Risk, Uncertainty and Monetary Policy*

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Abstract

We document a strong co-movement between the VIX, the stock market option-based implied volatility, and monetary policy. We decompose the VIX into two components, a proxy for risk aversion and expected stock market volatility ("uncertainty"), and analyze their dynamic interactions with monetary policy in a structural vector autoregressive framework. A lax monetary policy decreases risk aversion after about six months. Monetary authorities react to periods of high uncertainty by easing monetary policy. These results are robust to controlling for business cycle movements. We further investigate channels through which monetary policy may affect risk aversion, e.g., through its effects on broad liquidity measures and credit.

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I. Introduction

A popular indicator of risk aversion in financial markets, the VIX index, shows strong co-movements with measures of the monetary policy stance. Figure 1 considers the cross-correlogram between the real interest rate (the Fed funds rate minus inflation), a measure of the monetary policy stance, and the logarithm of end-of-month readings of the VIX index. The VIX contract, traded on the Chicago Board Options Exchange, essentially prices the "risk-neutral" expected stock market variance for the US S&P500 contract. The correlogram reveals a very strong positive correlation between real interest rates and future VIX levels. While the current VIX is positively associated with future real rates, the relationship turns negative and significant after 13 months: high VIX readings are correlated with expansionary monetary policy in the medium-run future.

The strong interaction between a "fear index" (Whaley (2000)) in the asset markets and monetary policy indicators may have important implications for a number of literatures. First, the recent crisis has rekindled the idea that lax monetary policy can be conducive to financial instability. The Federal Reserve's pattern of providing liquidity to financial markets following market tensions, which became known as the "Greenspan put", has been cited as one of the contributing factors to the build up of a speculative bubble prior to the 2007-09 financial crisis.[1] Whereas some rather informal stories have linked monetary policy to risk-taking in financial markets (Rajan (2006), Adrian and Shin (2008), Borio and Zhu (2008)), it is fair to say that no extant research establishes a firm empirical link between monetary policy and risk aversion in asset markets.[2]

Second, Bloom (2009) and Bloom, Floetotto and Jaimovich (2009) show that heightened "economic uncertainty" decreases employment and output. It is therefore conceivable that the monetary authority responds to uncertainty shocks, in order to affect economic outcomes. However, the VIX index, used by Bloom (2009) to measure uncertainty, can be decomposed into a component that reflects actual expected stock

[1] Investors increasingly believed that when market conditions were to deteriorate, the Fed would step in and inject liquidity until the outlook improved. The perception may have become embedded in asset pricing in the form of higher valuations, narrower credit spreads, and excessive risk-taking. See, for example, "Greenspan Put may be Encouraging Complacency," Financial Times, December 8, 2000.

[2] For recent empirical evidence that monetary policy affects the riskiness of loans granted by banks see, for example, Altunbas, Gambacorta and Marquéz-Ibañez (2009), Ioannidou, Ongena and Peydró (2009), Jiménez, Ongena, Peydró and Saurina (2009), and Maddaloni and Peydró (2009).

market volatility (uncertainty) and a residual, the so-called variance premium (see, for example, Carr and Wu (2009)), that reflects risk aversion and other non-linear pricing effects, perhaps even Knightian uncertainty. Establishing which component drives the strong comovements between the monetary policy stance and the VIX is therefore particularly important.

Third, analyzing the relationship between monetary policy and the VIX and its components may help clarify the relationship between monetary policy and the stock market, explored in a large number of empirical papers (Thorbecke (1997), Rigobon and Sack (2004), Bernanke and Kuttner (2005)). The extant studies all find that expansionary (contractionary) monetary policy affects the stock market positively (negatively). Interestingly, Bernanke and Kuttner (2005) ascribe the bulk of the effect to easier monetary policy lowering risk premiums, reflecting both a reduction in economic and financial volatility and an increase in the capacity of financial investors to bear risk. By using the VIX and its two components, we test the effect of monetary policy on stock market risk, but also provide more precise information on the exact channel.

This article characterizes the dynamic links between risk aversion, economic uncertainty and monetary policy in a simple vector-autoregressive (VAR) system. Such analysis faces a number of difficulties. First, because risk aversion and the stance of monetary policy are jointly endogenous variables and display strong contemporaneous correlation (see Figure 1), a structural interpretation of the dynamic effects requires identifying restrictions. Such structural identification is of considerable interest, as there may be causal relationships in either direction. Monetary policy may indeed affect asset prices through its effect on risk aversion, as suggested by the literature on monetary policy news and the stock market, but monetary policy makers may also react to a nervous and uncertain market place by loosening monetary policy. In the literature on the relationship between the stock market and monetary policy, another paper by Rigobon and Sack (2003) finds that the Federal Reserve does systematically respond to stock prices, for example.[3]

[3] The two papers by Rigobon and Sack (2003, 2004) use an identification scheme based on the heteroskedasticity of stock market returns. Given that we view economic uncertainty as an important endogenous variable in its own right with links to the real economy and risk premiums, we cannot use such an identification scheme.

Second, the relationship between risk aversion and monetary policy may also reflect the joint response to an omitted variable, with business cycle variation being a prime candidate. Recessions may be associated with high risk aversion (see Campbell and Cochrane (1999) for a model generating counter-cyclical risk aversion) and at the same time lead to lax monetary policy. Third, there are a number of measurement problems. Disagreement on how to measure risk aversion in financial markets is rife (see Baker and Wurgler (2007) and Coudert and Gex (2008) for surveys of indicators of investor sentiment in general and risk aversion in particular) and measuring the monetary policy stance is the subject of a large literature (see, for example, Bernanke and Mihov (1998a)). In addition, measuring policy shocks correctly is difficult. Models featuring time-varying risk aversion and/or uncertainty, such as Bekaert, Engstrom and Xing (2009), imply an equilibrium contemporaneous link between interest rates and risk aversion and uncertainty, through precautionary savings effects for example. Such relation should not be associated with a policy shock.

To overcome these difficulties, we strive to characterize the data as fully as possible. In Section II, we start with an analysis of the VIX and a measure of the monetary policy stance (the real interest rate) in a bivariate VAR. We show the dynamic effects of the VIX on monetary policy and vice versa, under various identification schemes. We also show robustness to a number of alternative measurements of the monetary policy stance. In Section III, we expand the VAR to account for the most obvious omitted variable, a business cycle indicator, and also split the VIX into a pure volatility component and a residual, which should be more closely associated with risk aversion. In the final section, we empirically examine various channels through which monetary policy may affect risk aversion and private sector risk-taking behavior, as suggested by recent research. Specifically, we consider the effects through the balance sheet of financial intermediaries (as proxied by repo growth and the growth rates of broad money aggregates) and through the expansion of credit (using the growth of credit and credit-to-GDP ratio).

Our main findings are as follows. A lax monetary policy decreases risk aversion in the medium run, while uncertainty (stock market volatility) appears to be unaffected by monetary policy. On the other hand, periods of high uncertainty are followed by a looser monetary policy stance. These effects are persistent. Moreover, they are robust to controlling for business cycle movements, as well as to using alternative measures of monetary policy. The effect of monetary policy on risk aversion is independent and does not necessarily run through repo or credit growth.

II. The VIX and Monetary Policy

We begin our analysis with a bivariate VAR on a measure of monetary policy and a measure of risk aversion, using monthly data for the United States from January 1990 to July 2007. Table 1 lists the variables, their labels and description. Note that we exclude recent data on the crisis, which presents special challenges.

