IMF Working Paper WP/15/186.

Bank of England (2009). “Minutes of the Monetary Policy Committee Meeting held on 4 and 5 March 2009”. http://www.bankofengland.co.uk/publications/minutes/Pages/mpc/pdf/2009/mpc0903.aspx

Bank of England (2012). “The distributional effects of asset purchases”. Bank of England Quarterly Bulletin, 2012 Q3.
http://www.bankofengland.co.uk/publications/Documents/quarterlybulletin/qb120306.pdf

Bank of England (2016). “Inflation Report”. August 2016.
http://www.bankofengland.co.uk/publications/Documents/inflationreport/2016/aug.pdf

Bank of Japan (1999). “Minutes of the Monetary Policy Meeting on February 12, 1999”. Available at https://www.boj.or.jp/en/mopo/mpmsche_minu/minu_1999/g990212.htm/ (accessed 12 November 2015)

Bank of Japan (2016). “New Framework for Strengthening Monetary Easing: "Quantitative and Qualitative Monetary Easing with Yield Curve Control".
http://www.boj.or.jp/en/announcements/release_2016/k160921a.pdf

Banbura, M. Giannone, D. and Reichlin, L. (2010). "Nowcasting," CEPR Discussion Papers 7883, C.E.P.R. Discussion Papers.

Baumeister, C. and Benati, L. (2013). “Unconventional Monetary Policy and the Great Recession: Estimating the Macroeconomic Effects of a Spread Compression at the Zero Lower Bound”. International Journal of Central Banking. Vol. 9 No. 2. June 2013.

Barroso, J. B., Pereira, L.A. and Sales, A.S. (2016): “Quantitative easing and related capital flows into Brazil: measuring its effects and transmission channels through a rigorous counterfactual evaluation”, Journal of International Money and Finance, Volume 67, October 2016, Pages 102-122

Bauer, M. and Rudebusch, G. (2014). "The Signaling Channel for Federal Reserve Bond Purchases," International Journal of Central Banking, International Journal of Central Banking, vol. 10(3), pages 233-289, September.

Benford, J., Berry, S., Nikolov, K., Robson, M. and Young, C. (2009). “Quantitative easing”. Bank of England Quarterly Bulletin, 2009 Q2. http://www.bankofengland.co.uk/publications/Documents/quarterlybulletin/qb090201.pdf

Bernanke, B. (2015). “Federal Reserve Policy in an International Context”, Speech at the 16th IMF Jacques Polak Annual Research Conference.

Bernanke, B., Reinhart, V. and Sack, B. (2004). “"Monetary policy alternatives at the zero bound: an empirical assessment," Finance and Economics Discussion Series 2004-48, Board of Governors of the Federal Reserve System.

Bluwstein, K. and Canova, F. (2015). "Beggar-thy-neighbor? The international effects of ECB unconventional monetary policy measures," CEPR Discussion Papers 10856, C.E.P.R. Discussion Papers.

Bollerslev, T., Tauchen, G., and Zhou, H. (2009), "Expected Stock Returns and Variance Risk Premia", Review of Financial Studies, Vol. 22 (11), pp. 4463-4492.

Borio, C. and Zabai, A. (2016), “Unconventional monetary policies: a re-appraisal”, BIS Working Papers No 570.

Bowman, D., Cai, F., Davies, S. and Kamin, S. (2015). “Quantitative easing and bank lending: Evidence from Japan”. Journal of International Money and Finance, Volume 57, October 2015, Pages 15-30.

Bridges, J. and Thomas, R. (2012). “The impact of QE on the UK economy – some supportive monetarist arithmetic”. Bank of England Working Paper No 442.

Brunner, K., and Meltzer, A. H. (1973), “Mr Hicks and the “Monetarists”, Economica, 40(157), 44–59.

Butt, N., Churm, R., McMahon, M., Morotz, A. and Schanz, J. (2014). “QE and the BoE lending channel in the United Kingdom”. No 511, Bank of England working papers, Bank of England

Canova, F. and de Nicoló, G. (2002). “Monetary Disturbances Matter for Business Fluctuations in the G7”, Journal of Monetary Economics. Vol. 49(6), pages 1131-59.

Chen, Q., Filardo, A. He, D. and Zhu, F. (2016). “Financial crisis, US unconventional monetary policy and international spillovers”, Journal of International Money and Finance, Volume 67, October 2016, Pages 62-81.

Christensen, J.H.E. and Krogstrup, S. (2016), “A Portfolio Model of Quantitative Easing”, Federal Reserve Bank of San Francisco Working Paper Series 2016-12

Chung, H., Laforte, J-P., Reifschneider, D., and Williams, J. (2011). “Have We Underestimated the Likelihood and Severity of Zero Lower Bound Events?” FRBSF Working Paper 2011-01, January

Clapham, J. (1958) “The Bank of England. A History”. Volume 1, 1694-1797. Cambridge University Press.

Clouse, J., Henderson, D., Orphanides, A., Small, D. and Tinsley, P. (2003). "Monetary Policy When the Nominal Short-Term Interest Rates Is Zero." Topics in Macroeconomics, 2003, 3(1), article 12.

Cœuré, B. (2015). “Embarking on public sector asset purchases”. Speech at the Second International Conference on Sovereign Bond Markets, Frankfurt, 10 March 2015. Available at https://www.ecb.europa.eu/press/key/date/2015/html/sp150310_1.en.html (accessed 12 November 2015)

Cross, M., Fisher, P. and Weeken, O. (2010). “The BoE’s balance sheet during the crisis”. Bank of England Quarterly Bulletin, 2010 Q1.

Cushman, D. and Zha, T. (1997). "Identifying monetary policy in a small open economy under flexible exchange rates," Journal of Monetary Economics, Elsevier, vol. 39(3), pages 433-448, August.

Eggertsson, G. and Woodford, M. (2003). "The Zero Bound on Interest Rates and Optimal Monetary Policy," Brookings Papers on Economic Activity, Economic Studies Program, The Brookings Institution, vol. 34(1), pages 139-235.

Ehlers, T. (2012). “The effectiveness of the Federal Reserve’s Maturity Extension Program – Operation Twist 2: the portfolio rebalancing channel and public debt management” p. 245-255 in Settlements, Bank for International eds., Threat of fiscal dominance?, vol. 65, Bank for International Settlements.

Farmer, R. (2012), “The Effect of Conventional and Unconventional Monetary Policy Rules on Inflation Expectations: Theory and Evidence,” Oxford Review of Economic Policy, 28(4), 622–39.

Faust, J. and Rogers, J. (2003). “Monetary Policy’s Role in Exchange Rate Behavior”. Journal of Monetary Economics. Vol. 50, pages 1403-24.

Ferguson, N., Schaab, A. and Schularick, M. (2015). "Central Bank Balance Sheets: Expansion and Reduction since 1900," CESifo Working Paper Series 5379, CESifo Group Munich.

Fawley, B. and Neeley, C. (2013). "Four stories of quantitative easing," Review, Federal Reserve Bank of St. Louis, issue Jan, pages 51-88.

Fisher, P. (2010). “An unconventional journey: The Bank of England’s Asset Purchase Programme”. Speech based on a presentation to contacts of the BoE’s Agency for the South-West Stonehouse Court, Gloucestershire, on 11 October 2010. Available at: http://www.bankofengland.co.uk/archive/Documents/historicpubs/speeches/2010/speech453.pdf

Fischer, S. (2015).”The Federal Reserve and the Global Economy”. IMF Economic Review, 63, 1, pp. 8-21,

Fleming, M. (2012). "Federal Reserve liquidity provision during the financial crisis of 2007-2009," Staff Reports 563, Federal Reserve Bank of New York.

Fratzscher, M., Lo Duca, M. and Straub, R. (2013). “On the spillovers of US quantitative easing”, Working Paper No. 1557, European Central Bank.

Friedman, B. (1978). “Crowding out or crowding in? Economic consequences of financing government deficits”. Brookings papers on Economic Activity: 593-641.

Gagnon, J., Raskin, M., Remache, J. and Sack, B. (2011). "The Financial Market Effects of the Federal Reserve's Large-Scale Asset Purchases," International Journal of Central Banking, International Journal of Central Banking, vol. 7(1), pages 3-43, March.

Garcia Pascual, A. and Wieladek, T. (2016). “The European Central Bank’s QE: A new hope”, CEPR Discussion Papers 11309.

Giannone, D., Primiceri, G. and Lenza, M. (2015). “Prior Selection for Vector Autoregressions”. Review of Economics and Statistics, 97(2), May 2015, pp. 412-435.

Glick, R. and Leduc, S. (2013). “The Effects of Unconventional and Conventional U.S. Monetary Policy on the Dollar”. Working Paper 2013-11, Federal Reserve Bank of San Francisco.

Goodhart, C. and Ashworth, J. (2012). “QE: a successful start may be running into diminishing returns”, Oxford Review of Economic Policy 28(4), 640-670.

Harrison, R. (2012). "Asset purchase policy at the effective lower bound for interest rates," Bank of England working papers 444, Bank of England.

Hills, S, Thomas, R and Dimsdale, N (2015) "Three Centuries of Data - Version 2.2", Bank of England.

Ito, T. (2014), “We Are All QE-sians Now”, IMES Discussion Paper Series 2014-E-5, Bank of Japan.

Joyce, M., McLaren, N. and Young, C. (2012). “Quantitative easing in the United Kingdom: evidence from financial markets on QE1 and QE2”. Oxf Rev Econ Policy (2012) 28 (4): 671-701.

Joyce, M., Tong, M. and Woods, R. (2011). “The United Kingdom’s quantitative easing policy: design, operation and impact”, Bank of England Quarterly Bulletin, 51, issue 3, p. 200-212

Joyce, M., Liu, Z. and Tonks, I. (2014). "Institutional investor portfolio allocation, quantitative easing and the global financial crisis," Bank of England working papers 510, Bank of England.

Kaminska, I., Meldrum, A. and Young, C. (2015). “Estimating and interpreting term premia in UK government bond yields: global influences on a small open economy”. Bank of England Bank Underground blog, 3 July 2015. Available at http://bankunderground.co.uk/2015/07/03/estimating-and-interpreting-term-premia-in-uk-government-bond-yields-global-influences-on-a-small-open-economy/ (accessed 12 November 2015).

Kaminska, I. and Roberts-Sklar, M. (forthcoming). “A Global Factor in Variance Risk Premia and Local Bond Pricing”. Bank of England Staff Working Papers, forthcoming.

Kozicki, S., Santor, E. and Suchanek, L. (2011). “Unconventional Monetary Policy: The International Experience with Central Bank Asset Purchases”, Bank of Canada Review, 2011, issue Spring, p. 13-25

Krishnamurthy, A. and Vissing-Jorgensen, A. (2011). "The Effects of Quantitative Easing on Interest Rates: Channels and Implications for Policy," NBER Working Papers 17555, National Bureau of Economic Research, Inc.

Lenza, M., Pill, H. and Reichlin, L. (2010). “Monetary Policy in Exceptional Times”. Economic Policy, April 2010, iss. 62, pp. 295-330

Litterman, R B (1986). ‘Forecasting with Bayesian Vector Autoregressions - Five Years of Experience’. Journal of Business & Economic Statistics. Vol. 4(1), pages 25-38.

Fratzscher, M., Lo Duca, M. and Straub, R. (2014). “"On the International Spillovers of US Quantitative Easing," Discussion Papers of DIW Berlin 1304, DIW Berlin, German Institute for Economic Research.

Malik S., & Meldrum, A. (2016). “Evaluating the robustness of UK term structure decompositions using linear regression methods.” Journal of Banking & Finance, 67, 85-102.

McCallum, B. (2000). "Theoretical Analysis Regarding a Zero Lower Bound on Nominal Interest Rates," NBER Working Papers 7677, National Bureau of Economic Research, Inc.

Meaning, J. and Warren, J. (2015), “The transmission of unconventional monetary policy in UK government debt markets”, National Institute Economic Review No. 234, November 2015

Meaning, J. and Zhu, F. (2012). “The impact of Federal Reserve asset purchase programmes: another twist”. BIS Quarterly Review, March 2012

Middeldorp, M. (2015). “Very much anticipated: ECB QE had a big impact on asset prices, even before it was officially announced”. Bank of England Bank Underground blog, 14 August 2015. Available at http://bankunderground.co.uk/2015/08/14/very-much-anticipated-ecb-qe-had-a-big-impact-on-asset-prices-even-before-it-was-officially-announced/

Miles, D. and Schanz, J. (2014). "The Relevance or Otherwise of the Central Bank's Balance Sheet," CESifo Working Paper Series 4615, CESifo Group Munich.

Modigliani, F. and Sutch, R. (1967). "Debt Management and the Term Structure of Interest Rates: An Empirical Analysis of Recent Experience," Journal of Political Economy, University of Chicago Press, vol. 75, pages 569.

Neely, C. (2015). “Unconventional Monetary Policy Had Large International Effects”, Journal of Banking and Finance 52, 101-111.

Reis, R. (2016), “QE in the future: the central bank’s balance sheet in a fiscal crisis”. Centre for Economic Policy Research Discussion Paper 11381

Roberts-Sklar, M. (2015). “The special relationship: UK and US bond yields”. Bank of England Bank Underground blog, 28 August 2015. Available at http://bankunderground.co.uk/2015/08/28/the-special-relationship-uk-and-us-bond-yields/ (accessed 12 November 2015).

Rogers, J., Scotti, C. and Wright, J. (2014). “Evaluating Asset-Market Effects of Unconventional Monetary Policy: A Cross-Country Comparison”. International Finance Discussion Papers No. 1101, Board of Governors of the Federal Reserve System

Rogers, John H., Chiara Scotti and Jonathan H. Wright (2016). “Unconventional Monetary Policy and International Risk Premia”. International Finance Discussion Papers 1172.

Rubio–Ramírez, J. F., Waggoner, D.F. and Zha, T. (2010). “Structural Vector Autoregressions: Theory of Identification and Algorithms for Inference”. Review of Economic Studies. Vol 77(2), pages 665–696.

Rudebusch, G.D. and Williams, J.C. (2008). "Revealing the Secrets of the Temple: The Value of Publishing Central Bank Interest Rate Projections," NBER Chapters, in: Asset Prices and Monetary Policy, pages 247-289 National Bureau of Economic Research, Inc

Sahay, R., Arora, V., Arvanitis, A. Faruqee, H., N'Diaye, P. and Mancini-Griffoli, T, (2014). “Emerging Market Volatility: Lessons from The Taper Tantrum”, No 14/9, IMF Staff Discussion Notes, International Monetary Fund.

Tobin, J. (1961), ‘Money, Capital and Other Stores of Value’, American Economic Review, Papers and Proceedings, 51(2), 26–37.

Tobin, J. (1963), ‘An Essay on the Principles of Debt Management’, in Fiscal and Debt Management Policies, Englewood Cliffs, NJ, Prentice Hall, 143–218.

Tobin, J. (1969), ‘A General Equilibrium Approach to Monetary Theory’, Journal of Money, Credit and Banking, 1(1), 15–29.

Trichet, J-C, (2010). “State of the Union: The Financial Crisis and the ECB's Response between 2007 and 2009”, Journal of Common Market Studies, 48, issue s1, p. 7-19,

Ueda, K. (2011). "The Effectiveness of Non-traditional Monetary Policy Measures: The Case of the Bank of Japan," CARF F-Series CARF-F-252, Center for Advanced Research in Finance, Faculty of Economics, The University of Tokyo

Ugai, H. (2007) “Effects of the Quantitative Easing Policy: A Survey of Empirical Analysis,” Monetary and Economic Studies, Vo.25, No.1, Bank of Japan, pp. 1-47.

Uhlig, H. (2005). “What are the Effects of Monetary Policy on Output? Results from an Agnostic Identification Procedure”. Journal of Monetary Economics. Vol. 52(2), pages 381-419

Vayonas, D. and Vila, J-L. (2009). “A Preferred-Habitat Model of the Term Structure of Interest Rates,” CEPR Discussion Papers 7547, C.E.P.R. Discussion Papers.

Weale, M. and Wieladek, T. (2016). “What are the macroeconomic effects of asset purchases?,” Journal of Monetary Economics. Volume 79, May 2016, Pages 81-93.

Williams, J. (2014). “Monetary Policy at the Zero Lower Bound: Putting Theory into Practice”. Hutchins Center on Fiscal & Monetary Policy at Brookings.

Woodford, M. (2012). "Methods of policy accommodation at the interest-rate lower bound," Proceedings - Economic Policy Symposium - Jackson Hole, Federal Reserve Bank of Kansas City, pages 185-288.

Wright, J. (2012), ‘What Does Monetary Policy Do at the Zero Lower Bound?’, Economic Journal, 122 (November), F447–66.

Appendix A: Structural VAR model

To evaluate the real economy impact of central bank balance sheet expansion, we use the following vector autoregression (VAR) model:

$$\boldsymbol{Y_t} = \boldsymbol{\alpha_c} + \sum_{k=1}^{L} \boldsymbol{B_k Y_{t-k}} + \boldsymbol{e_t} \qquad \boldsymbol{e_t} \sim \boldsymbol{N(0, \Sigma)} \qquad \textbf{(1)}$$

where $\boldsymbol{Y_t}$ is a vector of the following endogenous variables:

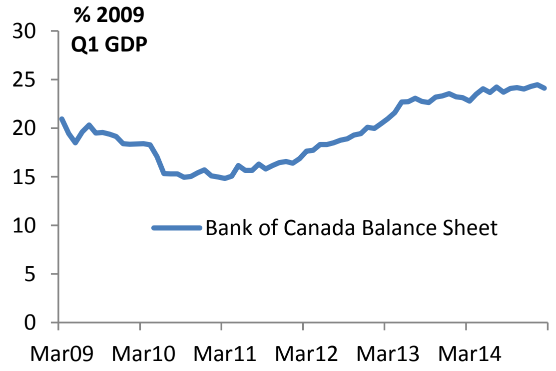
1. the size of the balance sheet divided by nominal GDP[16] – where available (for the UK and the US), we use the announcement of asset purchases, since economic theory dictates that announcements, rather than actual purchases, should affect the real economy – see **Figure A1a-f**;[17]
2. the log of CPI;
3. the log of real GDP;
4. the yield on the 10-year government bond or, for countries where the balance sheet expansion was not driven by QE, we use the 3-month LIBOR-OIS spread instead of the long rate[18]; and
5. the log of real equity prices at time $\boldsymbol{t}$.

$\boldsymbol{B_k}$ is the array of coefficients associated with the corresponding lagged vector of variables for lag $\boldsymbol{k}$. $\boldsymbol{e_t}$ is a vector of residuals at time $\boldsymbol{t}$. This is assumed to be normally distributed with variance-covariance matrix $\boldsymbol{\Sigma}$**.** When the time-series dimension is small, estimates of $\boldsymbol{B_k}$ are likely to be imprecise. Previous work has addressed this problem by relying on Bayesian methods of inference and imposing a Litterman (1986), or time-varying parameter, prior. But there is always the risk that tight priors dominate information from the data. Our approach avoids this problem using a non-informative Normal Inverse-Wishart prior, following the approach in Uhlig (2005).[19] We assume a lag length, **L**, of two throughout.[20]

The challenge for SVAR models is to disentangle orthogonal, structural economic shocks, $\boldsymbol{\varepsilon_{c,t}}$, from the correlated reduced form shocks $\boldsymbol{e_{c,t}}$. This is typically achieved using a matrix $\boldsymbol{C_0}$, such that $\boldsymbol{C_0 e_{c,t}} = \boldsymbol{\varepsilon_{c,t}}$. We use four ways of inferring $\boldsymbol{C_0}$: i) zero restrictions, ii) sign restrictions, iii) a combination of zero and sign restrictions, and finally iv) sign variance decomposition restrictions. The identification schemes are summarised in **Table A1**.

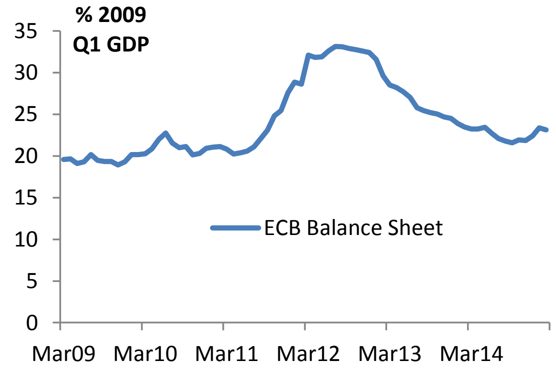
[16] Clearly, nominal GDP might be endogenous to the central bank's balance sheet expansion over time. We therefore scale the balance sheet by the level of nominal GDP in the first period prior of the expansion. In practice this means that the Bank of Canada's, Bank of England's, the ECB's, the Federal Reserves and the Risks Bank balance sheet is scaled by 2009Q1 nominal GDP for each economy. The Bank of Japan's balance sheet is scaled by Japanese 2001Q2 nominal GDP.
[17] Unlike conventional monetary policy, where announcement and implementation coincides, asset purchases were first announced and then implemented over a period of months/years.
[18] This is because in the presence of market frictions, central bank liquidity provision should lead to a smaller LIBOR-OIS spread. Including this variable should thus help to identify central bank balance sheet shocks better. It could be argued that the ECB;s LTRO program also led to a decline in sovereign borrowing costs. But including the long rate instead of the LIBOR-OIS spread does not affect our results.
[19] Uhlig (2005) sets the hyper-parameters for the prior equal to zero to ensure that it is completely non-informative. This is identical to estimating the mean parameters via OLS and generating Bayesian credible sets through Monte Carlo simulations, which is the approach that we follow. See Appendix D of his paper for more information.
[20] *Ex ante* lag length tests such as the Hannan-Quinn or BIC criterion suggest a lag length of 2. If the VAR is estimated with the correct lag length, the residuals should follow a white-noise process, and autocorrelation tests on the residuals of each equation of the VAR suggest that this is the case.

Figure A1a: Bank of Canada balance sheet



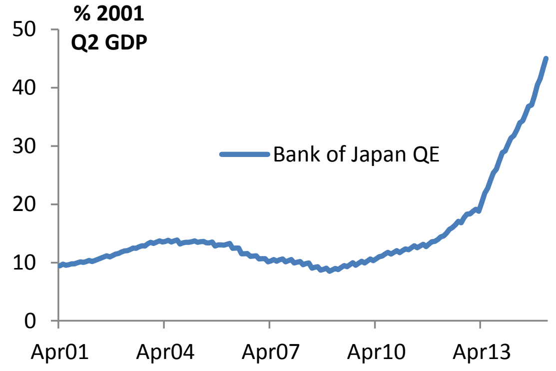
Source: Bank of Canada.

Figure A1b: ECB Balance Sheet



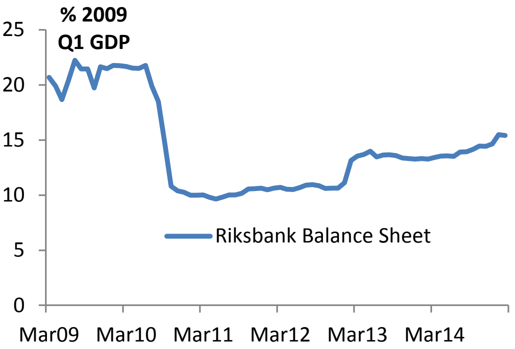
Source: European Central Bank.

Figure A1c: Bank of Japan QE



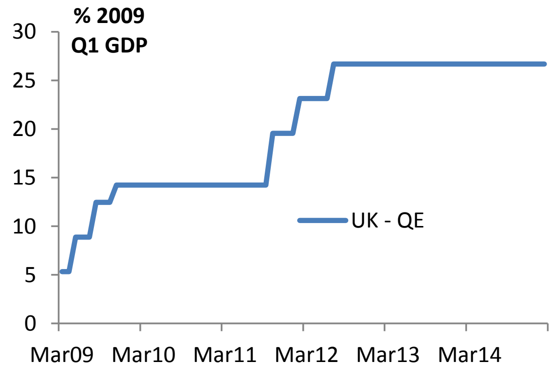
Source: Bank of Japan.

Figure A1d: Sweden Balance Sheet



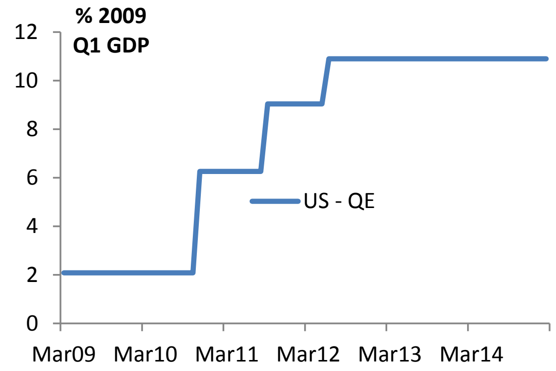
Source: Swedish Riksbank.

Figure A1e: UK QE



Source: Bank of England.

Figure A1f: US QE[21]



Source: Federal Reserve.

[21] In addition to sovereign debt, the Federal Reserve also bought mortgage backed securities and engaged in open-ended purchases of both sovereign debt and mortgage backed securities. Modelling the announcement impact of open-ended purchases is far from straight forward, but one approach is to include the present discounted value of purchases at announcement, calculated based on the period that purchases are believed to be open-ended for. At the time of the announcement, the yield curve implied an interest rate rise within 18 months. One way to calculate the economic impact is to therefore calculate the present discounted value of purchases for 18 months, discounted at the 10-year government bond yield at the time before the announcement. This is the approach that Weale and Wieladek (2016) follow to examine the impact of open-ended purchases on their results. When we follow their approach we find that the results are qualitatively robust (quantitatively the scaling changes of course), especially for output. These results are available upon request from the authors.

Table A1 – Identification schemes

	p Log CPI	y Log real GDP	QE (CB) QE (Balance Sheet Expansion)	i_t Long (LIBOR - OIS) Interest Rate (SPREAD)	sp_t Log Real Equity Price
			Identification Scheme I		
Log CPI	1	0	0	0	0
Log real GDP	X	1	0	0	0
Asset Purchases	X	X	1	0	0
Long Interest Rate	X	X	X	1	0
Log Real Equity Price	X	X	X	X	1
			Identification Scheme II		
Supply Shock	−	+		+	+
Demand Shock	+	+		+	+
Asset Purchase Shock	?	?	+	−	+
			Identification Scheme III		
Supply Shock	−	+	0		
Demand Shock	+	+	0		
Asset Purchase Shock	?	?	+		+
Uncertainty Shock			+		−
			Identification Scheme IV		
				Variance Decomposition Restrictions	
Supply Shock	−	+		$\frac{Var(Shock)}{Var(CB\ BS)} < MAX(\frac{Var(Shock)}{Var(CB\ BS)})$	
Demand Shock	+	+		$\frac{Var(Shock)}{Var(CB\ BS)} < MAX(\frac{Var(Shock)}{Var(CB\ BS)})$	
Asset Purchase Shock	?	?	+	$\frac{Var(Shock)}{Var(CB\ BS)} = MAX(\frac{Var(\ Shock)}{Var(CB\ BS)})$	

This table shows the restrictions imposed as part of all four identification schemes.

The transmission mechanisms of central bank balance sheet expansions are not sufficiently well understood to devise an identification scheme which would allow us to identify these type of shocks perfectly. It is for this reason that we sequentially relax the strongest identification restrictions from the first scheme to the last. Despite this order, it is nevertheless not possible to claim that one scheme is necessarily better identified or preferable to another. As a result, we study the effects of central bank balance sheet shocks in all four cases paying particular attention to results which are significant with at least three of the four schemes adopted in this paper.

Identification scheme I

Our first identification scheme relies on zero restrictions. We identify central bank balance sheet shocks using a lower-triangular scheme, with the central banks' balance sheet ordered after real GDP and prices, but before all of the other variables. The identifying assumptions are therefore that output and prices react to balance sheet changes with a lag and that, aside from responding to these two, the balance sheet does not react to any other variable upon impact. Given that our data are monthly, we argue that these are reasonable identification assumptions.

Identification scheme II

In scheme II we relax the zero restrictions from scheme I by adopting sign identification restrictions. VAR identification schemes that employ timing exclusion restrictions have been criticised in recent years, on the grounds that such restrictions do not naturally emerge from Dynamic Stochastic General Equilibrium (DSGE) models. Canova and De Nicolo (2002), Faust and Rogers (2003) and Uhlig (2005) have therefore proposed identifying shocks by means of the implied signs of the impulse responses that they produce.[22] Clearly, for identification restrictions of this type to be valid, they need to be strongly supported by economic theory.

Some of the many channels of QE discussed in Section 3, such as the signalling or uncertainty channel, may work for liquidity operations as well as QE. Others will be more specific to outright purchases. For balance sheet expansions driven by liquidity operations we assume that the 3-month LIBOR-OIS spread declines, while for asset purchases we assume a fall in the 10-year government bond yields. Portfolio rebalancing implies that lower yields or spreads are likely to lead to some reallocation towards other assets, such as equities, leading to a rise in real equity prices. So our definition of central bank balance sheet shock is that it leads to lower yields/LIBOR-OIS spread and a rise in equity prices.

The other shocks that we identify are an aggregate demand shock, which would typically lead to a rise in prices and output. The rise in prices, together with the fact that firms may require greater finance for production, is likely to lead to a non-negative response of either the LIBOR-OIS spread or the long-term interest rate. The rise in demand would also lead to an increase in expected profits and thus to a rise in real equity prices. The sign restrictions we use to identify an aggregate supply shock are identical, other than assuming that prices fall rather than rise. This identification scheme is implemented with the so-called "QR" approach presented in Rubio-Ramirez, Waggoner and Zha (2010). Unless otherwise noted, we impose all sign restrictions upon impact and one month thereafter with the exception of the central bank balance sheet expansions, where we impose the sign restriction upon impact and for five months thereafter here (and also in identification schemes III and IV).

Identification scheme III

In scheme III, we relax the restrictions on the long-term interest rate/LIBOR-OIS spread from scheme II by using both zero and sign restrictions. In scheme II we assume that central bank balance sheet shocks affect the real economy through either the portfolio balance channel (for asset purchases/QE) or by reducing market liquidity premia (for central bank balance sheet liquidity provision) to distinguish these shocks from aggregate supply and aggregate demand shocks. But *a priori* it is not clear to what extent the mechanisms that are required for this to be the case hold in reality. More importantly, to distinguish central bank balance sheet from aggregate supply shocks, it is necessary to assume that rates and spreads rise in response to an aggregate supply shock.

Theoretically, a positive aggregate supply shock may lead to a rise in investment, competition for funds and higher bond yields at both the short and long end of the yield curve, but also a decline in interest rates more generally as a result of the monetary policy reaction to lower consumer prices.

[22] For example, researchers that use this approach typically identify an expansionary monetary policy shock by assuming that it leads to an expansion of output, a rise in the price level and a fall in the short rate.

Empirically, Dedola and Neri (2007) and Peersman and Straub (2009) examine the reaction of the short-term interest rate in response to technology shocks in SVARs for the US and euro area, respectively. Peersman and Straub (2009) show a positive medium-term reaction of the short rate to technology shocks, while Dedola and Neri (2007) find no significant effect. While the restrictions we make on the LIBOR-OIS rate and government bond yields in Identification scheme II are therefore consistent with these previous results, we nevertheless drop them in identification scheme III.

This is possible, as long as one is willing to make the assumption that central bank balance sheet expansions do not react contemporaneously to aggregate demand and aggregate supply shocks. In that case, the restriction on real equity prices is sufficient to distinguish these shocks from asset purchases. Clearly, QE is an active balance sheet expansion and given that monetary policy makers do not observe aggregate demand or supply shocks within a month, the assumption of a zero contemporaneous reaction of asset purchases to aggregate demand and supply shocks is not unrealistic. But even if the central bank balance sheet expansion is passive and entirely driven by supply and demand for funds in the banking system, it takes time to approve new loans/react to shocks originating in other parts of the economy. An additional advantage is that this allows us to identify a fourth shock, namely a rise in uncertainty/risk premia. This shock is identified as a decline in real equity prices, to which the monetary policy authority reacts with balance sheet expansion, perhaps as a result of a coincident financial shock. Unlike demand and supply, these types of shocks can be observed in real time and are likely to affect funding conditions in the banking system immediately. We implement this scheme with the procedure in Arias, Rubio-Ramirez and Waggoner (2014), who generalise the standard QR restrictions algorithm to include zero restrictions as well.

Identification scheme IV

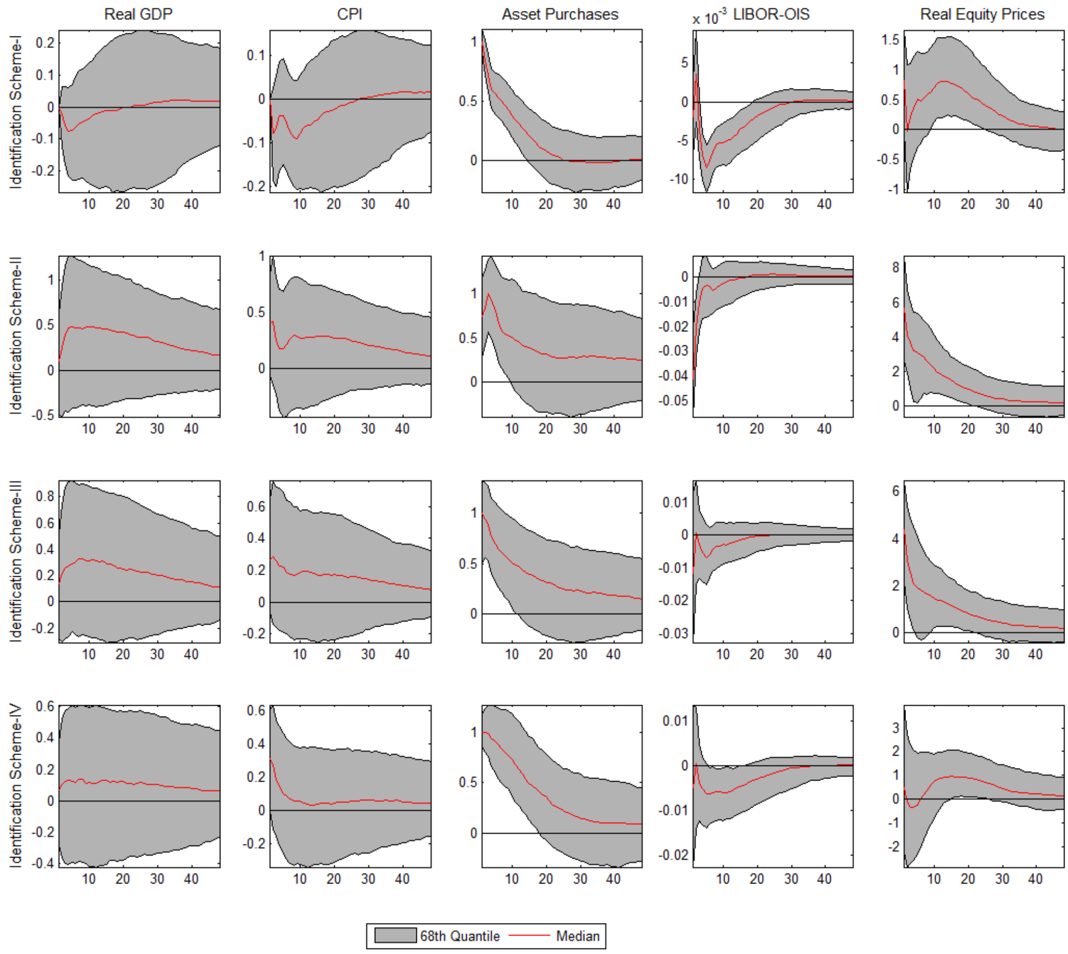
The first three identification schemes rely on the idea that shocks can be distinguished based on restrictions on impulse responses. But it is also possible to use variance decomposition restrictions to separate different economic shocks (Faust and Rogers (2003), Uhlig (2005)). The idea here is that a shock that is variable-specific should explain the largest fraction of the variance in that variable.[23] For example, short-rate shocks should explain the greatest fraction of the forecast error variance in the short-term interest rate. In identification scheme IV, we therefore require that asset purchase announcement shocks explain the largest fraction of variation in asset purchases upon impact and with a three period delay. This allows us to drop the zero restrictions and we do not have to rely on sign restrictions on either the long rate or the LIBOR-OIS spread to separate aggregate demand and supply shocks either. We implement this scheme in a similar fashion to identification scheme II, with the QR approach by Rubio-Ramirez, Waggoner and Zha (2010), but rather than keeping impulse responses which are consistent with a particular sign, we only keep those consistent with the variance decomposition restrictions in Table A1.

[23] Our approach is similar in spirit, but not technique, to the penalty function approach first proposed in Uhlig (2005), which is designed to maximise the variance forecast error decomposition of a variable, by penalising (or ruling out) impulse responses which are deemed to be unreasonable. Arias, Rubio-Ramirez and Waggoner (2014) show that this approach tends to impose additional restrictions, even on variables that were left unrestricted and leads to artificially narrow impulse response bands. We implement their technique, the same as in Rubio-Ramirez, Waggoner and Zha (2010) and just select decompositions that are associated with the maximum variance forecast error decomposition of our main variable of interest, but we do not rule out any responses in the way that Uhlig (2005) does.