To measure the monetary policy stance, we use the real interest rate, i.e., the Fed funds end-of-the-month target rate minus the CPI inflation rate. We then consider alternative measures of the monetary policy stance for robustness: Taylor rule deviations, the nominal Fed funds rate, and the growth of the monetary aggregate M1.

To measure risk aversion, we use end-of-month VIX levels. The VIX represents the implied volatility of a hypothetical at-the-money option on the S&P500 index with a horizon of 30 calendar days (22 trading days). Since 2004, this volatility estimate is based on a weighted average of European-style S&P500 options that straddle a 30-day maturity and cover a wide range of strikes (see CBOE (2004) for more details). The VIX is often viewed as a measure of risk aversion in the market place, although it obviously also reflects stock market uncertainty. We decompose the VIX information in Section III.

We collect these two variables in the vector $Z_t = [mp_t, ra_t]'$ where mp_t is a measure of monetary policy stance and risk aversion ra_t is represented by the logarithm of the implied volatility (LVIX). Without loss of generality, we ignore constants. Consider the following structural VAR:

$$A\, Z_t = \Phi\, Z_{t-1} + \varepsilon_t \tag{1}$$

where A is a 2x2 full-rank matrix and $E[\varepsilon_t\, \varepsilon_t'] = I$. Of main interest are the dynamic responses to the structural shocks ε_t.

Of course, we start by estimating the reduced-form VAR. We re-write (1) as follows:

$$Z_t = B\, Z_{t-1} + C\, \varepsilon_t \tag{2}$$

where B denotes $A^{-1}\, \Phi$ and C denotes A^{-1}. Moreover, let us define Σ to be the variance-covariance matrix of the reduced-form residuals, i.e., $\Sigma = E[(C\, \varepsilon_t)\, (C\, \varepsilon_t)'] = C\, C'$.

The first-order VAR in Equations (1) and (2) is useful to illustrate the identification problem: Equation (2) yields 7 coefficients in the matrices B and Σ, but Equation (1) has 8 unknowns. We later use formal selection criteria to select the correct order of the VAR. In general, for a VAR of order k with N variables, we have $(k+1)N^2$ parameters to identify and we can estimate $kN^2 + N(N+1)/2$ parameters. Hence, we need $N(N-1)/2$ restrictions to identify the system.

Reduced-form Evidence

Before we explore structural identification, Table 2 reports some reduced-form VAR statistics. Panel A produces three lag-selection criteria: Akaike (AIC), Hannan-Quinn (HQIC) and Schwarz (SBIC). While the Schwarz and HQIC criteria select relatively parsimonious VARs, the AIC criterion selects a VAR with 14 lags. We focus the remainder of the analysis in this section on the 14 lag VAR, for reasons detailed below. Panel B reports Granger causality tests. We find strong Granger causality in either direction, i.e., the monetary policy stance predicts risk aversion and risk aversion predicts the monetary policy stance.[4]

Finally, Panel C reports some specification tests on the residuals of the VAR. These tests (see Johansen (1995)) test for autocorrelation in the residuals of the VAR at lag j (j=1,2,3). The VAR with 14 lags clearly eliminates all serial correlation in the residuals.

We couch our main results in the form of impulse-response functions (IRFs henceforth), estimated in the usual way. We compute 90% bootstrapped confidence intervals based on 1000 replications, and focus our discussion on significant responses.

Figure 2 shows orthogonalized "reduced-form" IRFs, i.e., the impulse responses generated by the shock of either variable, using a Cholesky decomposition of the estimate of the variance-covariance matrix. We order the real interest rate first and the VIX second to capture the fact that the VIX, a stock market based variable, responds instantly to the monetary policy shocks, while the monetary policy stance is relatively more slow-moving. The response at lag zero represents the off-diagonal element in the Cholesky factor.

[4] In the 14 lag VAR, reporting the feedback coefficients is not very informative. In a first-order VAR, contractionary monetary policy predicts higher risk aversion next period whereas higher risk aversion predicts laxer monetary policy next month. Both coefficients are significant at the 5% level.

A one standard deviation negative shock to the real rate (equivalent to 25.60 basis points), after an initial increase, lowers LVIX by 0.0209 after 15 months. The impact reaches a maximum of 0.0295 after 32 months. The effect remains (borderline) significant up and till lag 52. A one standard deviation positive shock to LVIX (equivalent to 0.1341) leads to an 11.23 basis points decrease in the real interest rate after 23 months. The decrease reaches a maximum level of 17.06 basis points after 41 months.

Hence, apart from a somewhat puzzling significant negative short-run response of the VIX to real interest rates, our evidence reveals that lax monetary policy can indeed lower the VIX (and, if the VIX represents risk aversion, increase risk appetite) in the medium run (after one year), and that monetary policy also reacts to periods of high VIX levels by relaxing monetary policy, with a somewhat longer lag.

Structural Evidence

To obtain structural identification, we generally investigate three types of restrictions: exclusion restrictions on contemporaneous responses (setting coefficients in A to zero), long-run restrictions and exclusion restrictions on the feedback matrix Φ. In the setting of the two-variable VAR, the exclusion restriction that monetary policy does not contemporaneously react to risk aversion ($a_{12} = 0$) is identical to restriction implied by the Cholesky decomposition studied above. Our long-run restriction is inspired by the literature on long-run money neutrality: money should not have a long run effect on real variables. Bernanke and Mihov (1998b) and King and Watson (1992) marshal empirical evidence in favor of money neutrality using data on money (growth) and output (growth).

Following Blanchard and Quah (1989), the model with a long-run restriction (LR) involves a long-run response matrix, denoted by D:

$$D \equiv (I - B)^{-1} C \tag{3}$$

It follows that $D D' = (I - B)^{-1} C C' [(I - B)^{-1}]' = (I - B)^{-1} \Sigma [(I - B)^{-1}]'$. Hence, using the estimates of B and Σ from the reduced-form VAR, we obtain D, and thus $A^{-1} = C$.[5] Our assumption of long-run money neutrality in the two-variable system implies that $d_{21} = 0$:

$$D = \begin{array}{c} mp \\ ra \end{array} \begin{bmatrix} d_{11} & d_{12} \\ 0 & d_{22} \end{bmatrix} \tag{4}$$

[5] To facilitate interpretation of the impulse responses, we adopt a sign normalization requiring that the diagonal elements of A^{-1} be positive.

This restriction is much stronger than the standard view on money neutrality, which holds that permanent monetary policy shocks do no have a long-run effect on (real) output. Therefore, money neutrality involves a restriction, analogous to the restriction embedded in Equation (4), in a VAR on money *growth* and output *growth*. Because the VAR variables are stationary, our framework already implies that monetary policy does not have a long run effect on risk aversion. The restriction in (4) represents "super-neutrality": the total effect of monetary policy on risk aversion is restricted to be zero. In the more elaborate VARs of Section III, such long-run restrictions will be reserved to the relationship between monetary policy and business cycle variables.

Recently, the use of long-run restrictions to identify VARs has come under attack (see, for example, Chari, Kehoe and McGrattan (2008)). However, Christiano, Eichenbaum and Vigfusson (2008) show that many of the problems can be overcome by using long-run information (rather than a parsimonious VAR) to identify the long-run restrictions. Although they advocate using a non-parametrically estimated spectral density matrix, our VAR with 14 lags, the lag-length selected by the Akaike criterion, effectively uses long-run information to identify the restrictions.