Appendix B: Impulse Responses

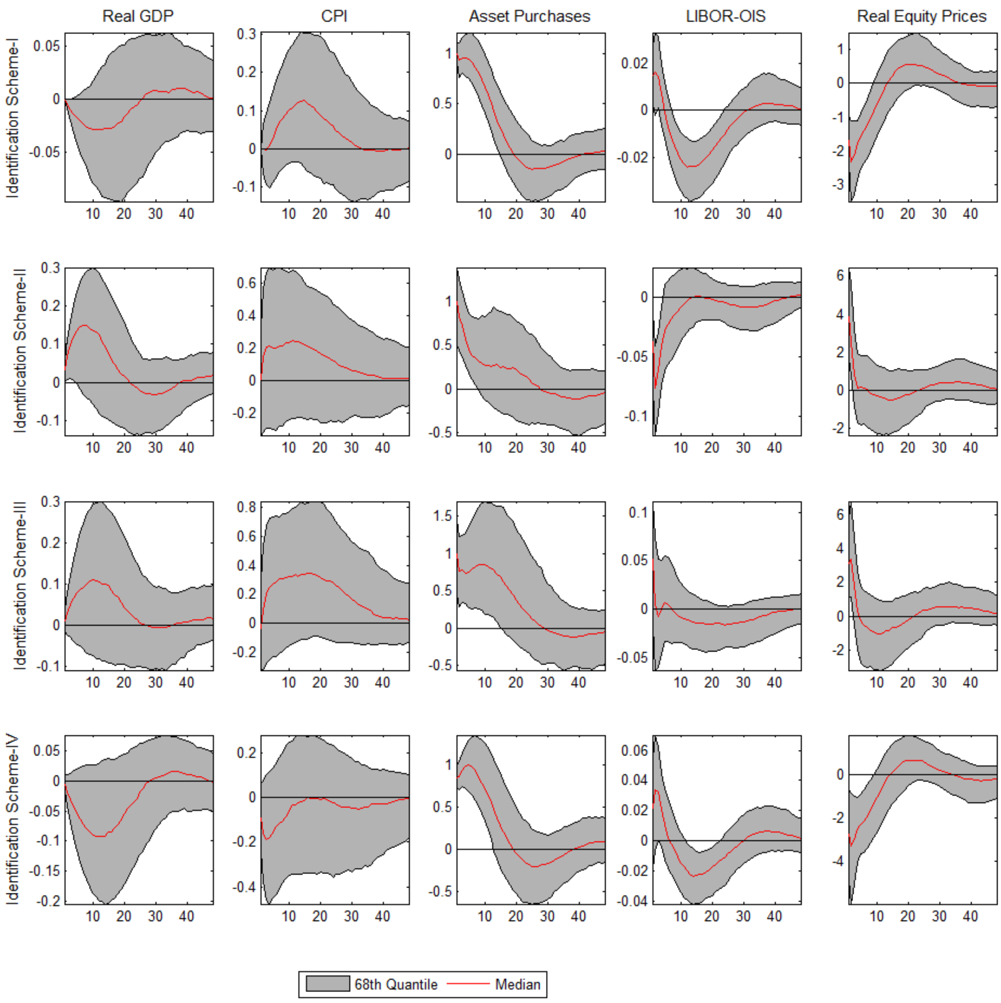
B1. Analysis of QE led central bank balance sheet expansions

Figure B1.1: Impulse Responses to a 1% central bank balance sheet rise (as % of GDP) in Canada



Source: Authors calculation.
Notes: The figure shows impulse responses of real GDP, CPI, the LIBOR-OIS spread, the central bank's balance sheet to GDP ratio and real equity prices from an unexpected 1% central bank balance sheet shock, obtained from a VAR estimated on these variables with monthly data from 2009m3 to 2015m2, when the zero lower bound was a binding constraint. The grey bands are 68% confidence bands and the red line is the median. Each row shows the results from a different identification scheme, with the labels corresponding to the labelling in the main text.

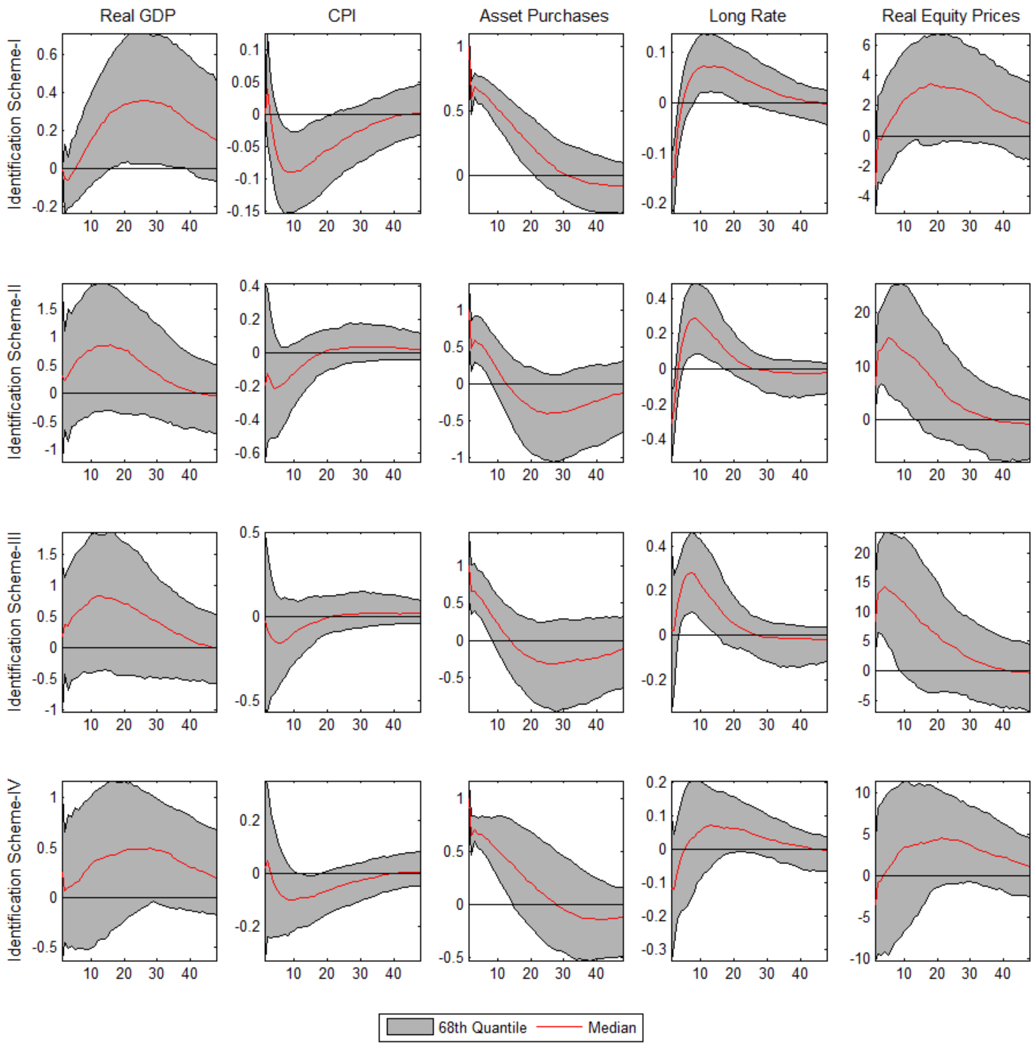
Figure B1.2: Impulse Responses to a 1% CB balance sheet rise (as % of GDP) in the Eurozone



Source: Authors calculation.

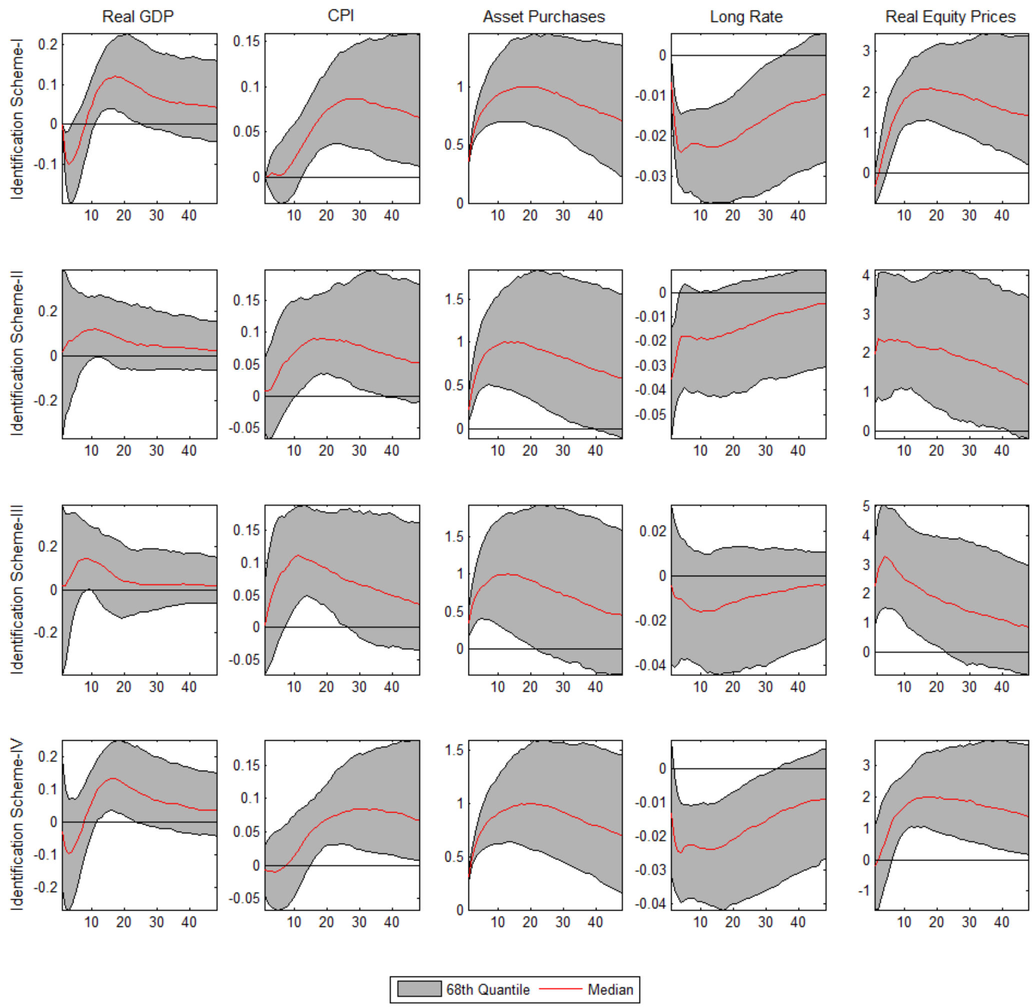
Notes: The figure shows impulse responses of real GDP, CPI, the LIBOR-OIS spread, the central bank's balance sheet to GDP ratio and real equity prices from an unexpected 1% central bank balance sheet shock, obtained from a VAR estimated on these variables with monthly data from 2009m3 to 2015m2, when the zero lower bound was a binding constraint. The grey bands are 68% confidence bands and the red line is the median. Each row shows the results from a different identification scheme, with the labels corresponding to the labelling in the main text.

Figure B1.3: Impulse Responses to a 1% CB asset purchase (as % of GDP) during QE1 in Japan



Source: Authors calculation.
Notes: The figure shows impulse responses of real GDP, CPI, the 10-year government bond yield, the central bank's sovereign debt (QE) holdings to GDP ratio and real equity prices from an unexpected 1% asset purchase shock, obtained from a VAR estimated on these variables with monthly data from 2001m4 to 2008m7, when the zero lower bound was a binding constraint. The grey bands are 68% confidence bands and the red line is the median. Each row shows the results from a different identification scheme, with the labels corresponding to the labelling in the main text.

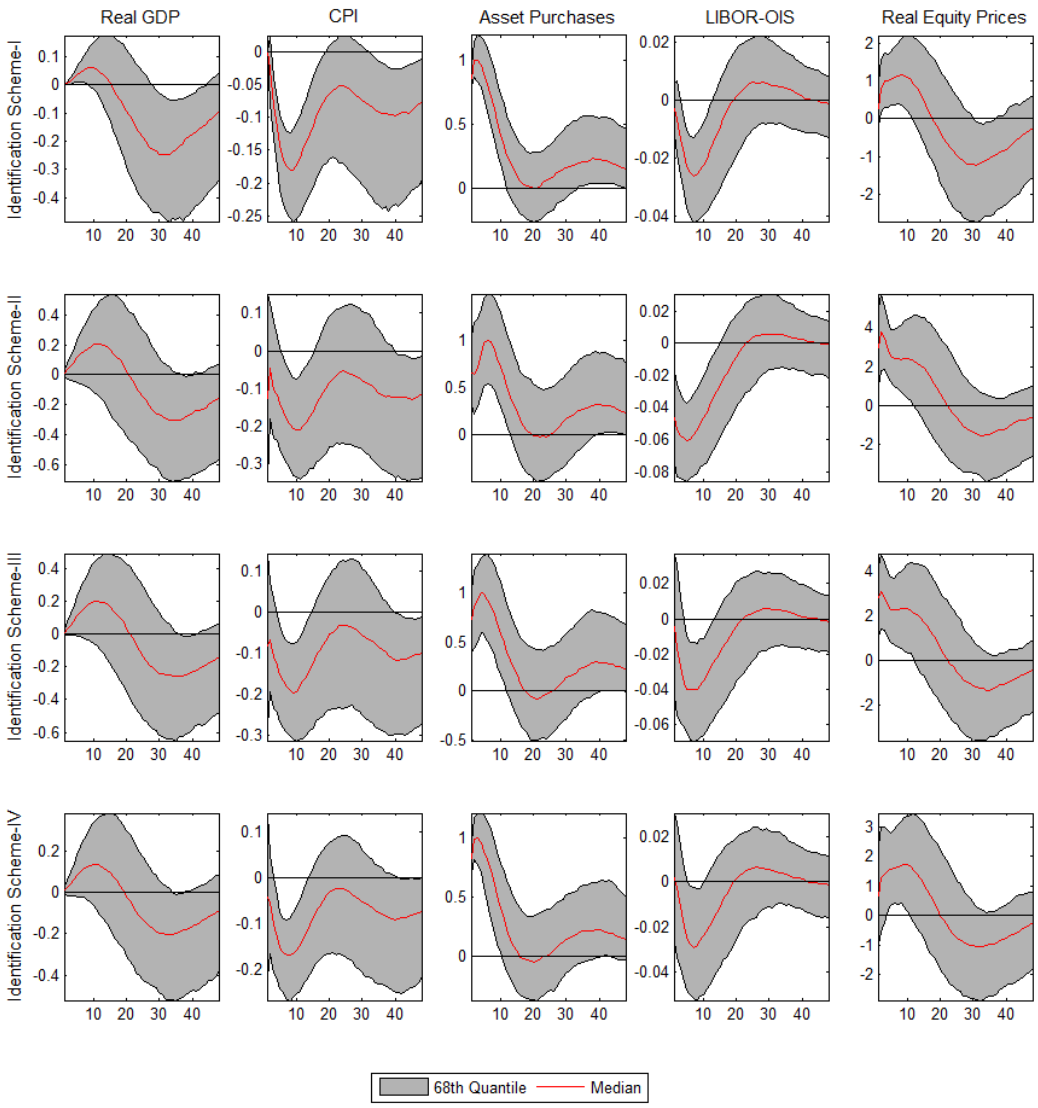
Figure B1.4: Impulse Responses to a 1% CB asset purchase (as % of GDP) during QE2 in Japan



Source: Authors calculation.

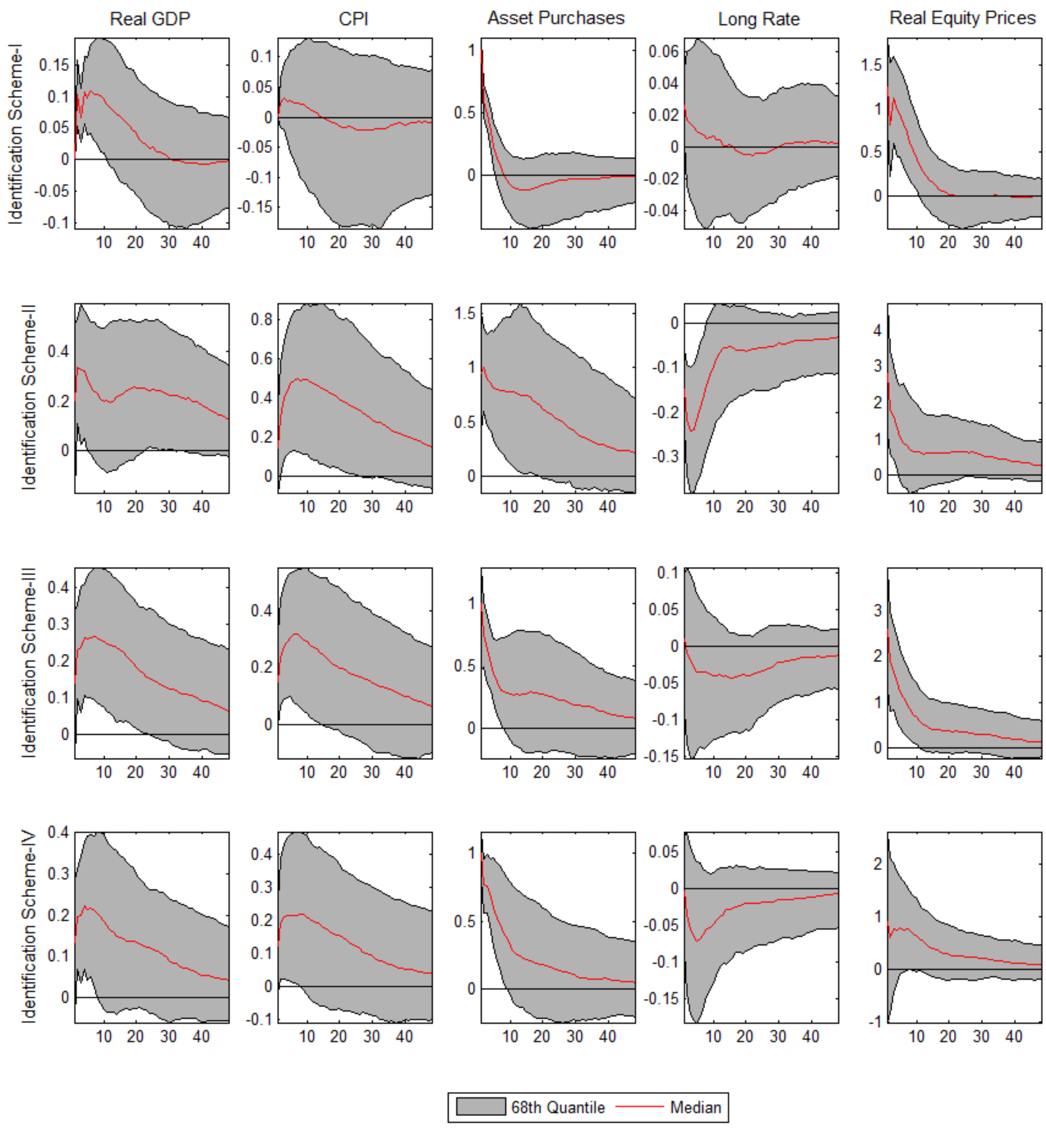
Notes: The figure shows impulse responses of real GDP, CPI, the 10-year government bond yield, the central bank's sovereign debt holdings to GDP ratio and real equity prices from an unexpected 1% asset purchase shock, obtained from a VAR estimated on these variables with monthly data from 2008m8 to 2015m2, when the zero lower bound was a binding constraint. The grey bands are 68% confidence bands and the red line is the median. Each row shows the results from a different identification scheme, with the labels corresponding to the labelling in the main text.

Figure B1.5: Impulse Responses to a 1% CB balance sheet rise (as % of GDP) in Sweden



Source: Authors calculation.
Notes: The figure shows impulse responses of real GDP, CPI, the LIBOR-OIS spread, the central bank's balance sheet to GDP ratio and real equity prices from an unexpected 1% central bank balance sheet shock, obtained from a VAR estimated on these variables with monthly data from 2009m3 to 2015m2, when the zero lower bound was a binding constraint. The grey bands are 68% confidence bands and the red line is the median. Each row shows the results from a different identification scheme, with the labels corresponding to the labelling in the main text.

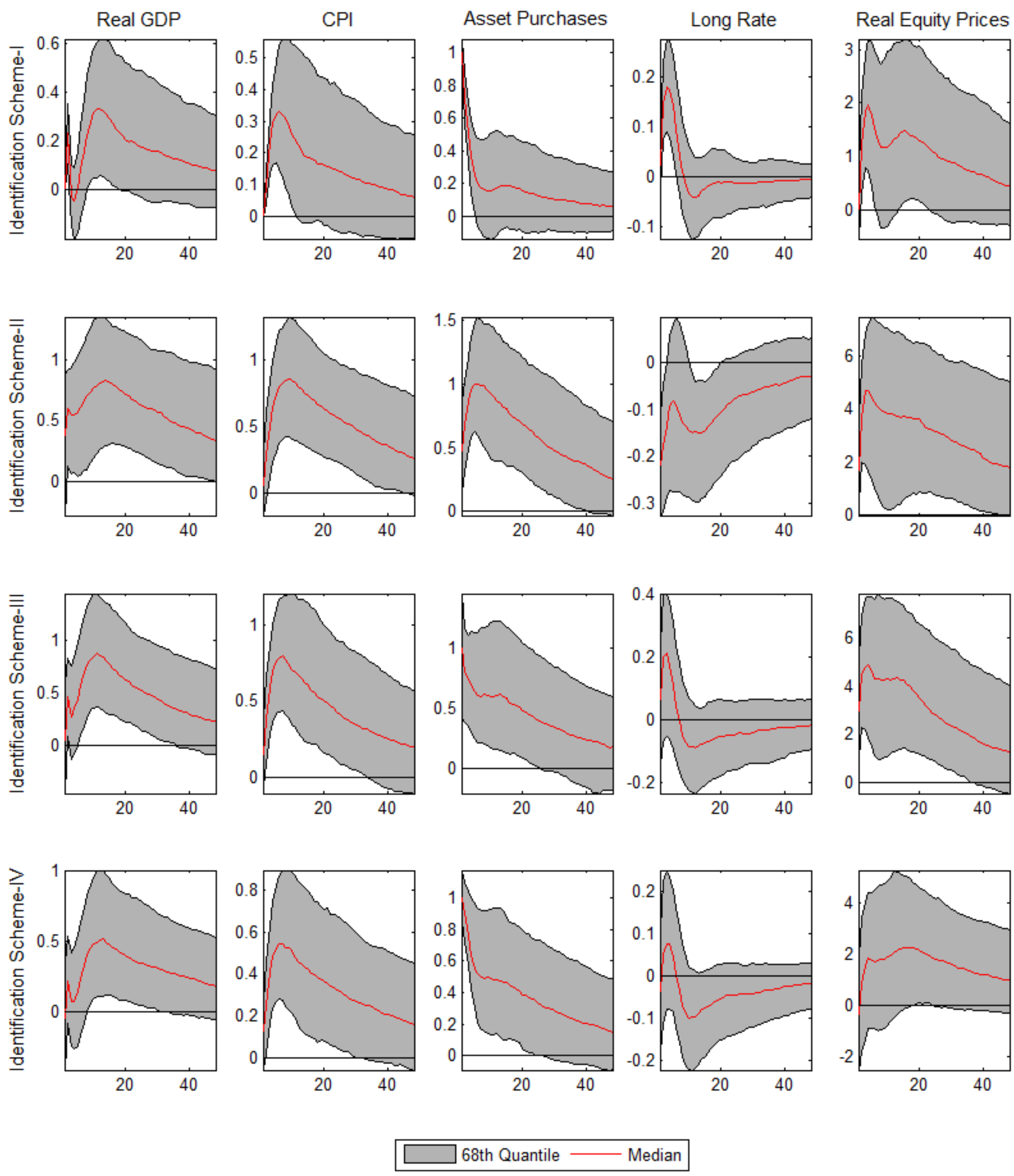
Figure B1.6: Impulse Responses to a 1% CB asset purchase announcement (as % of GDP) in the UK



Source: Authors calculation.

Notes: The figure shows impulse responses of real GDP, CPI, the 10-year government bond yield, the central bank's asset purchase announcement of sovereign debt purchases to GDP ratio and real equity prices from an unexpected 1% asset purchase announcement shock, obtained from a VAR estimated on these variables with monthly data from 2009m3 to 2015m2, when the zero lower bound was a binding constraint. The grey bands are 68% confidence bands and the red line is the median. Each row shows the results from a different identification scheme, with the row labels corresponding to the labelling in the main text.

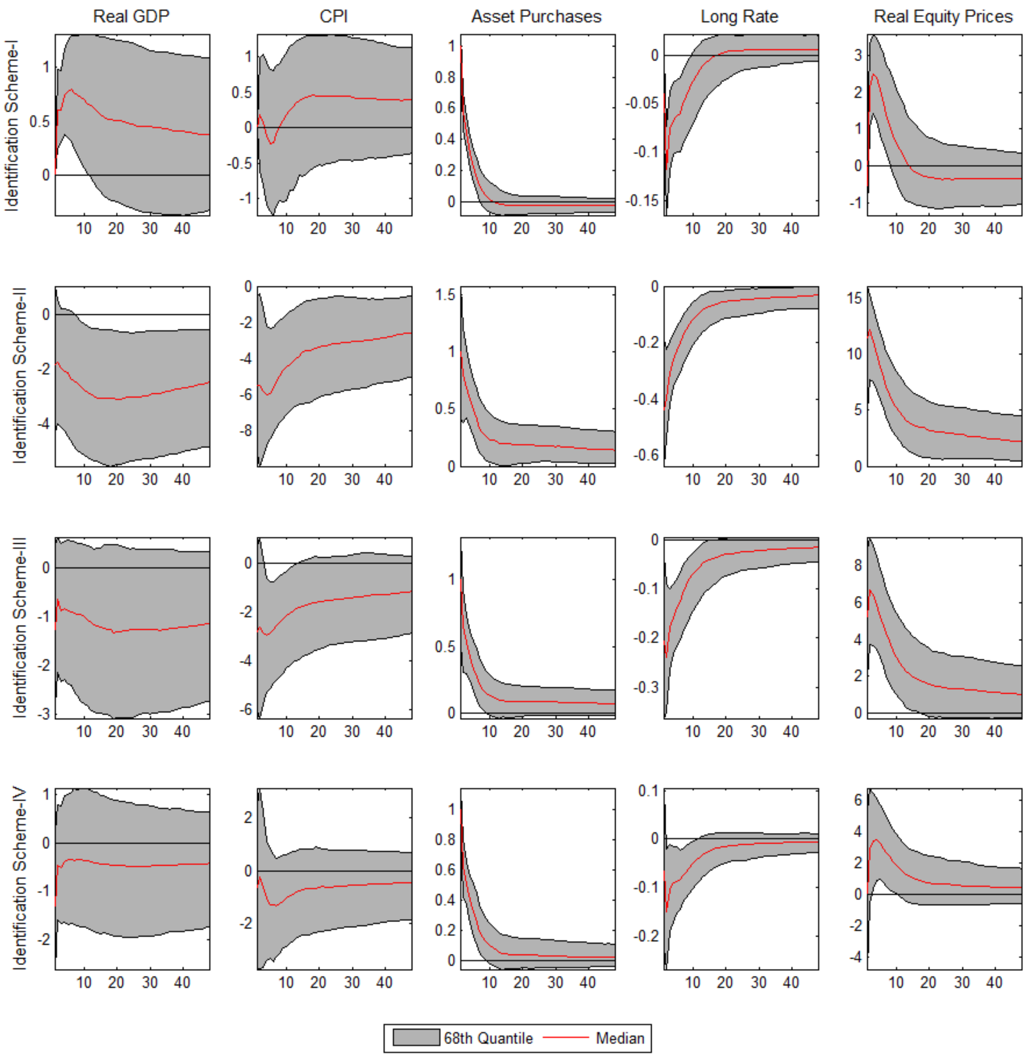
Figure B1.7: Impulse Responses to a 1% CB asset purchase announcement (as % of GDP) in the US



Source: Authors calculation.

Notes: The figure shows impulse responses of real GDP, CPI, the 10-year government bond yield, the central bank's asset purchase announcement of sovereign debt purchases to GDP ratio and real equity prices from an unexpected 1% asset purchase announcement shock, obtained from a VAR estimated on these variables with monthly data from 2009m3 to 2015m2, when the zero lower bound was a binding constraint. The grey bands are 68% confidence bands and the red line is the median. Each row shows the results from a different identification scheme, with the row labels corresponding to the labelling in the main text.

Figure B1.8: Impulse Responses to a 1% UK CB rise (as % of GDP) between 1719 and 1822

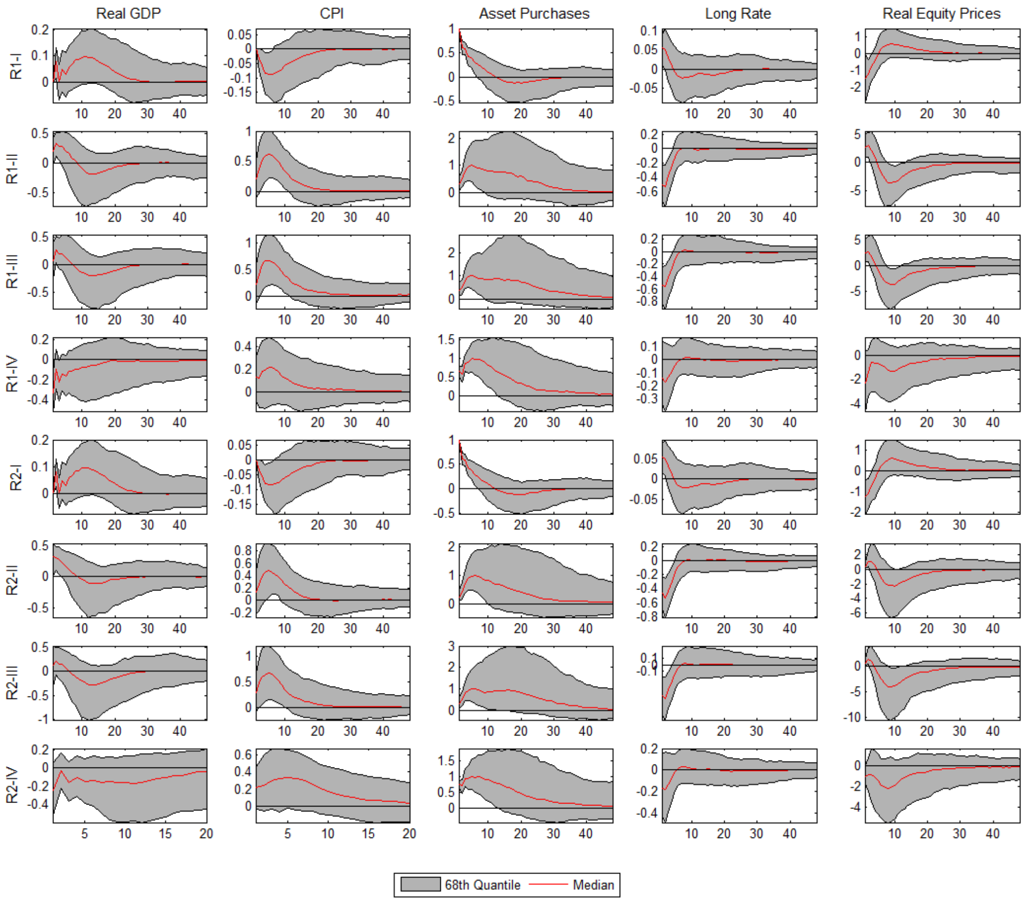


Source: Authors calculation.

Notes: The figure shows impulse responses of real GDP, CPI, the 10-year government bond yield, the central bank's balance sheet to GDP ratio and real equity prices from an unexpected 1% central bank balance sheet shock, obtained from a VAR estimated on these variables with annual data from 1719 to 1822, when the Bank of England's policy rate was continuously set to 5%. The grey bands are 68% confidence bands and the red line is the median. Each row shows the results from a different identification scheme, with the row labels corresponding to the labelling in the main text.

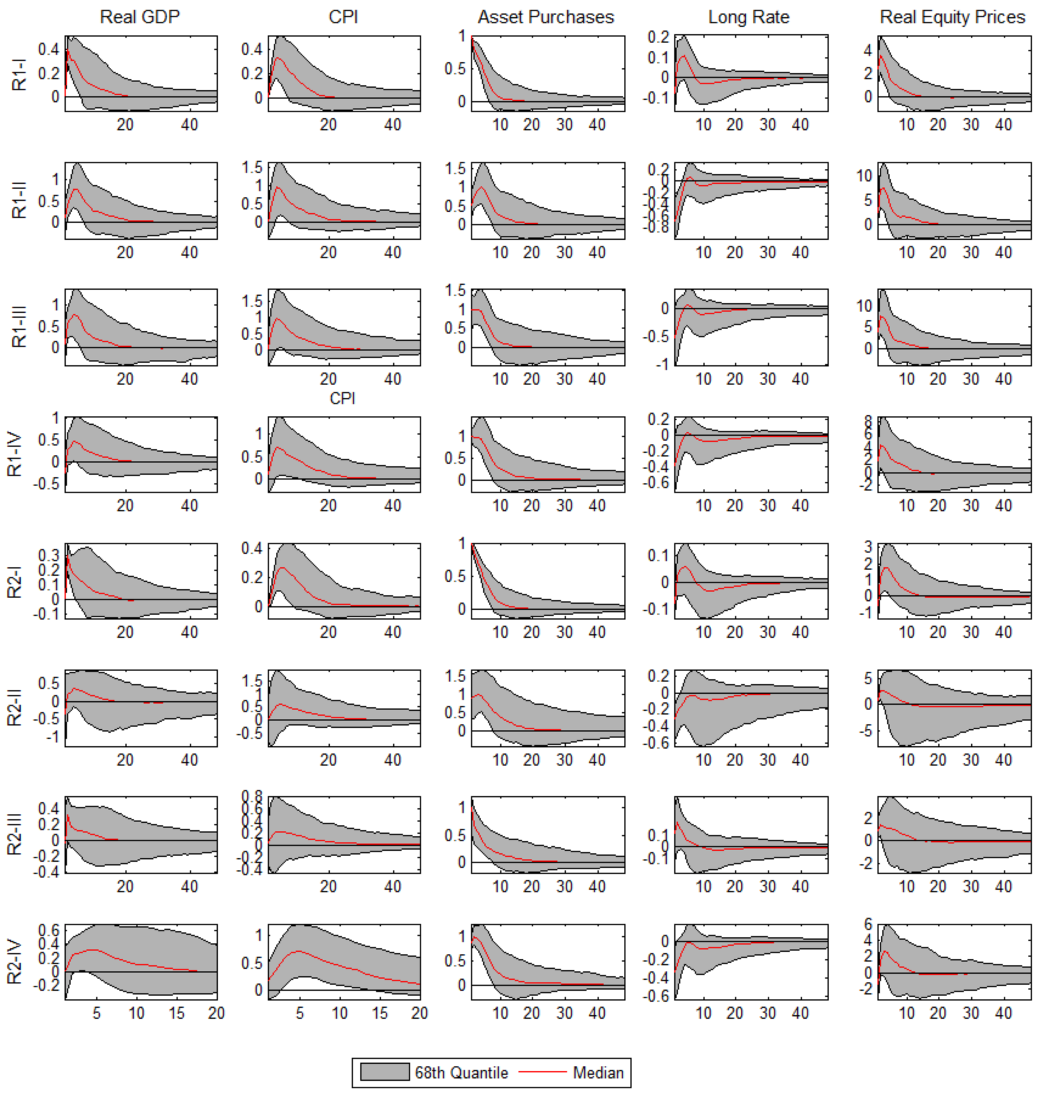
B2. Analysis of state dependent balance sheet expansions

Figure B2.1: Impulse Responses to a 1% UK CB asset purchase announcement in Regimes with different Market Liquidity



Source: Authors calculation.
Notes: The figure shows impulse responses of real GDP, CPI, the 10-year government bond yield, the central bank's asset purchase announcement of sovereign debt purchases to GDP ratio and real equity prices from an unexpected 1% asset purchase announcement shock, obtained from a VAR estimated on these variables with monthly data from 2009m3 to 2015m2, when the zero lower bound was a binding constraint. The grey bands are 68% confidence bands and the red line is the median. Each row shows the results from a different identification scheme, with the row labels corresponding to the labelling in the main text. R1 refers to impulse responses from VAR coefficients for the financial frictions regime. R2 refers to impulse responses from VAR coefficients for the normal times regime.