As a third type of restriction, we restrict the feedback matrix (the first-order lagged or "short-run" response), imposing that monetary policy does not have a short-run effect on risk aversion or, equivalently, $\phi_{21} = 0$:[6]

$$\Phi = \begin{array}{c} mp \\ ra \end{array} \begin{bmatrix} \phi_{11} & \phi_{12} \\ 0 & \phi_{22} \end{bmatrix} \tag{5}$$

This exogeneity assumption on risk aversion is consistent with external habit models, such as Campbell and Cochrane (1999) and Bekaert, Engstrom and Xing (2009), where the state variable driving risk aversion follows a univariate autoregressive process, but its shocks may be correlated with other state variables.

All three identification schemes satisfy necessary and sufficient conditions for global identification of structural vector autoregressive systems (see Rubio-Ramírez, Waggoner and Zha (2009)).[7]

[6] Whatever the order of the VAR, the feedback restrictions are always imposed on the first-lag matrix.
[7] In this paper, we only consider systems that are globally identified. This consideration will restrict the set of specifications we report in Section III and in the Appendix.

Figure 3 shows the impulses-response functions under the last two structural restrictions. In the model with the long-run restriction, a one standard deviation negative shock to the real rate (equivalent to 16.02 basis points), after an initial increase, lowers LVIX by 0.0141 after 36 months. The maximum impact is a decrease by 0.0221 after 57 months. A one standard deviation positive shock to LVIX (equivalent to 0.0647) first increases the real rate by a maximum of 28.86 basis points after 11 months and then leads to a decrease in the real rate by a maximum of 11.06 basis points after 58 months.

In the model with the short-run restriction, a one standard deviation negative shock to the real rate (equivalent to 26.51 basis points) lowers LVIX by 0.0221 after 16 months. The maximum impact is 0.0312 after 32 months. A one standard deviation positive shock to LVIX (equivalent to 0.1402) leads to a 12.90 basis points decrease in the real rate after 23 months. The maximum impact is 17.58 basis points after 31 months.

Consequently, the effects of monetary policy on risk aversion, uncovered in the reduced-form analysis, are preserved under reasonable structural restrictions. A somewhat puzzling short-lived negative effect of interest rates on risk aversion remains robust as well. In the opposite direction, the real interest rate decreases following a positive shock to risk aversion in the model with the short-run restriction. However, in the model with the long-run restriction, this decrease only becomes significant after more than 50 lags and the initial effect is positive.

Robustness

We first consider the robustness of our results with respect to three alternative measures of monetary policy stance in Table 3. The first measure we consider is Taylor rule residuals, i.e., the difference between the nominal Fed funds rate and the Taylor rule rate (TR rate). The TR rate is estimated as in Taylor (1993):

$$TR_t = Inf_t + NatRate_t + 0.5*(Inf_t - TargInf) + 0.5*OG_t \quad (6)$$

where Inf is the annual inflation rate, NatRate is the "natural" real Fed funds rate (consistent with full employment), which Taylor assumed to be 2%, TargInf is a target inflation rate, also assumed to be 2%, and OG (output gap) is the percentage deviation of real GDP from potential GDP. We assume that the growth of potential GDP is 3% per year. We also consider other measures of the monetary policy stance, namely the nominal

Fed funds rate instead of the real rate, and the growth rate of the monetary aggregate M1, which is commonly assumed to be under tight control of the central bank.

The results confirm that a looser monetary policy stance (lower Fed funds rate interest rate relative to the Taylor rule rate, lower Fed funds rate, or higher M1 growth) leads to lower implied volatility. Specifically, a one standard deviation negative shock to the Taylor rule deviation (equivalent to 8.86 basis points) lowers LVIX by a maximum of 0.0413 (equivalent to 52.68% of its standard deviation) after 46 months in the structural model with the long-run restriction. A one standard deviation negative shock to the Taylor rule deviations (equivalent to 33.59 basis points) lowers LVIX by a maximum of 0.0864 (equivalent to 27.04% of its standard deviation) after 32 months in the structural model with the short-run restriction.

The effects for the Fed funds rate are similar. A one standard deviation negative shock to the Fed funds rate (equivalent to 13.76 basis points) lowers LVIX by a maximum of 0.0121 (equivalent to 9.47% of its standard deviation) after 25 months in the structural model with the long-run restriction. A one standard deviation negative shock to the Fed funds rate (equivalent to 16.41 basis points) lowers LVIX by a maximum of 0.0215 (equivalent to 14.25% of its standard deviation) after 20 months in the structural model with the short-run restriction.

A one standard deviation positive shock to the M1 growth (equivalent to 0.4489 percentage points) lowers LVIX by a maximum of 0.0103 (equivalent to 9.56% of its standard deviation) after 23 months in the structural model with the long-run restriction. A one standard deviation positive shock to the M1 growth (equivalent to 0.0661 percentage points) lowers LVIX by a maximum of 0.0266 (equivalent to 153.76% of its standard deviation) after 16 months in the structural model with the short-run restriction. So, we find a robust causal reaction of the VIX to all four monetary policy measures.

The negative (medium-term) effect risk aversion has on the monetary policy stance is mostly preserved when imposing the Cholesky factorization or the short-run restriction, but it does not appear in the model with the long-run restriction when alternative measures of the monetary policy stance are used. The response of monetary policy to implied volatility may just reflect a reaction of both variables to economic conditions, a hypothesis we formally check in Section III.

Next, we consider the robustness of our results to the lag-length specification in the VAR. The 14-lag VAR may be over-parameterized; consequently, we reduce the lag length to 9 lags. By reducing the lag length to 9 lags, we obtain a saturation ratio of slightly over 10. The saturation ratio is the total number of observations divided by total number of parameters estimated. Second, we estimate a VAR with 1 lag, as selected by the Schwarz criterion (SBIC). In both instances, our results (not reported) are similar to the results reported in Table 3.

III. Risk, Uncertainty and Monetary Policy

In this section, we analyze a four-variable VAR. First, we add a business cycle indicator. It is conceivable that the intriguing links between the VIX and monetary policy simply reflect monetary policy and implied volatility jointly reacting to business cycle conditions. For example, news indicating weaker than expected growth in the economy may make a cut in the Fed funds target rate more likely, but at the same time cause people to be effectively more risk averse, for example because a larger number of households feel more constrained in their consumption relative to "habit," or because people fear a more uncertain future. To analyze business cycle effects, we use the log of jobless claims as a recession indicator, bc_t.

Second, we split the VIX into a measure of stock market or economic uncertainty, uc_t, and a residual that should be more closely associated with risk aversion, ra_t. While we used the VIX index as a measure of risk aversion, it is also an index of stock market volatility (economic uncertainty). The recent finance literature emphasizes its two different components, true economic uncertainty (the physical conditional variance of the stock market) and the remainder, which is called the variance premium (see, e.g., Carr and Wu (2009)) and usually computed as the difference between the squared VIX and an estimate of the conditional variance.[8] Recent finance models attribute this difference either to non-Gaussian components in fundamentals and (stochastic) risk aversion (see, for instance, Bekaert and Engstrom (2009), Bollerslev, Tauchen and Zhou (2009), Drechsler and Yaron (2009)) or Knightian uncertainty (see Drechsler (2009)). The fact

[8] In the technical finance literature, the variance premium is actually the negative of the construct that we use. However, increased risk aversion makes the variance premium more negative, and we want our variable to act as a risk aversion indicator.

that the variance premium is nearly always positive suggests that these non-linear features of the data are important. In the context of an external habit model, Bekaert, Engstrom and Xing (2009) recently show how "risk aversion" and "economic uncertainty" may have different effects on asset prices. These differences may be important to acknowledge in monetary policy transmission.