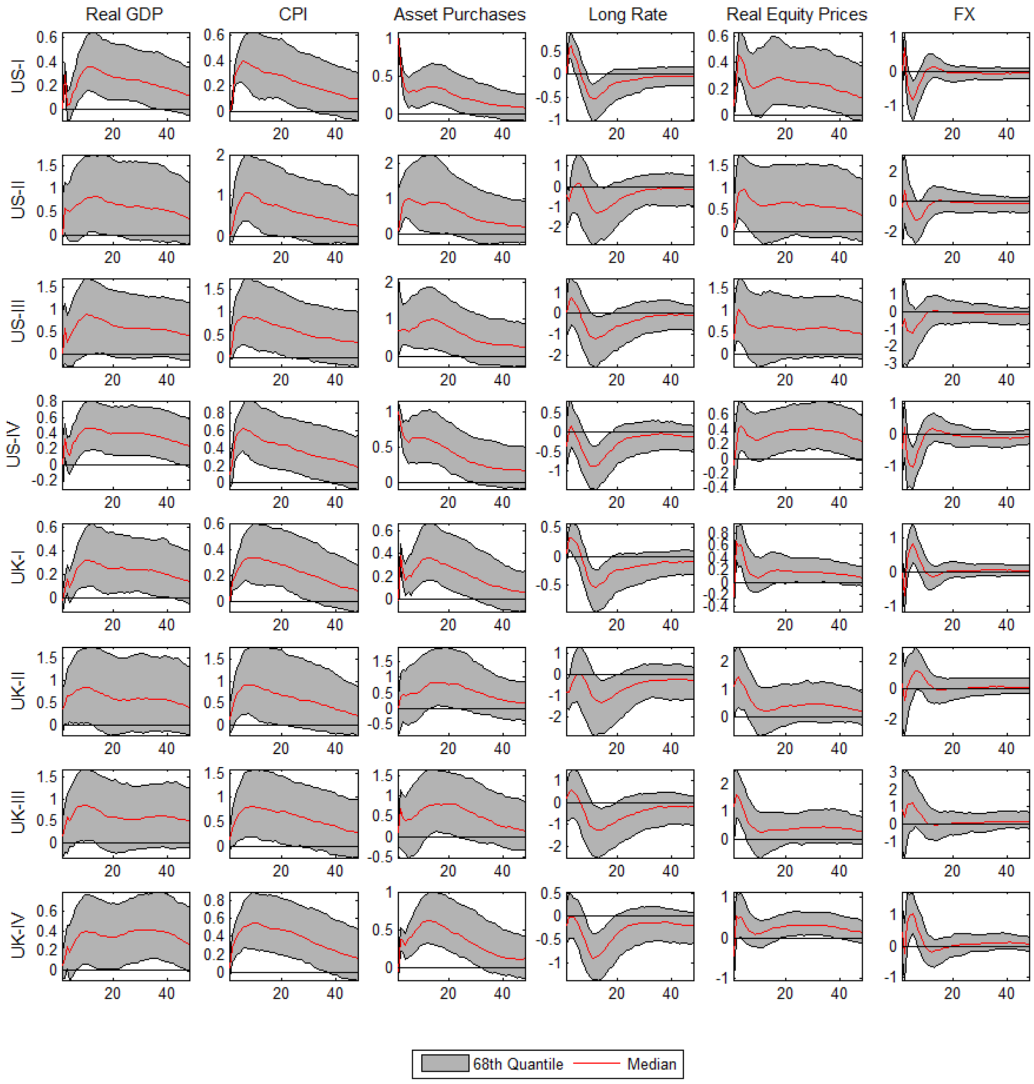
Figure B2.2: Impulse Responses to a 1% US CB asset purchase announcement in Regimes with different Market Liquidity



Source: Authors calculation.
Notes: The figure shows impulse responses of real GDP, CPI, the 10-year government bond yield, the central bank's asset purchase announcement of sovereign debt purchases to GDP ratio and real equity prices from an unexpected 1% asset purchase announcement shock, obtained from a VAR estimated on these variables with monthly data from 2009m3 to 2015m2, when the zero lower bound was a binding constraint. The grey bands are 68% confidence bands and the red line is the median. Each row shows the results from a different identification scheme, with the row labels corresponding to the labelling in the main text. R1 refers to impulse responses from VAR coefficients for the financial frictions regime. R2 refers to impulse responses from VAR coefficients for the normal times regime.

B3. Analysis of International Spill-overs

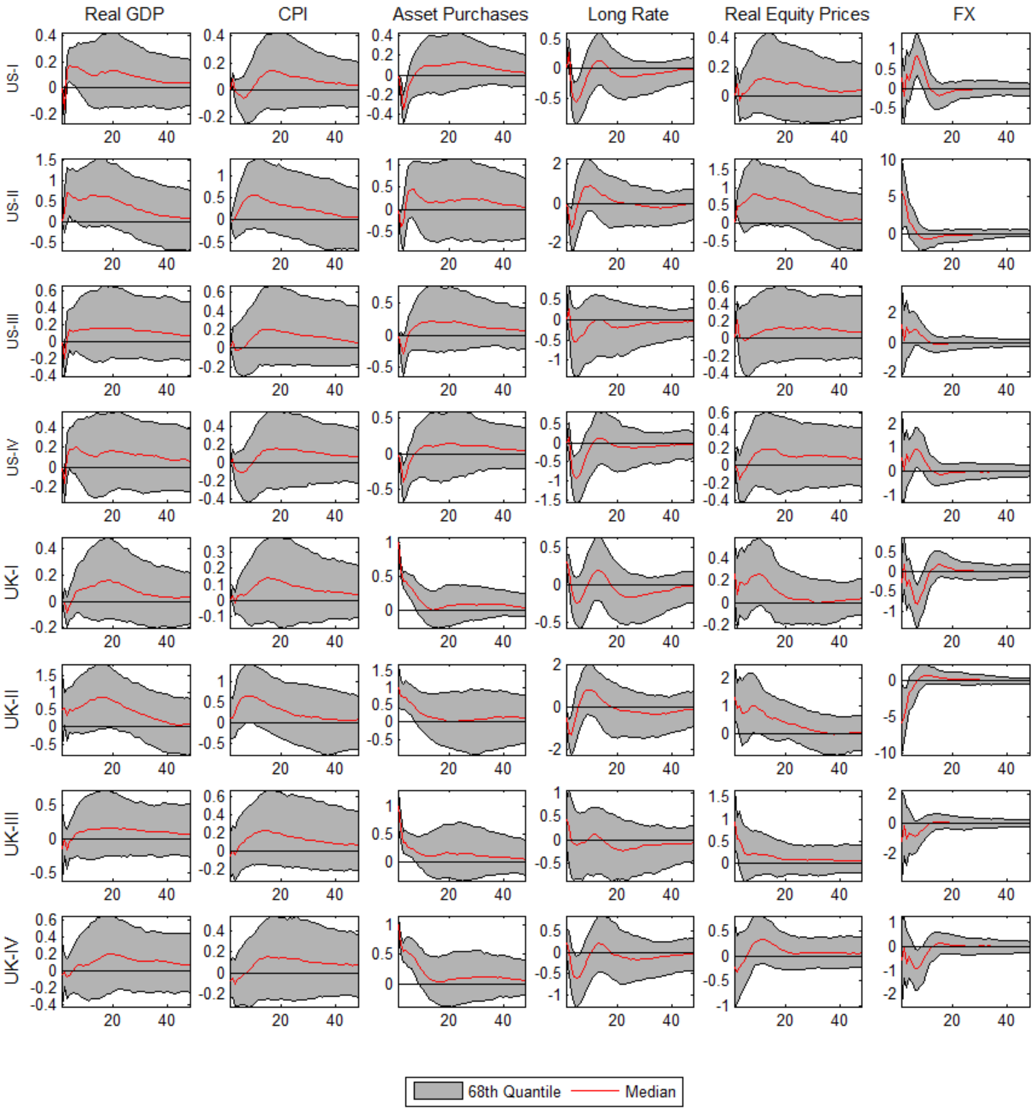
Figure B3.1: US and UK Responses to US Asset Purchases across different Identification Schemes



Source: Authors calculation.

Notes: The figure shows impulse responses of real GDP, CPI, the 10-year government bond yield, the central bank's balance sheet to GDP ratio and real equity prices in both the US and the UK, as well as the nominal bilateral exchange rate, from an unexpected 1% US asset purchase announcement shock , in terms of 2009Q1 nominal GDP, obtained from a VAR estimated on these variables with monthly data from 2009m3 to 2015m2. Due to the short sample, we imposed a Litterman (1986) prior with the hyperparameters estimated from the data as in the approach of Primiceri, Giannone and Lenza (2015). See appendix C for more details. Each row shows the results from a different identification scheme for that given country. For example, US-I indicated the responses for US variables with identification scheme I, while UK-III indicates the responses for UK variables with identification scheme III.

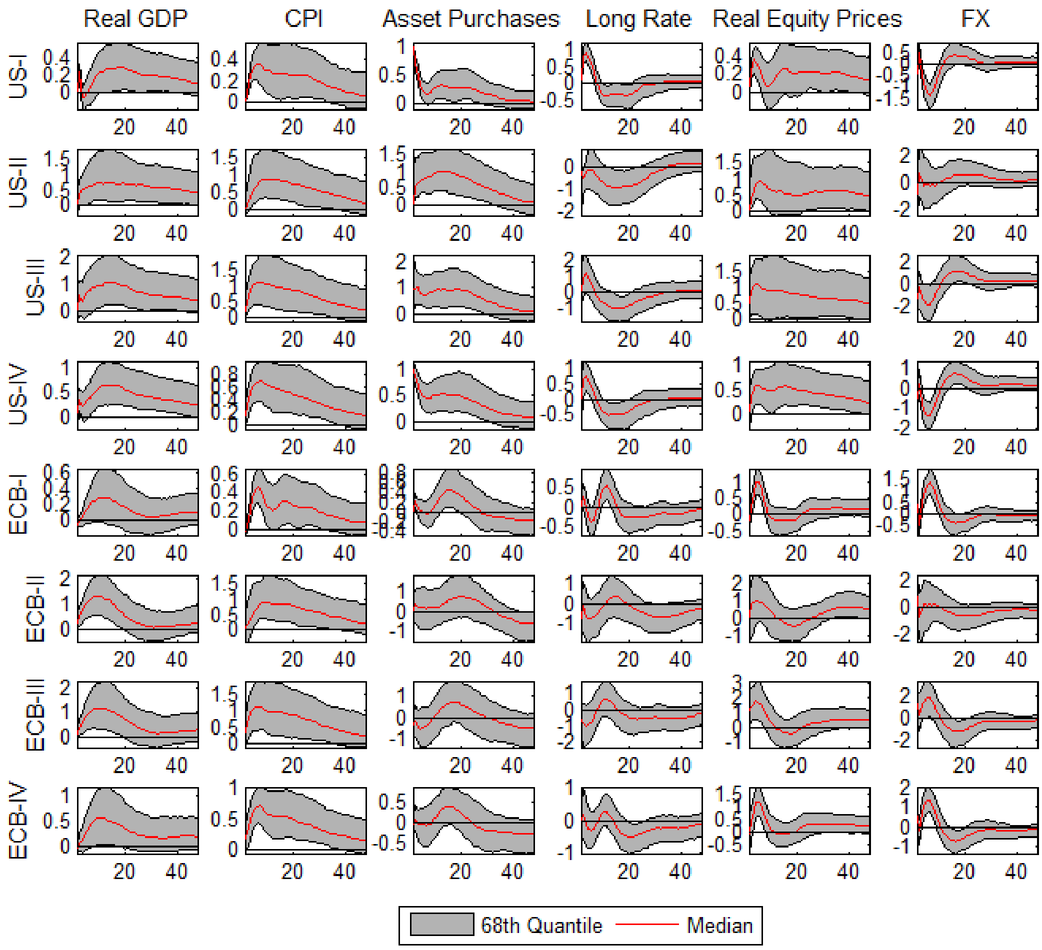
Figure B3.2: US and UK Responses to UK Asset Purchases across different Identification Schemes



Source: Authors calculation.

Notes: The figure shows impulse responses of real GDP, CPI, the 10-year government bond yield, the central bank's balance sheet to GDP ratio and real equity prices in both the US and the UK, as well as the nominal bilateral exchange rate from an unexpected 1% UK asset purchase announcement shock , in terms of 2009Q1 nominal GDP, obtained from a VAR estimated on these variables with monthly data from 2009m3 to 2015m2. Due to the short sample, we imposed a Litterman (1986) prior with the hyperparameters estimated from the data as in the approach of Primiceri, Giannone and Lenza (2015). See appendix C for more details. Each row shows the results from a different identification scheme for that given country. For example, US-I indicated the responses for US variables with identification scheme I, while UK-III indicates the responses for UK variables with identification scheme III.

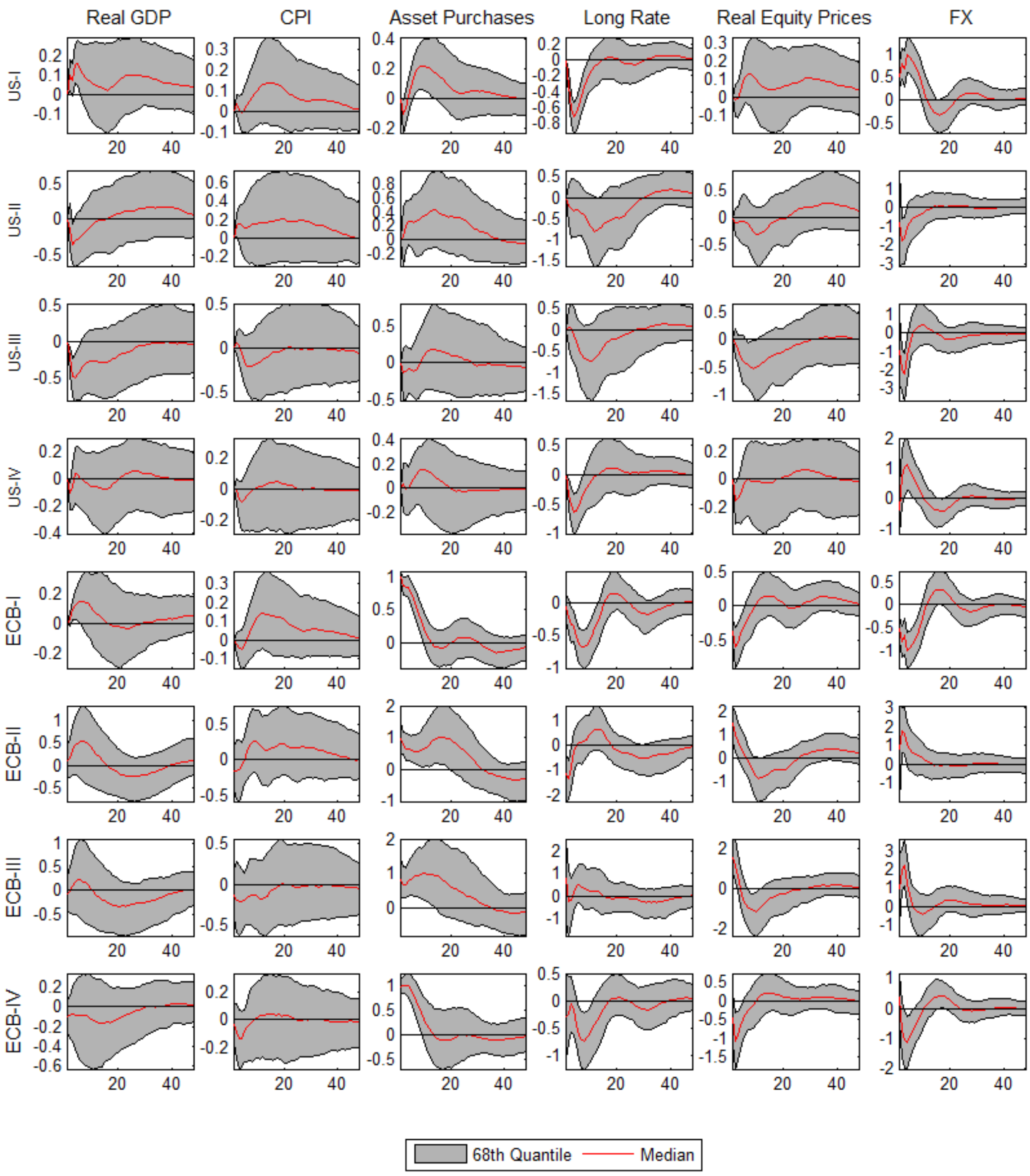
Figure B3.3: US and ECB Responses to US Asset Purchases across different Identification Schemes



Source: Authors calculation.

Notes: The figure shows impulse responses of real GDP, CPI, the 10-year government bond yield, the central bank's balance sheet to GDP ratio and real equity prices in both the US and the euro area, as well as the nominal bilateral exchange rate, from an unexpected 1% US asset purchase announcement shock , in terms of 2009Q1 nominal GDP, obtained from a VAR estimated on these variables with monthly data from 2009m3 to 2015m2. Due to the short sample, we imposed a Litterman (1986) prior with the hyperparameters estimated from the data as in the approach of Primiceri, Giannone and Lenza (2015). See appendix C for more details. Each row shows the results from a different identification scheme for that given country. For example, US-I indicated the responses for US variables with identification scheme I, while ECB-III indicates the responses for euro area variables with identification scheme III.

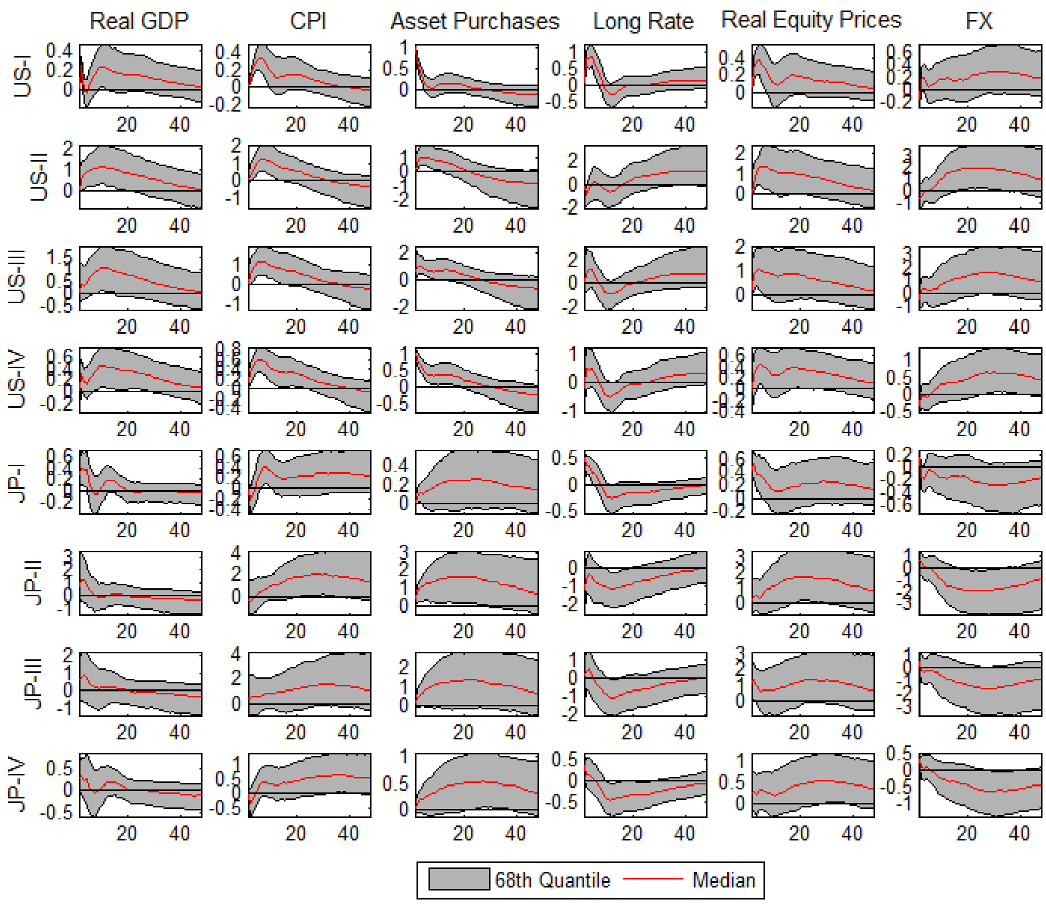
Figure B3.4: US and ECB Responses to ECB balance sheet shocks across different Identification Schemes



Source: Authors calculation.