To decompose the VIX index into its two components, we borrow a measure of the conditional variance of stock returns from Bekaert and Engstrom (2009), who project monthly realized variances (computed using squared 5-minute returns) on a set of instruments. We call the logarithm of this variance estimate "uncertainty" (uc_t). The logarithm of the difference between the squared VIX and this conditional variance is our improved risk aversion measure (ra_t), although it may also capture Knightian uncertainty and other nonlinearities. Appendix 1 sets out a one-period discrete state economy to provide intuition on the relationship between volatility, the VIX and risk aversion. It shows how the variance premium monotonically increases in the level of risk aversion.

Consequently, we now analyze a four-variable system with $Z_t = [mp_t, bc_t, uc_t, ra_t]'$. This may provide important inputs to a rapidly growing macroeconomic literature on news-driven business cycles. Beaudry and Portier (2006), for example, present empirical evidence suggesting that business cycle fluctuations may be driven to a large extent by changes in stock market expectations, which anticipate total factor productivity movements. Bloom (2009) also shows that "economic uncertainty" has real effects, in particular it generates a sharp drop in employment and output, which rebounds in the medium term, and a mild long-run overshoot. He explains these facts in the context of a production model where uncertainty increases the region of inaction in hiring and investment decisions of firms facing non-convex adjustment costs. In his empirical work, Bloom uses the VIX index to create an index of "exogenous" volatility shocks. However, as the VIX reflects both uncertainty and risk aversion, it is conceivable that it is the risk aversion component of the VIX index that generates the real effects, not the economic uncertainty component. Moreover, these shocks may be simply correlated with business cycles, as predicted by external habit models, for example.[9] In a recent Economist article,

[9] To be fair, Bloom (2009) attempts to identify exogenous shocks to the VIX, which are less likely to be of a cyclical nature.

Blanchard (2009) describes the VIX index as an indicator of Knightian uncertainty, arguing that such uncertainty may prolong the current crisis. In both cases, the implication is that monetary policy may want to respond strongly to uncertainty shocks, in Bloom's case to economic uncertainty shocks, in Blanchard's case to what we call risk aversion shocks.

Reduced-form Evidence

Table 4 reports some basic VAR statistics. The selection criteria, reported in Panel A, now select much shorter VAR orders, with the Akaike criterion only selecting a third-order VAR. When we estimate that VAR, there is some evidence of remaining serial correlation at the second lag (see Panel C). Panel B reports Granger causality tests for the three-lag VAR. We continue to find strong overall Granger causality in the risk aversion and real interest rate equations. However, while for risk aversion the strong predictive power appears to be still driven by monetary policy, risk aversion no longer significantly predicts the real rate. Uncertainty and jobless claims do predict the monetary policy stance. Granger causality is not significantly present in either the jobless rate equation or the uncertainty equation. While the p-values for the various variables and the overall p-values are relatively low in the jobless equation (with risk aversion predicting or anticipating jobless rates significantly at the 5% level), uncertainty is really only related to past uncertainty.

Figure 4 reports the orthogonalized reduced-form impulse responses for the four-variable VAR. Motivated by the Granger causality results, we use a Cholesky ordering with uncertainty ordered first, jobless claims second, followed by the real interest rate and risk aversion.[10] Ordering jobless claims second is consistent with the exclusion restrictions used in Christiano, Eichenbaum and Evans (2005), where the business cycle variables also respond sluggishly to interest rates. A one standard deviation negative shock to the real rate (equivalent to 31.30 basis points) lowers risk aversion by 0.0441 after 3 months. The impact reaches a maximum of 0.0686 after 11 months and remains significant up and till lag 33. A one standard deviation negative shock to the real rate has

[10] We have also experimented with alternative orderings, in particular ordering jobless claims first, followed by uncertainty, real interest rate and risk aversion, and the results are similar.

no statistically significant impact on uncertainty. It immediately raises jobless claims (an increase of 0.0063). The effect becomes statistically insignificant thereafter.

A one standard deviation positive shock to risk aversion (equivalent to 0.2827) immediately increases jobless claims (an increase of 0.0068), an effect that remains significant up and till lag 25. It has no statistically significant impact on the real rate or uncertainty.

As for the impact of uncertainty shocks, a one standard deviation positive shock to uncertainty (equivalent to 0.5728) lowers the real rate immediately (by 7.49 basis points). The maximum impact of 14.71 basis points occurs after 5 months, and the impact remains significant up and till lag 15. A one standard deviation positive shock to uncertainty increases risk aversion significantly in the short-run with a maximum impact of 0.1507 in the initial period. It has no statistically significant impact on jobless claims.

A one standard deviation positive shock to jobless claims (equivalent to 0.0557) lowers the real rate immediately (by 6.07 basis points). The impact reaches a maximum of 20.47 basis points after 13 months, and remains significant up and till lag 31. A one standard deviation positive shock to jobless claims lowers risk aversion in the medium term (between lags 10 and 41) with the maximum impact of 0.0654 at lag 24. It has no statistically significant impact on uncertainty.

Reduced-form impulse responses indicate that the real interest rate responds primarily to uncertainty shocks, rather than risk aversion shocks. On the other hand, real rate shocks have a persistent effect on risk aversion while they do not affect uncertainty.

Structural Evidence

To identify a four-variable system, we need 6 restrictions on the VAR. Our strategy is to verify a number of alternative identification schemes, and see whether the structural results are robust.

One set of restrictions combines five contemporaneous restrictions (also imposed under the Cholesky ordering above) with the assumption that the effects of monetary policy on the business cycle cancel out over time, i.e., a form of long-run money neutrality.[11] That is, we replace the contemporaneous exclusion restriction regarding the

[11] Because we view jobless claims as a stationary variable, this assumption is different and stronger than standard applications of long-run money neutrality. For robustness, we use the log-difference of industrial

effect of monetary policy on the business cycle by the analogous long-run restriction. Consequently, the restrictions correspond to the following contemporaneous matrix A and long-run matrix D:

$$\mathrm{A} = \begin{array}{c} ra \\ mp \\ bc \\ uc \end{array} \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ 0 & a_{22} & a_{23} & a_{24} \\ 0 & a_{32} & a_{33} & a_{34} \\ 0 & 0 & 0 & a_{44} \end{bmatrix} \tag{7}$$

$$\mathrm{D} = \begin{array}{c} ra \\ mp \\ bc \\ uc \end{array} \begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} \\ d_{21} & d_{22} & d_{23} & d_{24} \\ d_{31} & 0 & d_{33} & d_{34} \\ d_{41} & d_{42} & d_{43} & d_{44} \end{bmatrix} \tag{8}$$

This system satisfies necessary and sufficient conditions for global identification of structural vector autoregressive systems (see Rubio-Ramírez et al. (2009)).

An alternative identification scheme combines two long-run money neutrality restrictions with four restrictions on the first-order lagged response (short-run restrictions) as follows:

$$\Phi = \begin{array}{c} mp \\ bc \\ ra \\ uc \end{array} \begin{bmatrix} \phi_{11} & \phi_{12} & \phi_{13} & \phi_{14} \\ \phi_{21} & \phi_{22} & \phi_{23} & \phi_{24} \\ \phi_{31} & 0 & \phi_{33} & \phi_{34} \\ 0 & 0 & 0 & \phi_{44} \end{bmatrix} \tag{9}$$

$$\mathrm{D} = \begin{array}{c} mp \\ bc \\ ra \\ uc \end{array} \begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} \\ 0 & d_{22} & d_{23} & d_{24} \\ d_{31} & d_{32} & d_{33} & d_{34} \\ 0 & d_{42} & d_{43} & d_{44} \end{bmatrix} \tag{10}$$

We assume that uncertainty is not affected by the other variables in the short-run and that the business cycle does not have a short-run effect on risk aversion. This choice is motivated by the Granger causality results as well as the cross-correlations between variables, suggesting both risk aversion and uncertainty are relatively "exogenous" variables with respect to the business cycle. Of course, a number of theories (Sharpe

production and the log-difference of hours worked as alternative business cycle variables, in which case the restriction indeed implies that monetary policy has no long-run effect on the level of industrial output and hours worked (see p. 17).

(1990), Campbell and Cochrane (1999)) suggest that risk aversion moves counter-cyclically. While such dynamics can still be accommodated in the VAR through contemporaneous responses and links in the higher order feedback matrices, we relax the risk aversion – business cycle feedback restriction in a number of alternative identification schemes in the Appendix. We keep the long-run restriction for the effects of monetary policy on the business cycle and additionally impose that the effects of monetary policy on uncertainty sum to zero. This implies that whatever short-run effect monetary policy may have on uncertainty, it must eventually be reversed and the total effect must be zero. In the Appendix, we consider an analogous "neutrality" assumption for risk aversion. The system in Equations (9) and (10) also satisfies necessary and sufficient conditions for global identification

We report the resulting structural impulse-response functions in Figure 5. In a model with contemporaneous/long-run restrictions, a one standard deviation negative shock to the real rate (equivalent to 32.51 basis points) lowers risk aversion by 0.0413 after 3 months. The impact reaches a maximum of 0.0654 after 11 months and remains significant up and till lag 36. In a model with short/long-run restrictions, a one standard deviation negative shock to the real rate (equivalent to 9.08 basis points) lowers risk aversion by 0.0491 after 6 months. The impact reaches a maximum of 0.0574 after 13 months and remains significant up and till lag 35. So, the effect of monetary policy on risk aversion is consistent with the reduced-form results under both identification schemes. The impact of a one standard deviation positive shock to risk aversion (equivalent to 0.2889 in the model with contemporaneous/long-run restrictions and to 0.0366 in the model with short/long-run restrictions) on the real rate is mostly negative but not statistically significant.

The impact of real rate shocks on uncertainty is not statistically significant. In the other direction, in the model with contemporaneous/long-run restrictions, the real rate decreases by 7.54 basis points in period 0 following a positive one standard deviation shock to uncertainty (equivalent to 0.5856). The impact reaches a maximum of 14.18 basis points in period 5 and remains significant up and till period 16. In the model with short/long-run restrictions, the real rate decreases by 6.50 basis points in period 0 following a positive one standard deviation shock to uncertainty (equivalent to 0.5826).

The impact reaches a maximum of 10.91 basis points in period 5, and remains significant up and till period 6. Hence, we find a structural effect of uncertainty on the subsequent monetary policy stance in the expected direction under both identification schemes.

As for interactions with the business cycle variable (Panels E - J), monetary policy has no statistically significant effect on jobless claims. A one standard deviation positive shock to jobless claims (equivalent to 0.0566 in the model with contemporaneous/long-run restrictions and to 0.0455 in the model with short/long-run restrictions) lowers the real rate in the medium-term. Specifically, the real rate decreases by a maximum of 14.07 basis points after 19 months, with the impact remaining significant up and till lag 30. In a model with short/long-run restrictions, the real rate decreases by 14.97 basis points after 12 months. The impact reaches a maximum of 15.51 basis points in period 15 and remains significant up and till period 39. Hence, monetary policy reacts as expected to business cycle fluctuations. Higher risk aversion increases jobless claims in the short to medium run, but the effect is only statistically significant in the model with contemporaneous/long-run restrictions (Panel G). In the other direction, higher jobless claims increase risk aversion in the short-run but the effect is not statistically significant. Such effect is consistent with habit-based theories of countercyclical risk aversion as in Campbell and Cochrane (1999). There is no statistically significant interaction between jobless claims and uncertainty in either direction. These results potentially shed new light on the analysis in Bloom (2009), who found that uncertainty shocks generate significant business cycle effects, using the VIX as a measure of uncertainty. Our results suggest that the link between the VIX and the business cycle may well be driven by the risk aversion rather than the uncertainty component of the VIX.[12]

Finally, increases in uncertainty predict future increases in risk aversion under both identification schemes, which is consistent with the results from the reduced-form impulse responses (Panel L). Risk aversion has no significant effect on uncertainty (Panel K).

[12] Popescu and Smets (2009) analyze the business cycle behavior of measures of perceived uncertainty and financial risk premia in Germany. They also find that positive financial risk aversion shocks have a large and persistent negative impact on the economy and are more important in driving business cycles than uncertainty shocks.

Robustness

Our results are largely robust to the specific identification scheme used. In Appendix A, we report other identification schemes that we tried and we summarize the main results. We restrict attention to cases that are globally identified. In all cases, we find that monetary policy has a persistent positive effect on risk aversion, with the effect concentrated around 14 to 35 months. The negative effect of uncertainty on the real interest rate is always present but not always statistically significant under alternative schemes. The effect of risk aversion on real interest rates is not robust across specifications. The effect is also negative (and insignificant) in one alternative scheme, but positive and significant in five other schemes. The latter schemes impose long run money neutrality for risk aversion (see Table 8). That is, they force the total effect of monetary policy on risk aversion to sum to zero, which is perhaps too strong an assumption. Finally, we consistently find that uncertainty does not respond to monetary policy shocks.

We also check robustness to lag-length. A VAR with 4 lags eliminates all serial correlation in the residuals and still has a saturation ratio of 10 (see Section II, p. 10 for a discussion of the saturation ratio). The results are unaltered. To check for robustness with respect to our business cycle measure, jobless claims, we estimate the model using the unemployment rate, the log-difference of hours worked and the log-difference of industrial production as alternative business cycle variables. When using hours worked or industrial production, the long-run money neutrality assumption has the standard interpretation of monetary policy having no long-run effect on the business cycle variable, measured in levels. The estimates again are consistent with our previous findings.

We conclude that a lax monetary policy decreases risk aversion significantly, with the effect being significant in the medium run, while the real interest rate tends to decrease in response to high uncertainty. The latter effect's statistical significance is less robust. So, our previous results extend to the four-variable set-up, i.e., even controlling for business cycle movements and extracting the risk aversion component out of the VIX. Uncertainty (stock market volatility) appears to be unaffected by the other factors.

IV. Channels

We have unearthed some intriguing interactions between the component in the VIX index not related to actual stock market volatility, and the stance of monetary policy. If monetary policy indeed affects risk aversion, our results could be important in the current debate about the origins of the 2007-2009 crisis. While pinpointing in detail how monetary policy affects risk aversion is beyond the scope of the article, we use this section to empirically analyze some potential channels, discussed in a number of recent articles.

Adrian and Shin (2008) suggest that the link between monetary policy and asset prices runs through the balance sheets of financial intermediaries and that repo growth rates adequately proxy for the riskiness of balance sheets. Using US data, they find that the growth of outstanding repos forecasts the difference between implied and realized volatility and that rapid growth in repos is associated with loose monetary policy (defined as the Fed funds rate).