Notes: The figure shows impulse responses of real GDP, CPI, the 10-year government bond yield, the central bank's balance sheet to GDP ratio and real equity prices in both the US and the euro area, as well as the nominal bilateral exchange rate, from an unexpected 1% ECB balance sheet expansion shock, in terms of 2009Q1 nominal GDP, obtained from a VAR estimated on these variables with monthly data from 2009m3 to 2015m2. Due to the short sample, we imposed a Litterman (1986) prior with the hyperparameters estimated from the data as in the approach of Primiceri, Giannone and Lenza (2015). See appendix C for more details. Each row shows the results from a different identification scheme for that given country. For example, US-I indicated the responses for US variables with identification scheme I, while ECB-III indicates the responses for euro area variables with identification scheme III.

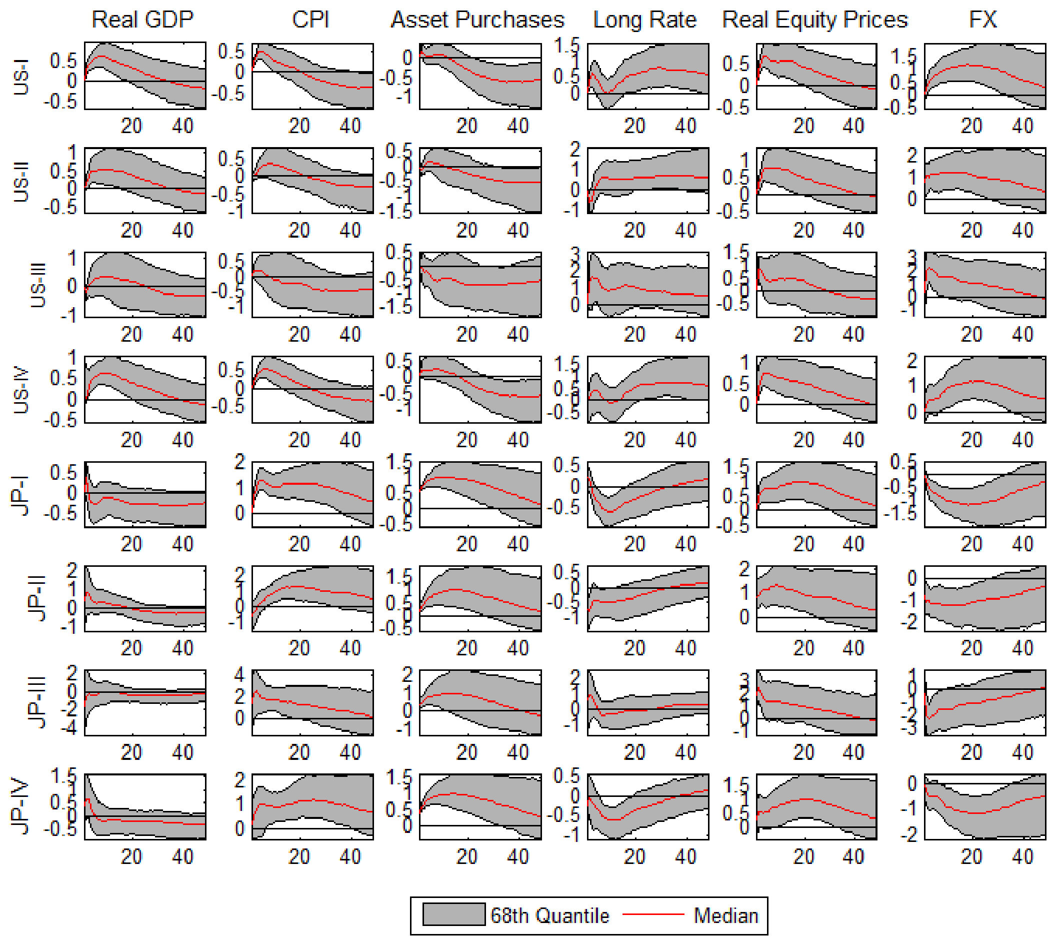
Figure B3.5: US and JP Responses to US Asset Purchases across different Identification Schemes



Source: Authors calculation.

Notes: The figure shows impulse responses of real GDP, CPI, the 10-year government bond yield, the central bank's balance sheet to GDP ratio and real equity prices in both the US and Japan, as well as the nominal bilateral exchange rate, from an unexpected 1% US asset purchase announcement shock , in terms of 2009Q1 nominal GDP, obtained from a VAR estimated on these variables with monthly data from 2009m3 to 2015m2. Due to the short sample, we imposed a Litterman (1986) prior with the hyperparameters estimated from the data as in the approach of Primiceri, Giannone and Lenza (2015). See appendix C for more details. Each row shows the results from a different identification scheme for that given country. For example, US-I indicated the responses for US variables with identification scheme I, while JP-III indicates the responses for Japanese variables with identification scheme III.

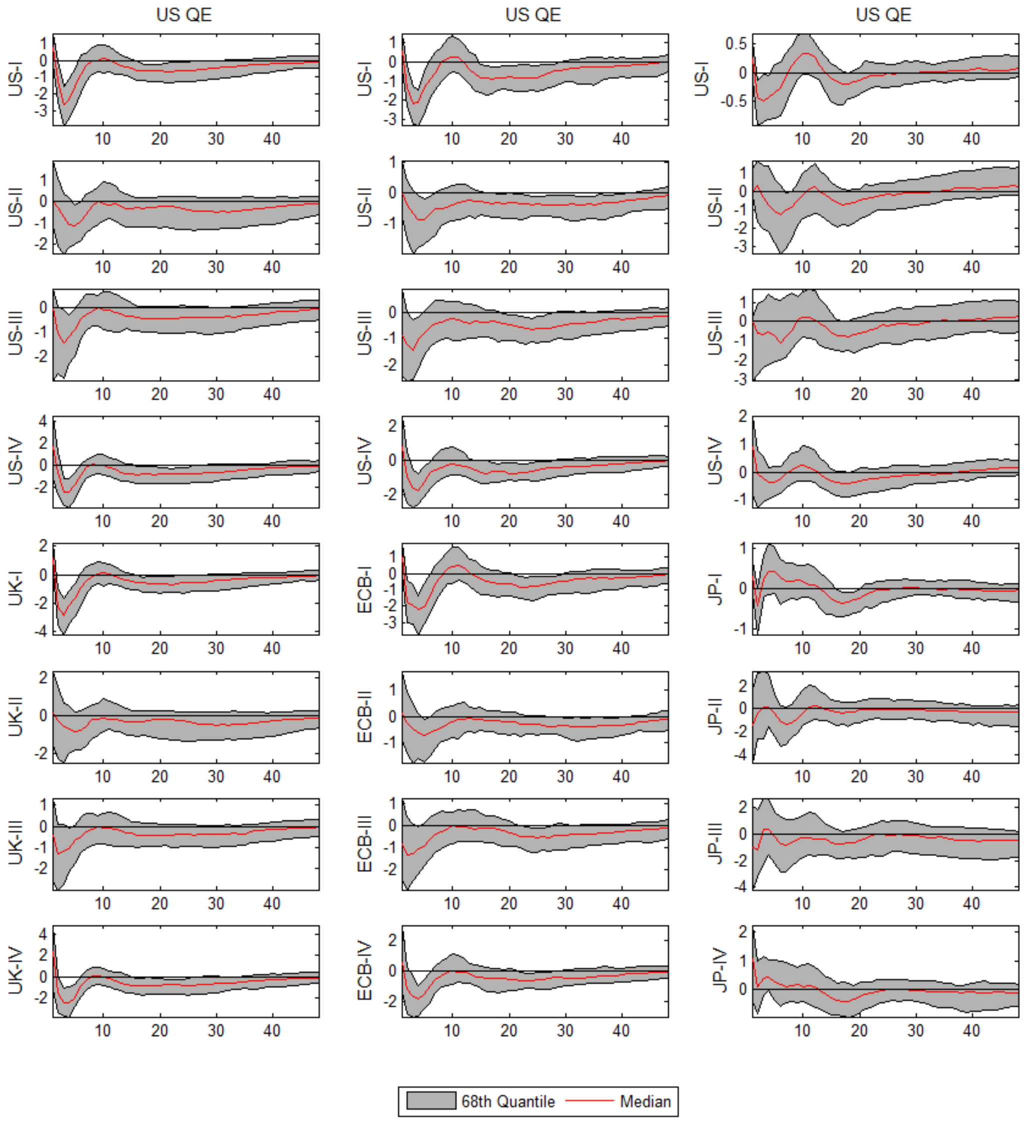
Figure B3.6: US and Japanese Responses to Japanese Asset Purchases across different Identification Schemes



Source: Authors calculation.

Notes: The figure shows impulse responses of real GDP, CPI, the 10-year government bond yield, the central bank's balance sheet to GDP ratio and real equity prices in both the US and Japan, as well as the nominal bilateral exchange rate, from an unexpected 1% Japanese asset purchase shock, in terms of 2009Q1 nominal GDP, obtained from a VAR estimated on these variables with monthly data from 2009m3 to 2015m2. Due to the short sample, we imposed a Litterman (1986) prior with the hyperparameters estimated from the data as in the approach of Primiceri, Giannone and Lenza (2015). See appendix C for more details. Each row shows the results from a different identification scheme for that given country. For example, US-I indicated the responses for US variables with identification scheme I, while JP-III indicates the responses for Japanese variables with identification scheme III.

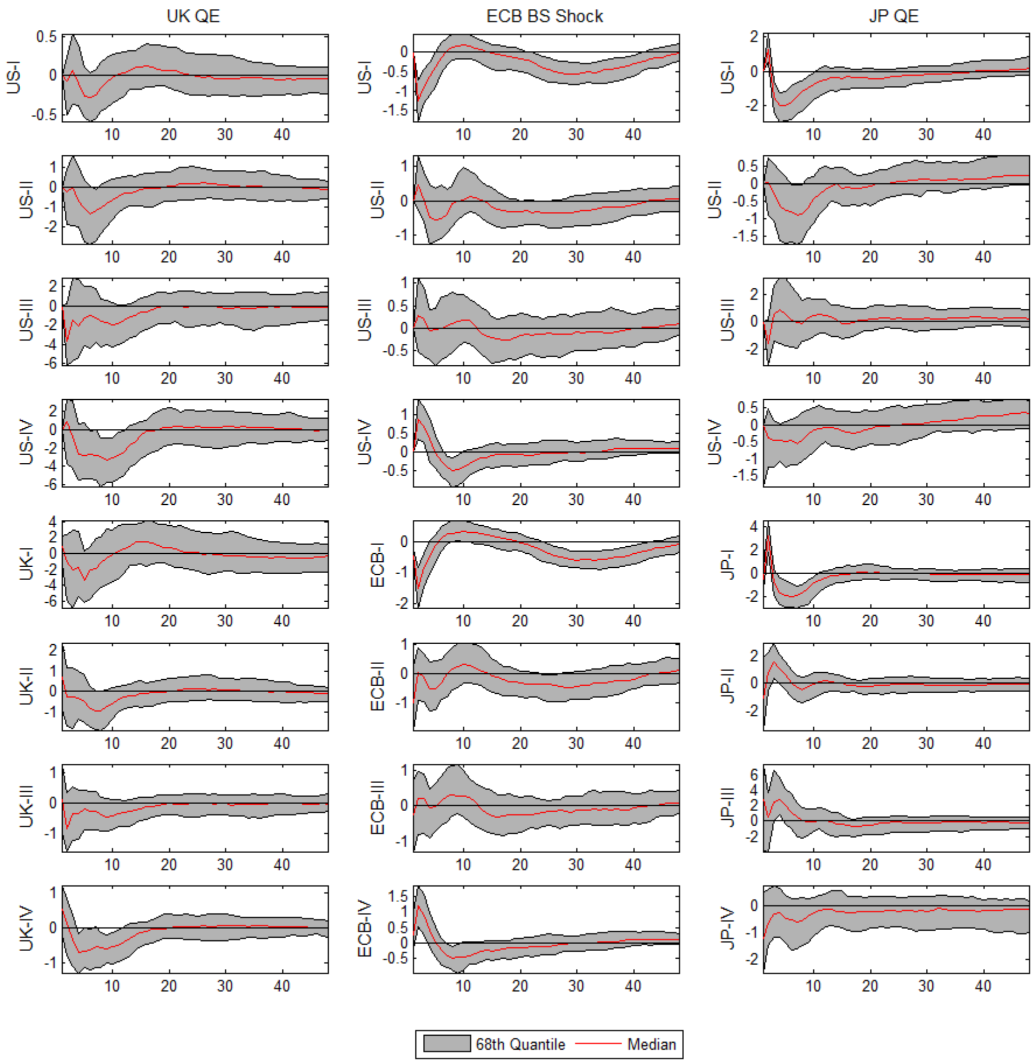
Figure B3.7: Response of US, UK, euro area and Japan implied volatility indices to US Asset Purchase announcement shocks



Source: Authors calculation.

Notes: The figure shows impulse responses of the US, UK, euro area and Japan implied volatility indices from an unexpected 1% US asset purchase announcement shock, in terms of 2009Q1 nominal GDP, obtained from a VAR estimated on these variables with monthly data from 2009m3 to 2015m2. Due to the short sample, we imposed a Litterman (1986) prior with the hyperparameters estimated from the data as in the approach of Primiceri, Giannone and Lenza (2015). See appendix C for more details. Each row shows the results from a different identification scheme for that given country. For example, US-I indicated the responses for US equity implied volatility (the VIX) with identification scheme I, while JP-III indicates the responses for Japanese equity implied volatility with identification scheme III.

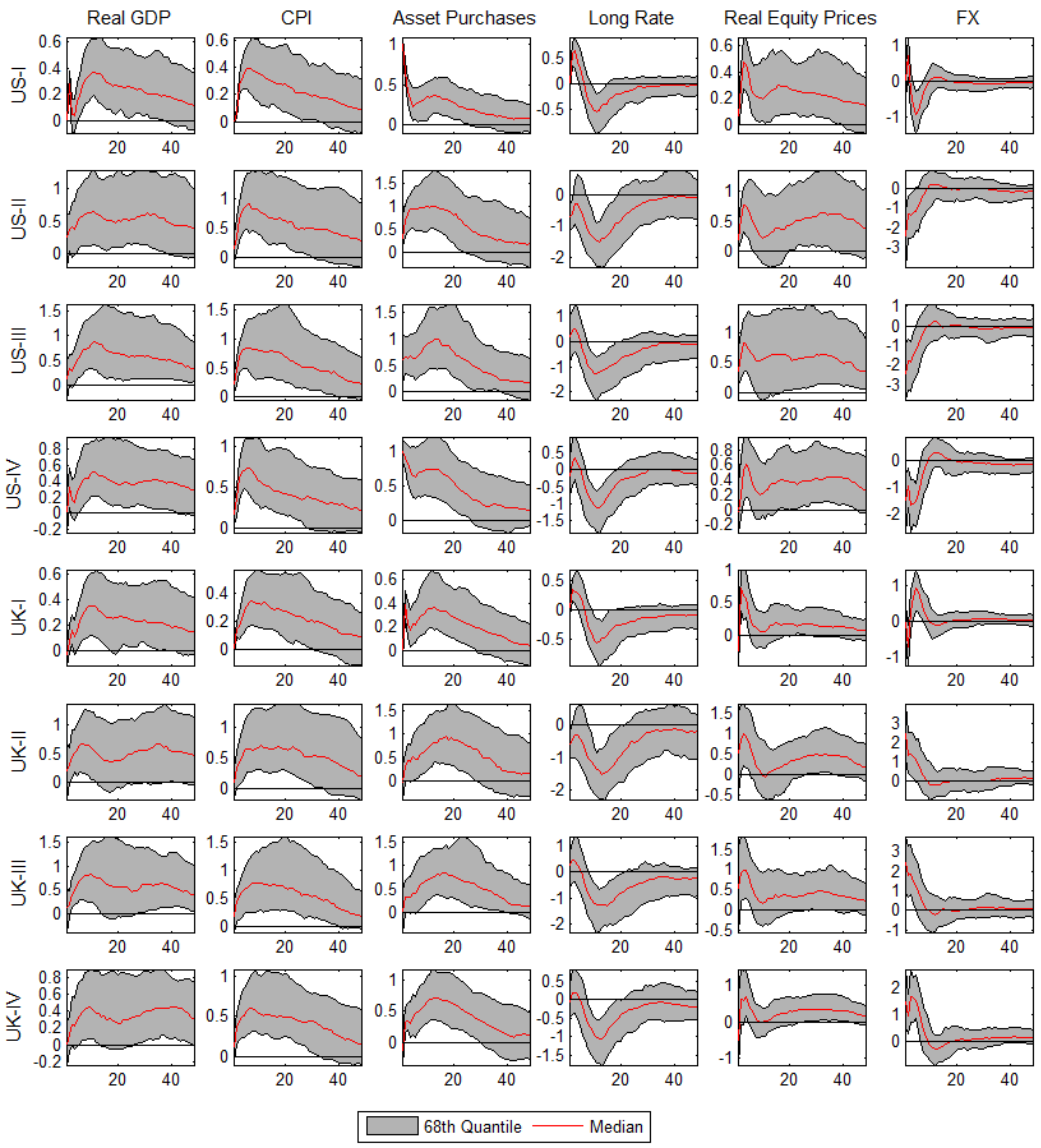
Figure B3.8: Response of US, UK, euro area and Japan implied volatility indices to UK, ECB and Japan Central Bank Balance Sheet expansion shocks



Source: Authors calculation.