To examine the Adrian-Shin channel in our structural framework, we use a four-variable VAR as in the previous section but with repo growth replacing the "business cycle" variable. First, we examine whether introduction of this variable eliminates the effect of the real interest rate on risk aversion we uncovered in the previous section. Table 6 summarizes the results. Lax monetary policy is still associated with lower risk aversion after 3 to 5 months (depending on the specification used). This effect is persistent. In the opposite direction, the responses are not statistically significant. In Table 7, we investigate the interaction between the real rate and uncertainty, finding the results to be very similar to those obtained in the previous section: the real rate decreases following a positive shock to uncertainty.

Second, we analyze the direct link between repo growth and risk aversion. While higher repo growth has a negative effect on risk aversion under both structural specifications, the effect is not statistically significant. Hence, our VAR suggests that the monetary policy – risk aversion link does not only run through repo growth.

Many commentators have noted a rather large build up of liquidity through money growth prior to financial crises (see also Adalid and Detken (2007), Alessi and Detken (2009)). We thus use the growth rates of a broad money aggregate as a "channel" variable, replacing the business cycle variable in the four-variable VAR. In particular, we consider the growth rate of M2 net of M1. This part of the money growth is arguably less under control of a central bank and rather reflects activities of the financial sector. It may also reflect savings behavior of individuals, who might flee into safe assets during crisis times.

Using this set-up, we confirm our finding that lower real rates lead to lower risk aversion in all specifications considered (see Table 6). We also confirm that positive uncertainty shocks lower the real rate (Table 7). As for the impact of money growth on risk aversion, we find that higher growth rate of (M2 - M1) has a positive impact on risk aversion. This effect is significant between lags 5 and 23 in the model with contemporaneous/long-run restrictions and at lag 4 in the model with short/long-run restrictions. Estimating the same system with M1 growth replacing (M2 - M1) growth reveals that higher M1 growth lowers risk aversion significantly between lags 7 and 38 in the model with contemporaneous/long-run restrictions and between lags 10 to 39 in the model with short/long-run restrictions. The interactions of risk aversion and uncertainty with the real rate remain unchanged. In sum, once a broader monetary aggregate is cleansed of M1 growth, the relation with risk aversion turns positive. This result is surprising as we would expect high liquidity to be associated with low risk aversion. It is of course conceivable that the finding is related to flights-to-safety effects in the sense that risk-averse investors may flee to relatively safe assets that are incorporated in the M2 measure (e.g., money market and time deposits). However, if this is true, we should find a structural link from risk aversion to M2-M1 and not vice versa.

According to Borio and Lowe (2002), medium-term swings in asset prices are associated with a rapid credit expansion, Moreover, they stress that such financial imbalances may build up in a low inflation environment and that in some cases it is appropriate for monetary policy to respond to these imbalances. Consequently, they suggest a link between credit growth and monetary policy. It is conceivable that periods of high risk appetite coincide with periods of rapid credit expansion, suggesting a channel for the effect of monetary policy on risk aversion.

To investigate the role of credit, we consider two separate four-variable VAR systems, with (private) credit growth and the first-difference of the credit-to-GDP ratio replacing the “business cycle” variable. The significant impact of monetary policy on risk aversion is present again (see Table 6). Higher uncertainty decreases the real rate in all specifications, with the effect being statistically insignificant for the credit-to-GDP ratio in the model with short/long-run restrictions (see Table 7). We do not find statistically significant effects of credit developments on risk aversion in the stock market.

While our results are robust to three different identification schemes, two of them rely on a long-run money neutrality assumption that is less palatable for our channel variables than it is for the business cycle variable, to which it was applied in the previous section. We therefore examine one more alternative identification scheme, switching the channel and uncertainty variables in the Cholesky ordering we use for the first identification scheme. Again, the results are robust. In sum, considering channels through which monetary policy may affect risk aversion does not eliminate the direct effect of the real interest rate on risk appetite. Moreover, higher M1 growth has an independent, persistently negative impact on risk aversion.

V. Conclusions

A number of recent studies point at a potential link between loose monetary policy and excessive risk-taking in financial markets. Rajan (2006) conjectures that in times of ample liquidity supplied by the central bank, investment managers have a tendency to engage in risky, correlated investments. To earn excess returns in a low interest rate environment, their investment strategies may entail risky, tail-risk sensitive and illiquid securities (“search for yield”). Moreover, a tendency for herding behaviour emerges due to the particular structure of managerial compensation contracts. Managers are evaluated vis-à-vis their peers and by pursuing strategies similar to others, they can ensure that they do not under perform. This “behavioral” channel of monetary policy transmission can lead to the formation of asset prices bubbles and can threaten financial stability. Given the dramatic crisis witnessed in 2007-2009, Rajan’s story sounds prophetic. Yet, there is no empirical evidence on the links between risk aversion in financial markets and monetary policy.

This article has attempted to provide a first characterization of the dynamic links between risk, uncertainty and monetary policy, using a simple vector-autoregressive framework. We find a robust structural interaction between implied volatility and monetary policy. We decompose implied volatility into two components, risk aversion and uncertainty, and find interactions between each of the components and monetary policy to be rather different. Lax monetary policy increases risk appetite (decreases risk aversion) in the future, with the effect lasting for more than two years and starting to be significant after about six months. Uncertainty appears to be exogenous and does not respond to monetary policy. On the other hand, high uncertainty leads to laxer monetary policy in the future, with the effect lasting for over a year. These results are robust to controlling for business cycle movements. Consequently, our VAR analysis provides a clean interpretation of the stylized facts regarding the dynamic relations between the VIX and the monetary policy stance depicted in Figure 1. The primary component driving the co-movement between past monetary policy stance and current VIX levels (first column of Figure 1) is risk aversion. The uncertainty component of the VIX lies behind the negative relation in the opposite direction (second column of Figure 1).

We hope that our analysis will inspire further empirical work and research on the exact theoretical links between monetary policy and risk-taking behavior in asset markets. In particular, recent work in the consumption-based asset pricing literature attempts to understand the structural sources of the VIX dynamics (see Bekaert and Engstrom (2009), Bollerslev, Tauchen and Zhou (2008), Drechsler and Yaron (2009)). Yet, none of these models incorporates monetary policy equations. In macroeconomics, a number of articles have embedded term structure dynamics into the standard New-Keynesian workhorse model (Bekaert, Cho, Moreno (2010), Rudebusch and Wu (2008)), but no models accommodate the dynamic interactions between monetary policy, risk aversion and uncertainty, uncovered in this article. The effects missed are economically important. In Figure 6, we show structural variance decompositions calculated from the four-variable VAR for risk aversion and for monetary policy. Monetary policy shocks account for approximately 25-30% of the variance of risk aversion (depending on the identification scheme used) at horizons longer than 25 months. Stock market volatility, our proxy for economic uncertainty, accounts for 10-18% of the variance of our monetary policy variable, and is at least as important as business cycle variation at short horizons.

The policy implications of our work are also potentially very important. Fed chairman Bernanke (see Bernanke (2002)) interprets his work on the effect of monetary policy on the stock market (Bernanke and Kuttner (2005)) as suggesting that monetary policy would not have a sufficiently strong effect on asset markets to pop a “bubble” (see also Bernanke and Gertler (2001), Gilchrist and Leahy (2002), and Greenspan (2002)). However, if monetary policy significantly affects risk appetite in asset markets, this conclusion may not hold. If one channel is that lax monetary policy induces excess leverage as in Adrian and Shin (2008), perhaps monetary policy is potent enough to weed out financial excess. Conversely, in times of crisis and heightened risk aversion, monetary policy can influence risk aversion in the market place, and therefore affect real outcomes. Blanchard (2009) noted that the economy and financial markets had “nothing to fear but fear itself”, suggesting a role for policy to reduce these fears. His conclusion that markets were “fearful” was exactly inspired by unusually elevated VIX levels.