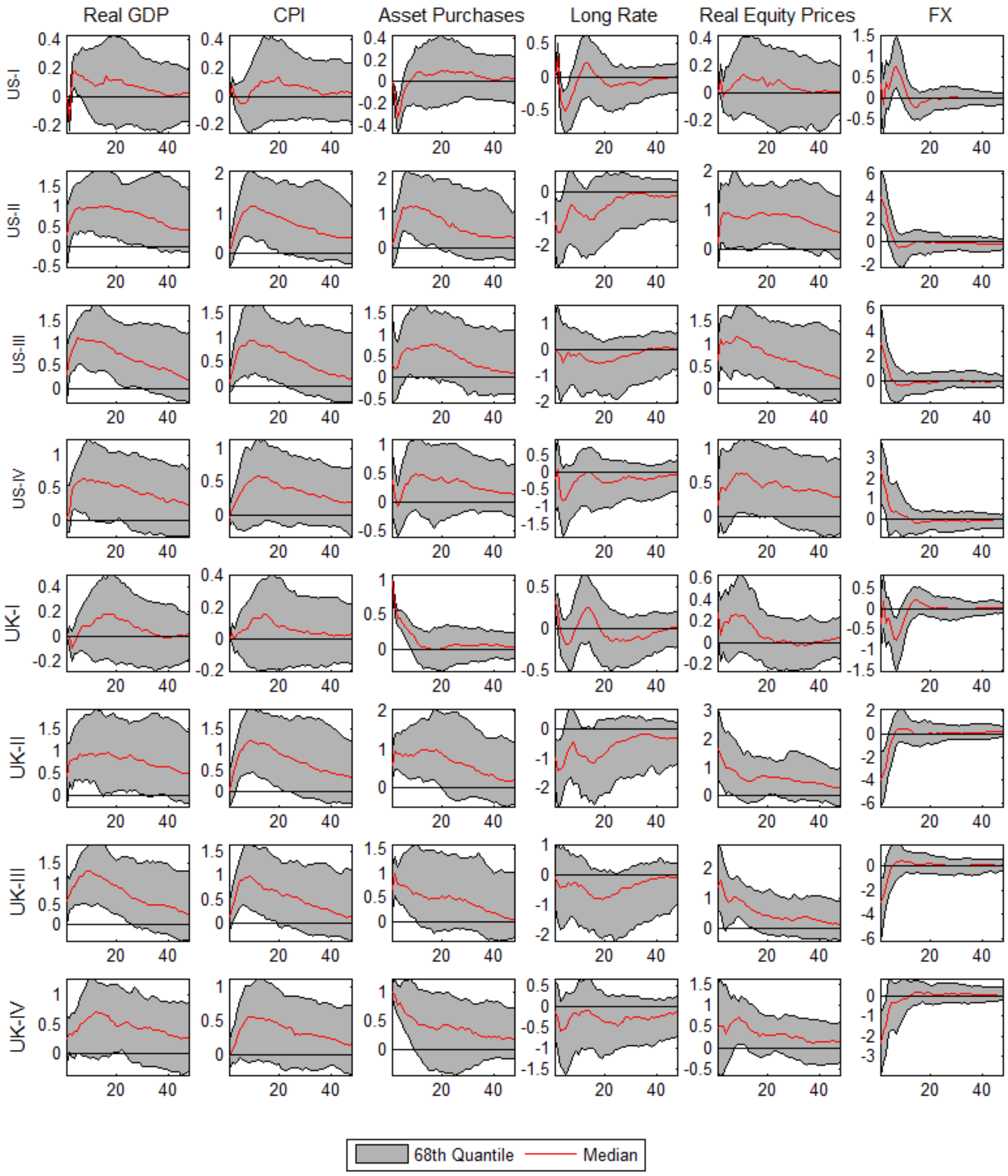
Notes: The figure shows impulse responses of the US, UK, euro area and Japan implied volatility indices from an unexpected 1% UK, ECB and Japanese central bank balance sheet shock, in terms of 2009Q1 nominal GDP, obtained from a VAR estimated on these variables with monthly data from 2009m3 to 2015m2. Due to the short sample, we imposed a Litterman (1986) prior with the hyperparameters estimated from the data as in the approach of Primiceri, Giannone and Lenza (2015). See appendix C for more details. Each row shows the results from a different identification scheme for that given country. For example, US-I indicated the responses for US equity implied volatility (the VIX) with identification scheme I, while JP-III indicates the responses for Japanese equity implied volatility with identification scheme III. The columns show the origin of the shock. For example, implied volatility responses in the column 'JP QE' refer to response of implied volatility to a 1% Japanese asset purchase shock.

Figure B3.9: US and UK Responses to US Asset Purchases across different Identification Schemes – International Identification Scheme - II



Source: Authors calculation.
Notes: The figure shows impulse responses of real GDP, CPI, the 10-year government bond yield, the central bank's balance sheet to GDP ratio and real equity prices in both the US and the UK, as well as the nominal bilateral exchange rate, from an unexpected 1% US asset purchase announcement shock , in terms of 2009Q1 nominal GDP, obtained from a VAR estimated on these variables with monthly data from 2009m3 to 2015m2. Due to the short sample, we imposed a Litterman (1986) prior with the hyperparameters estimated from the data as in the approach of Primiceri, Giannone and Lenza (2015). See appendix C for more details. Each row shows the results from a different identification scheme for that given country. For example, US-I indicated the responses for US variables with identification scheme I, while UK-III indicates the responses for UK variables with identification scheme III.

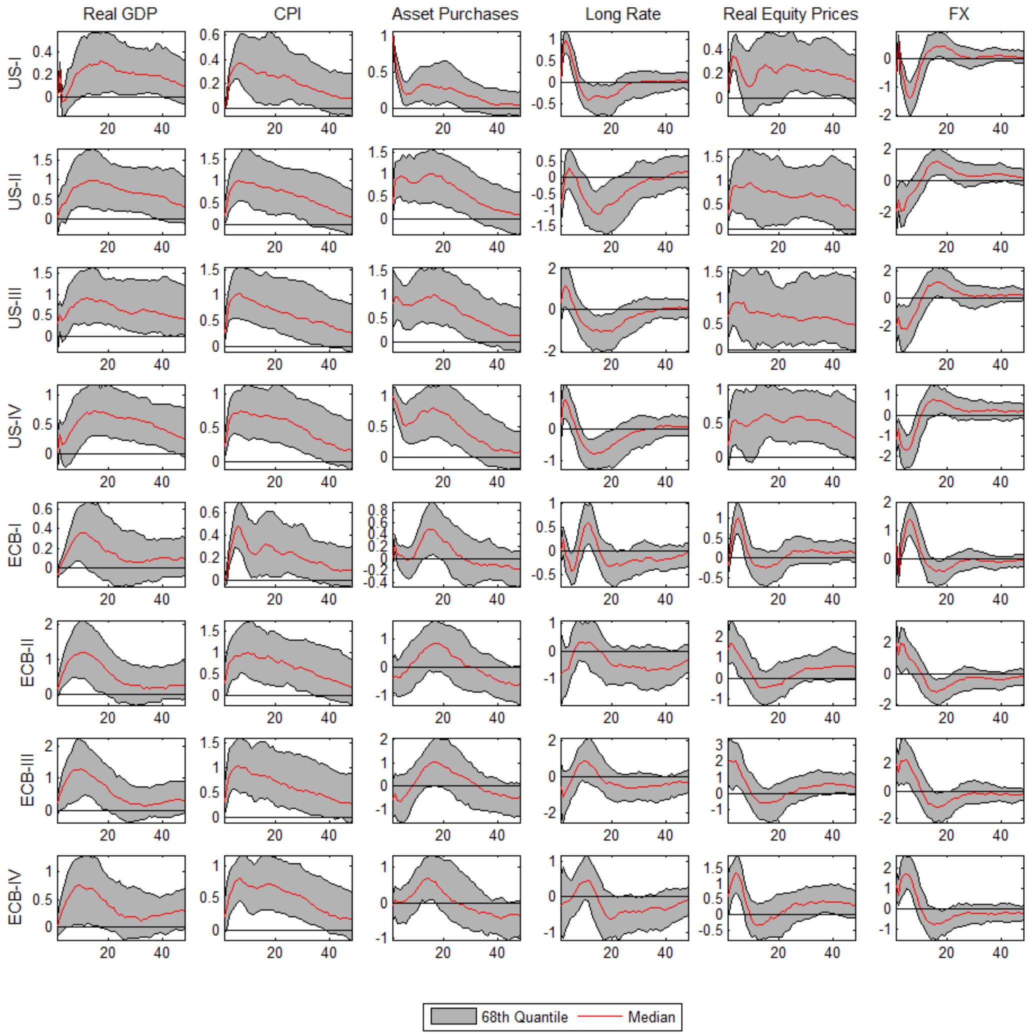
Figure B3.10: US and UK Responses to UK Asset Purchases across different Identification Schemes – International Identification Scheme - II



Source: Authors calculation.

Notes: The figure shows impulse responses of real GDP, CPI, the 10-year government bond yield, the central bank's balance sheet to GDP ratio and real equity prices in both the US and the UK, as well as the nominal bilateral exchange rate, from an unexpected 1% UK asset purchase announcement shock , in terms of 2009Q1 nominal GDP, obtained from a VAR estimated on these variables with monthly data from 2009m3 to 2015m2. Due to the short sample, we imposed a Litterman (1986) prior with the hyperparameters estimated from the data as in the approach of Primiceri, Giannone and Lenza (2015). See appendix C for more details. Each row shows the results from a different identification scheme for that given country. For example, US-I indicated the responses for US variables with identification scheme I, while UK-III indicates the responses for UK variables with identification scheme III.

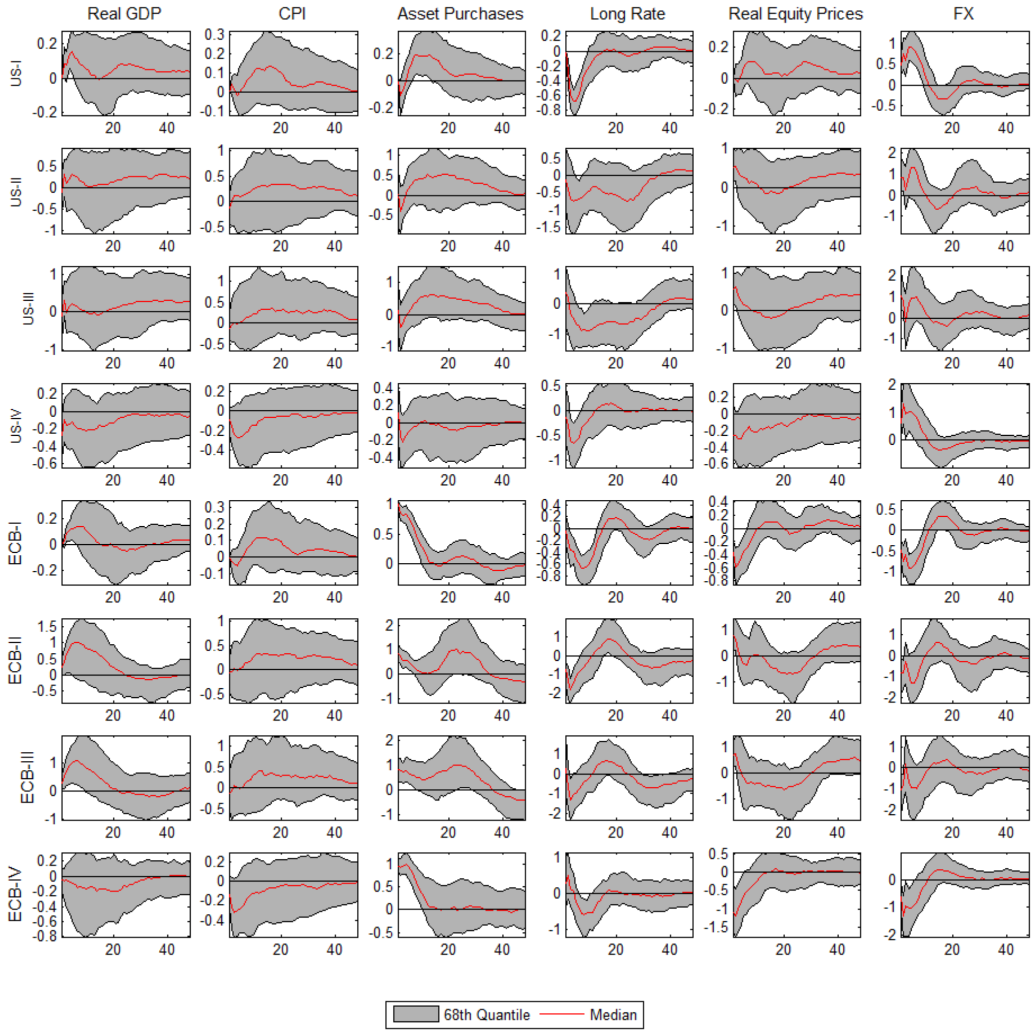
Figure B3.11: US and ECB Responses to US Asset Purchases across different Identification Schemes – International Identification Scheme - II



Source: Authors calculation.

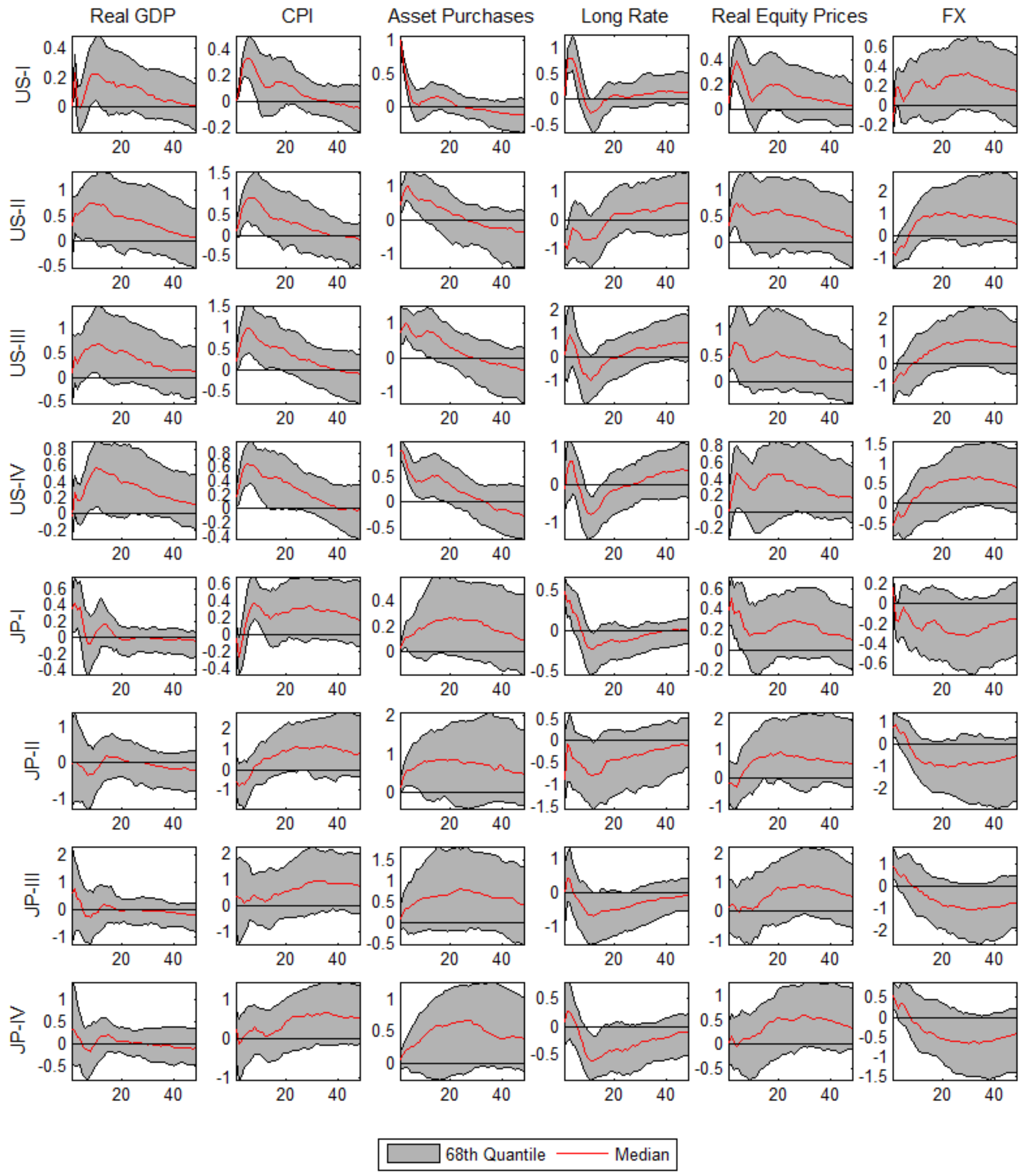
Notes: The figure shows impulse responses of real GDP, CPI, the 10-year government bond yield, the central bank's balance sheet to GDP ratio and real equity prices in both the US and the euro area, as well as the nominal bilateral exchange rate, from an unexpected 1% US asset purchase announcement shock , in terms of 2009Q1 nominal GDP, obtained from a VAR estimated on these variables with monthly data from 2009m3 to 2015m2. Due to the short sample, we imposed a Litterman (1986) prior with the hyperparameters estimated from the data as in the approach of Primiceri, Giannone and Lenza (2015). See appendix C for more details. Each row shows the results from a different identification scheme for that given country. For example, US-I indicated the responses for US variables with identification scheme I, while ECB-III indicates the responses for euro area variables with identification scheme III.

Figure B3.12: US and ECB Responses to ECB balance sheet shocks across different Identification Schemes – International Identification Scheme - II



Source: Authors calculation.
Notes: The figure shows impulse responses of real GDP, CPI, the 10-year government bond yield, the central bank's balance sheet to GDP ratio and real equity prices in both the US and the euro area, as well as the nominal bilateral exchange rate, from an unexpected 1% ECB balance sheet expansion shock, in terms of 2009Q1 nominal GDP, obtained from a VAR estimated on these variables with monthly data from 2009m3 to 2015m2. Due to the short sample, we imposed a Litterman (1986) prior with the hyperparameters estimated from the data as in the approach of Primiceri, Giannone and Lenza (2015). See appendix C for more details. Each row shows the results from a different identification scheme for that given country. For example, US-I indicated the responses for US variables with identification scheme I, while ECB-III indicates the responses for euro area variables with identification scheme III.