One disadvantage of our framework is that it does not really test the Rajan (2006) and related stories. Current stories about the potential pernicious effects of lax monetary policy give a prominent role to the length of the policy, and are explicitly asymmetric (they are about policy being too lax, not too contractionary). Such features are really not present in our linear VAR framework. We conduct one preliminary and informal test, investigating whether the duration of a lax policy regime would play a role in the dynamic interactions we observe. To that end, we construct a “duration-adjusted monetary policy” (DUMP for short) variable which takes on the value of $\log(1+d_t+d_t^2)*TRdev_t$, where d_t is the number of periods for which the deviation from the Taylor rule, TRdev, is negative. If the deviation is positive, DUMP is given by the $TRdev_t$ itself. This variable thus puts more weight on those periods in which monetary policy was loose for a prolonged period of time. We estimate the four-variable system composed of DUMP, jobless claims, uncertainty and risk aversion. We find that, in a model with contemporaneous/long-run restrictions, a one standard deviation negative shock to DUMP lowers risk aversion by 0.0497 after 3 months. The impact reaches a maximum of 0.0711 after 9 months. In a model with short/long-run restrictions, a one standard deviation negative shock to duration lowers risk aversion by a maximum of 0.0677 after 3 months.

In sum, monetary policy that is “too low for too long” decreases risk aversion in the stock market. The impact is somewhat stronger and more immediate than the one we found using unadjusted indicators of monetary policy stance. While suggestive, we plan to investigate potential asymmetric and duration effects more formally in an explicitly non-linear framework in the near future.

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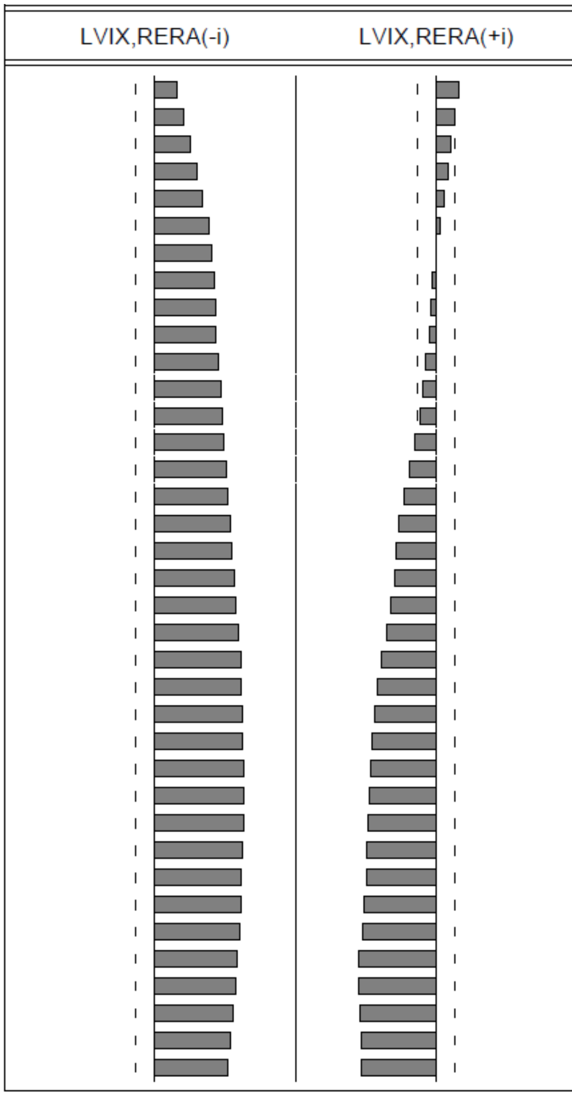
Table 1: Description of variables

Name	Label	Description
Credit growth	CG	Month-on-month growth of business loans
Credit-to-GDP ratio	CGDP	Ratio of credit to GDP (intrapolated)
Fed funds rate	FED	Fed funds target rate
Hours worked	HW	Average weekly hours (private industries)
Implied volatility S&P500	LVIX	Log of (VIX / $\sqrt{12}$)
Industrial production	IP	Industrial production index
Jobless claims	LJOB	Log of jobless claims
M1 money aggregate growth	M1	Month-on-month growth of M1
M2 net of M1 money growth	M2-M1	Month-on-month growth of (M2-M1)
Real interest rate	RERA	FED minus annual CPI inflation rate
Repo growth	GREPO	Monthly growth in repos outstanding
Risk aversion	RA	Log of (squared VIX / 12 minus exp(UC))
Taylor Rule deviations	TRULE	FED minus TaylorRuleRate (see p.7)
Uncertainty (conditional variance)	UC	Log of (conditional variance / 12)
Unemployment rate	URATE	Unempl. rate minus 3-year moving average

Notes: Monthly frequency, end-of-the-moth data (seasonally adjusted where applicable). Source: Thomson Datastream; data on risk aversion and uncertainty are from Bekaert and Engstrom (2009).

Figure 1: Cross-correlogram LVIX RERA



i	lag	lead
0	0.1716	0.1716
1	0.2169	0.1391
2	0.2651	0.1119
3	0.3119	0.0846
4	0.3547	0.0586
5	0.3988	0.0300
6	0.4225	-0.0039
7	0.4401	-0.0283
8	0.4473	-0.0350
9	0.4560	-0.0513
10	0.4684	-0.0759
11	0.4912	-0.0935
12	0.5057	-0.1193
13	0.5150	-0.1628
14	0.5314	-0.2032
15	0.5485	-0.2321
16	0.5634	-0.2719
17	0.5731	-0.2947
18	0.5846	-0.3107
19	0.5979	-0.3344
20	0.6151	-0.3614
21	0.6329	-0.3979
22	0.6438	-0.4308
23	0.6491	-0.4544
24	0.6515	-0.4686
25	0.6598	-0.4800
26	0.6604	-0.4876
27	0.6568	-0.5018
28	0.6524	-0.5128
29	0.6474	-0.5163
30	0.6381	-0.5254
31	0.6251	-0.5465
32	0.6123	-0.5663
33	0.5960	-0.5718
34	0.5761	-0.5616
35	0.5586	-0.5513
36	0.5454	-0.5536

Notes: The first column presents the (lagged) cross-correlogram between the log of the VIX (LVIX) and past values of the real interest rate (RERA). The second column presents the (lead) cross-correlogram between LVIX and future values of RERA. Dashed vertical lines indicate 95% confidence intervals for the cross-correlation. The third column presents the cross-correlation values. The index i indicates the number of months either lagged or led for the real interest rate variable.