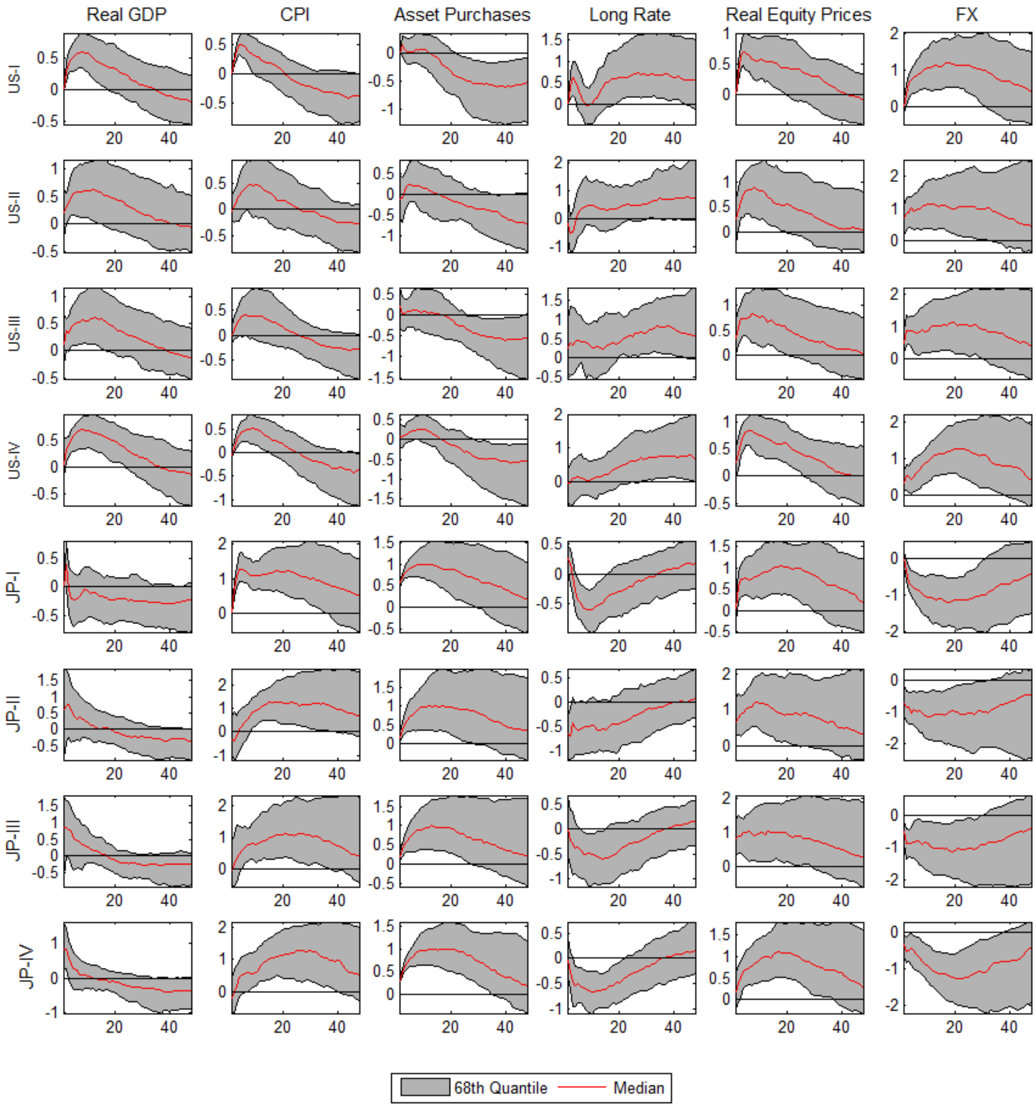
Figure B3.13: US and JP Responses to US Asset Purchases across different Identification Schemes – International Identification Scheme - II



Source: Authors calculation.

Notes: The figure shows impulse responses of real GDP, CPI, the 10-year government bond yield, the central bank's balance sheet to GDP ratio and real equity prices in both the US and Japan, as well as the nominal bilateral exchange rate, from an unexpected 1% US asset purchase announcement shock , in terms of 2009Q1 nominal GDP, obtained from a VAR estimated on these variables with monthly data from 2009m3 to 2015m2. Due to the short sample, we imposed a Litterman (1986) prior with the hyperparameters estimated from the data as in the approach of Primiceri, Giannone and Lenza (2015). See appendix C for more details. Each row shows the results from a different identification scheme for that given country. For example, US-I indicated the responses for US variables with identification scheme I, while JP-III indicates the responses for Japanese variables with identification scheme III.

Figure B3.14: US and Japanese Responses to Japanese Asset Purchases across different Identification Schemes – International Identification Scheme - II



Source: Authors calculation.

Notes: The figure shows impulse responses of real GDP, CPI, the 10-year government bond yield, the central bank's balance sheet to GDP ratio and real equity prices in both the US and Japan, as well as the nominal bilateral exchange rate, from an unexpected 1% Japanese asset purchase shock, in terms of 2009Q1 nominal GDP, obtained from a VAR estimated on these variables with monthly data from 2009m3 to 2015m2. Due to the short sample, we imposed a Litterman (1986) prior with the hyperparameters estimated from the data as in the approach of Primiceri, Giannone and Lenza (2015). See appendix C for more details. Each row shows the results from a different identification scheme for that given country. For example, US-I indicated the responses for US variables with identification scheme I, while JP-III indicates the responses for Japanese variables with identification scheme III.

Appendix C – Multi-Country VAR Details

When gauging the international spill-over effects of QE, it is necessary to modify the VAR model in several ways. Rather than 5 variables, this model now consists of 11 variables, 5 from one country, 5 from the other and the bilateral nominal exchange rate. Clearly, with only 72 months of data, it is now necessary to impose a prior on the coefficients. We implement the standard Litterman (1986) prior through the dummy variable approach outlined in Banbura, Giannone and Reichlin (2010).[24] This prior assumes that non-stationary variables evolve like a random walk, while stationary variables behave like white noise. In our application all variables, but the long-term interest rates and the nominal bilateral exchange rate[25] are treated as non-stationary.[26] One disadvantage of imposing any prior is that it is always difficult to know whether the results are driven by the data or the tightness of the prior. Giannone, Primiceri and Lenza (2014) recently proposed an approach to estimate the optimal degree of tightness and the other parameters of this prior by maximizing the likelihood function. This is the approach that we follow to implement this prior.[27]

The VAR model we propose to examine the transmission of balance sheet expansions across countries is the following:

$$\boldsymbol{Y_t = \alpha_c + \sum_{k=1}^{L} A_k Y_{t-k} + e_t} \qquad \boldsymbol{e_t \sim N(0, \Sigma)} \qquad \textbf{(1)}$$

where $\boldsymbol{Y_{c,t}}$ is a vector of the following endogenous variables: the log of CPI in country 1, the log of real GDP in country 1, the announcement of asset purchases scaled by nominal GDP in country 1; the yield on the 10-year government bond in country 1, the log of real equity prices in country, the log of CPI in country 2, the log of real GDP in country 2, the announcement of asset purchases scaled by nominal GDP in country 2; the yield on the 10-year government bond in country 2, the log of real equity prices in country 2 and the nominal exchange rate among the two countries at time $\boldsymbol{t}$. $\boldsymbol{A_k}$ is the array of coefficients associated with the corresponding lagged vector of variables for lag $\boldsymbol{k}$. $\boldsymbol{e_{c,t}}$ is a vector of residuals for country $\boldsymbol{c}$ at time $\boldsymbol{t}$. This is assumed to be normally distributed with variance-covariance matrix $\boldsymbol{\Sigma_c}$. When the time-series dimension is small, estimates of $\boldsymbol{A_k}$ are likely to be imprecise. While one way of addressing this problem is to include pre 2009m3 data, that would carry the risks that our estimates could be biased by coincidence of the various government interventions in the banking system in response to the global financial crisis. Instead, we follow previous work and rely on Bayesian methods of inference to address the sample size issue with the Litterman (1986) prior. The former imposes the prior assumption that non-stationary variables

[24] In addition to the prior, we also remove the mean from each variable and normalise each variable to have a standard deviation of one. This is a standard data transformation in estimating multi-country panel VARs (see Canova and Cicarelli (2006) for example).

[25] Whether or not the exchange rate is a random walk is still debated in relevant academic literature (See Sarno and Taylor, 2005) for a detailed survey of this issue. We note that over the time period examined here, the exchange rate does not exhibit strong trends, which suggests that our assumption is correct. However, modelling the exchange rate as a non-stationary variable instead does not change our results materially.

[26] One could argue that this assumption is invalid for the ECB's balance sheet to GDP ratio, which shows a hump shape past mid-2013. Modelling this as stationary does not make a difference to our results.

[27] See Appendix C.

follow a random walk, while stationary variables follow a white noise process. We assume a lag length, **L**, of two throughout.[28]

<u>Identifying assumptions in multi-country model</u>

We also need to change identification assumptions. We order the countries by size and impose block exogeneity, but only on the impact matrix. This is means that shocks in the smaller country can affect the larger one, but only with a lag. Shocks in the larger country can affect both countries simultaneously. This is a standard assumption when studying the impact of shocks originating in a large country on a smaller one. The bilateral exchange rate is always ordered last to allow it to react to shocks in both countries upon impact. For example, Cushman and Zha (1997) use this assumption to examine the impact of US shocks on Canada, while Mumtaz and Surico (2008) impose this assumption In a factor augmented VAR to study the impact of world shocks on UK macroeconomic variables. Bluwstein and Canova (2015) assume block exogeneity on the impact matrix and lagged coefficients. This means that shocks in the small countries never affect developments in the larger one. This assumption seems right when the small country is truly a small open economy, as in their case.

Because the smaller countries in our application (the euro area, Japan and the UK) are not the proto-typical small open economy, allowing them to affect the larger country, at least with lags, is probably a better assumption in our case. Imposing this type of block exogeneity is necessary to impose identification schemes I-III. For scheme I, this assumption means that we can apply a Choleski decomposition to the entire vector of variables in our two country VAR.[29] This also allows us to identify an asset purchase (liquidity operation) shock in the smaller country as a shock to the asset purchase announcement variable in that country. For identification schemes II and III, the assumption of block exogeneity allows us to identify a shock in the 2nd country with sign restrictions. This is identified with exactly the same restrictions as for the first country, but with the additional assumption that the shock in the second country does not affect the first one upon impact in line with block exogeneity. For identification scheme IV, it is not necessary to assume block exogeneity, since the assumptions that the shock to the central bank balance sheet operation explains the largest fraction of the variance in that variable is a mutually exclusive restriction across both countries.

<u>The Litterman prior</u>

In general, prior beliefs on VAR coefficients can be expressed as

$$E[(A_{ij,k})] = \delta_{i,j,k} \quad V[(A_{ij,k})] = \left\{ v \frac{\lambda^2}{k^2} \frac{\sigma_i^2}{\sigma_j^2} \right\} \qquad \textbf{(2)}$$

[28] Ex-ante lag length tests such as the Hanan-Quin or BIC criterion suggest a lag length of 2. Similarly, if the VAR is estimated with the correct lag length, the residuals should follow a white-noise process and autocorrelation tests on the residuals of each equation of the VAR suggests that this is the case.

[29] We order the variables in our VAR as: US CPI, US real GDP, US asset purchase announcement, US long rate, US real share prices, 2nd country CPI, 2nd country real GDP, 2nd country central bank balance sheet operation, 2nd country long rate, 2nd country real share prices. The bilateral nominal exchange rate enters as the last variable and is allowed to react to all other shocks contemporaneously.

$\delta_{i,j}$ is the prior mean for the VAR coefficient in row *i,* column *j* at lag length *k* . $v\frac{\lambda^2}{k^2}\frac{\sigma_i^2}{\sigma_j^2}$ is the corresponding prior variance. A smaller prior variance means that larger weight is put on the prior relative to the data. The values of this variance, v, σ_i^2, λ, σ_j^2 and k are typically calibrated. Following the approach set out in Kadiyala and Karlsson (1997), v is typically set to unity, as this allows researchers to relax the assumption of the diagonal variance-covariance that is typically embedded in the standard Litterman prior (1986). λ is the key parameter determining the tightness of the prior. If $\lambda = 0$, then the posterior coefficient estimate of $A_{ij,k}$ from this model will coincide with the prior, $\delta_{i,j}$. On the other hand, if $\lambda \to \infty$, the prior structure is not binding and the posterior estimate will coincide with the OLS estimate. The parameterisation of $V[(A_{ij,c,k})]$ has the convenient property that the degree of tightness can be summarised in one parameter, λ. But this comes with one drawback: the coefficients in $\boldsymbol{A_{c,k}}$ may have different magnitudes. In specifying a single parameter that determines the degree of tightness, there is therefore the risk that some coefficients are allowed to differ from the prior by a small fraction of their own size, while others can differ by orders of magnitude. Following Litterman (1986), we use the ratio $\frac{\sigma_i^2}{\sigma_j^2}$, as a scaling factor for each coefficient, where *i* is the equation and *j* the number of the variable regardless of lag. σ_i^2 is the estimated variance of the residuals of an auto-regression for the endogenous variable in equation *i*, of the same order as the VAR, and is obtained pre-estimation. σ_j^2 is the corresponding variance for variable *j* and obtained in an identical manner. To the extent that unexpected movements in variables will reflect the difference in the size of VAR coefficients, scaling by this ratio of variances allows us to address this issue.

In his original paper, Litterman (1986) sets $\delta_{i,j,c,k} = 1$ if $k = 1$ and $j = i$ for all of the variables, assuming that they all behave like a random walk. But Banbura, Gianonne and Reichlin (2010) argue that this is not appropriate for stationary variables, for which they suggest setting $\delta_{i,j,c,k} = 0$, which is the prescription that we follow here. Typically, the value of λ is set to a small number, reflecting the researchers' belief that the prior reflects the properties of the data. The results may depend on the value of λ and it is uncertain what the right value of this parameter for a given VAR model is. Previous work has suggested two different ways to estimate λ. Banbura, Giannone and Reichlin (2010) solve numerically for the value of λ that provides the smallest root mean square forecast errors. Most recently, Primiceri, Giannone and Lenza (2015) propose treating this parameter as a hierarchical parameter within the VAR model and show how to estimate it by maximising the likelihood function of this model. This is indeed the approach that we follow here. We first use their approach to estimate the λ associated with the highest likelihood and then in a second step use the dummy variable approach presented in Banbura, Giannone and Reichlin (2010) to implement this model.

Appendix D – Data

Variable	Source and transformation for the US	Source and transformation for the UK
Real GDP	Monthly GDP from Macroeconomic Advisers; Expressed in natural logarithm	Monthly GDP from Mitchell et al (2005); Consistent with September 2014 quarterly data. Expressed in natural logarithm
CPI	Monthly seasonally adjusted Consumer Price Index for all items from FRED (CPIAUCSL); Expressed in natural logarithm	Monthly Seasonally adjusted CPI from the Bank of England database; Expressed in natural logarithm
Asset purchase announcements	Minutes of the Federal Open Market Committee (FOMC); Scaled by annualised 2009Q1 GDP	Minutes of the Monetary Policy Committee (MPC); Scaled by annualised 2009Q1 GDP
10-year yield on government bonds	Monthly average of the 10 - year Yield on US Treasury Bonds taken from DataStream (USBD10Y)	Monthly average of the 10 -year Yield on UK Gilts taken from the Bank of England website
Real share prices	Monthly average of S&P500 index from DataStream (S&PCOMP), divided by CPI and expressed in natural logarithms	Monthly average of FTSE100 index from DataStream (FTSE100), divided by CPI and expressed in natural logarithms
VIX	Monthly average of the CBOE Volatility Index taken from FRED	Monthly average of the implied volatility of the FTSE 100 taken from the Bank of England database

Variable	Source and transformation for the euro area	Source and transformation for Japan
Real GDP	Monthly GDP was constructed based on the monthly quarter on quarter growth euro area real GDP growth rate, taken from the Euro-Coin website. Specifically, we use the 2009Q1 value of real GDP as an initial condition and back out the monthly value subsequently. We use X12 to remove seasonality from this indicator. It is expressed in natural logarithm.	Due the absence of a monthly GDP for Japan, we use the monthly industrial activity indicator. The quarterly growth rates of this indicator are highly correlated with real GDP growth rates, suggesting that this is a comprehensive indicator of real activity at monthly frequency. This is taken from DataStream and expressed in natural logarithm.
CPI	Monthly seasonally adjusted euro area CPI is taken from DataStream. Expressed in natural logarithm	Monthly Seasonally adjusted CPI from DataStream. Expressed in natural logarithm
Asset purchase announcements	Monthly average of Total Assets of the ECB, taken from the ECB Statistical Warehouse. Then expressed as a ratio to 2009Q1 euro area GDP.	Monthly average of sovereign bond purchases by the Bank of Japan, taken from DataStream. Then expressed as a ratio to 2003Q1 euro area GDP.
10-year yield on government bonds	Monthly average of the 10 - year Yield on a GDP-weighted average of Euro-Area sovereign bonds taken from DataStream.	Monthly average of the 10 -year Yield on Japanese government debt taken from DataStream.
Real share prices	Monthly average on a GDP-weighted average of Euro-Area stock markets taken from DataStream, divided by CPI and expressed in natural logarithms	Monthly average of the NIKKEI index from DataStream, divided by CPI and expressed in natural logarithms
VIX	Monthly average of the implied volatility of the GDP-weighted average of Euro-Area stock markets.	Monthly average of the implied volatility of the NIKKEI taken from the Bank of England database

Variable	Source and transformation for Canada	Source and transformation for Sweden
Real GDP	We take the monthly real GDP measure at basic prices provided on the statistics Canada website. It is expressed in natural logarithm.	As monthly GDP for Sweden was not available, we use industrial production from the OECD main economic indicator database. It is expressed in natural logarithm.
CPI	Monthly seasonally adjusted Canadian CPI is taken from DataStream. Expressed in natural logarithm	Monthly Seasonally adjusted CPI from DataStream. Expressed in natural logarithm
Asset purchase announcements	Monthly average of Total Assets, taken from the Bank of Canada's website. Then expressed as a ratio to 2009Q1 Canadian GDP.	Monthly average of Total Assets, taken from the Riksbank's website. Then expressed as a ratio to 2009Q1 Swedish GDP.
10-year yield on government bonds	Monthly average of the 10 - year Yield on Canadian sovereign debt taken from DataStream.	Monthly average of the 10 -year Yield on Swedish government debt taken from DataStream.
Real share prices	Monthly average of S&P Toronto Stock Exchange Composite from DataStream (S&PCOMP), divided by CPI and expressed in natural logarithms	Monthly average of the OMX Stockholm all share index from DataStream, divided by CPI and expressed in natural logarithms

- Bilateral FX rates are taken from DataStream.
- Historical UK data are taken the Bank of England's historical database, also available at: http://www.bankofengland.co.uk/research/Pages/onebank/datasets.aspx