Table 2: Bivariate VAR results (RERA, LVIX)

Panel A: Lag-length selection

lag	AIC	HQIC	SBIC
1	-0.1170	-0.0899	-0.0501*
2	-0.1383	-0.0841	-0.0045
3	-0.2496	-0.1683*	-0.0488
4	-0.2686	-0.1603	-0.0010
5	-0.2776	-0.1421	0.0570
6	-0.2691	-0.1066	0.1323
7	-0.2525	-0.0629	0.2158
8	-0.2318	-0.0151	0.3034
9	-0.2469	-0.0031	0.3552
10	-0.2298	0.0411	0.4392
11	-0.2534	0.0445	0.4825
12	-0.2453	0.0797	0.5575
13	-0.4196	-0.0675	0.4501
14	-0.5056*	-0.1265	0.4310
15	-0.4717	-0.0655	0.5318

Panel B: Granger causality

Equation	Excluded	chi2	df	p-value
LVIX	RERA	28.7290	14	0.0110
RERA	LVIX	48.2480	14	0.0000

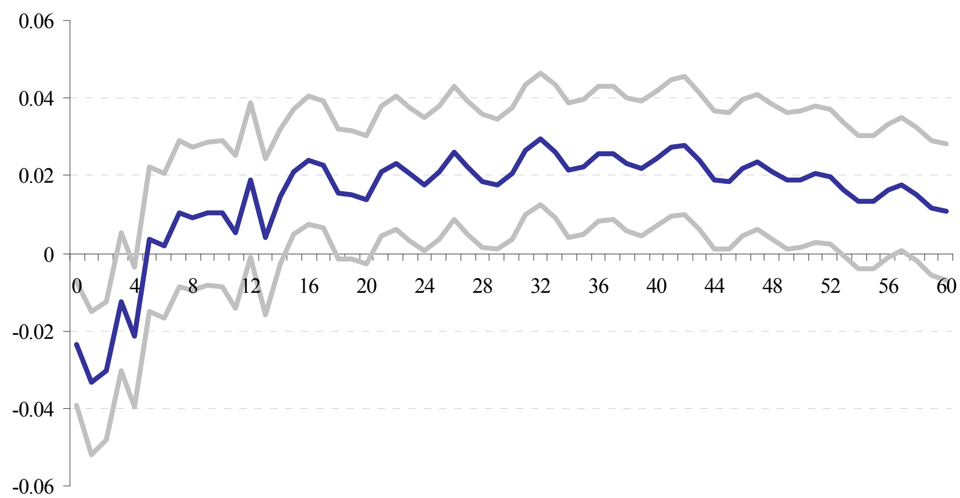
Panel C: Lagrange-multiplier test

lag	chi2	df	p-value
1	1.5554	4	0.8168
2	3.0961	4	0.5419
3	5.4070	4	0.2480

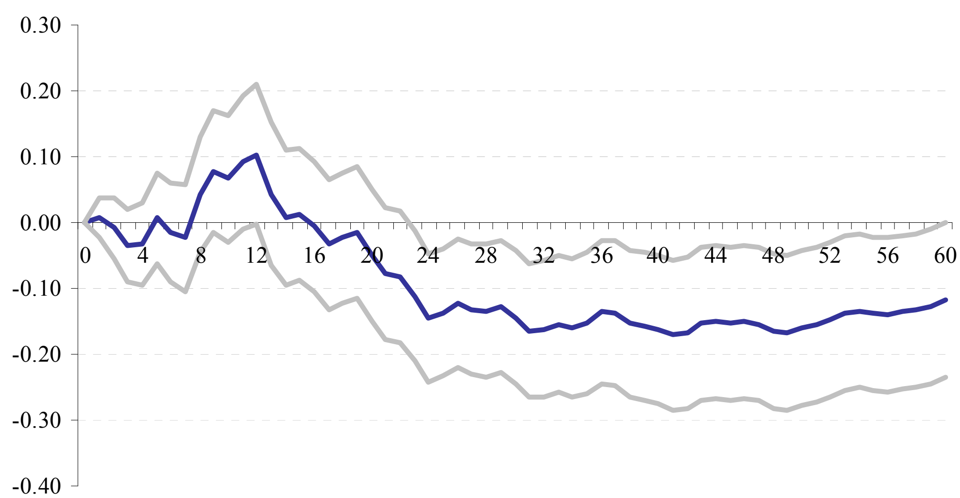
Notes: Bivariate VAR on the log of VIX (LVIX) and the real interest rate (RERA). Panel A presents lag-length selection results based on three criteria: Akaike (AIC), Hannan-Quinn (HQIC) and Schwarz (SBIC). The star indicates the lag chosen. Panel B presents Granger causality results for the model with 14 lags (selected by Akaike). Panel C presents Lagrange-multiplier specification tests for the model with 14 lags (selected by Akaike). The null hypothesis is that there is no autocorrelation at lag order j=1,2,3 and the degrees of freedom are given by the square of the number of equations in the VAR, as the test examines the null hypothesis that the residuals of lag j are not jointly significant in the VAR.

Figure 2: Orthogonalized reduced-form IRFs (RERA, LVIX)

Panel A: Impulse RERA, response LVIX



Panel B: Impulse LVIX, response RERA

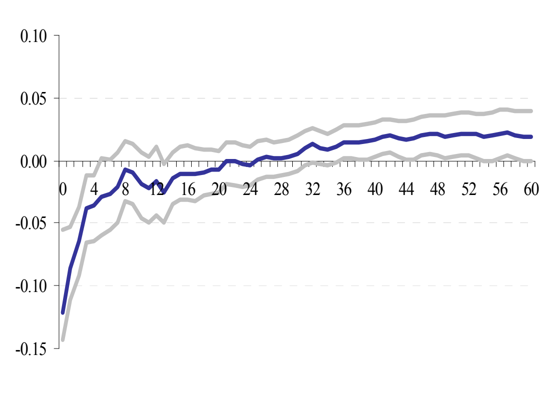


Notes: Medians (blue lines) and 90% confidence intervals (grey lines) of the estimated orthogonalized IRFs for the model with 14 lags (selected by Akaike). Order of variables in the VAR is RERA LVIX. Panel A presents the response of LVIX to a one standard deviation shock to RERA. Panel B presents the response of RERA to a one standard deviation shock to LVIX.

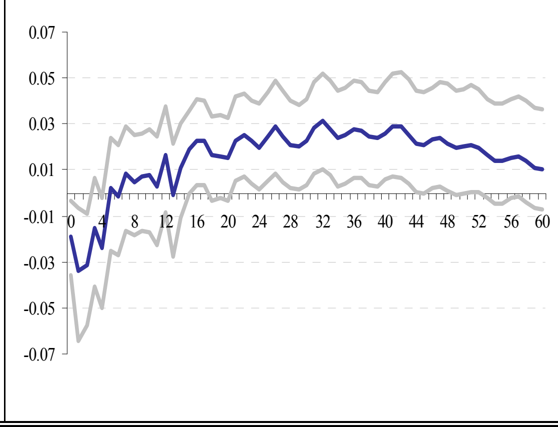
Figure 3: Structural-form IRFs (RERA, LVIX)

Panel A: Impulse RERA, response LVIX

Long-run restriction

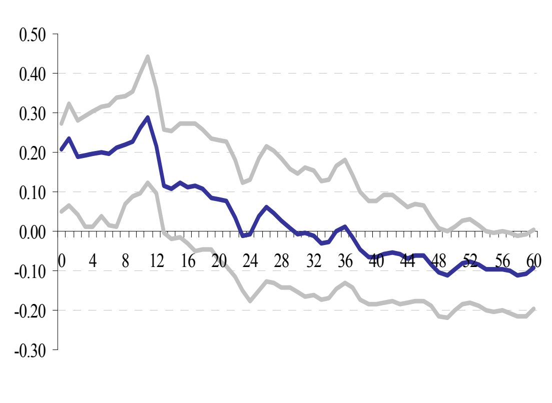


Short-run restriction

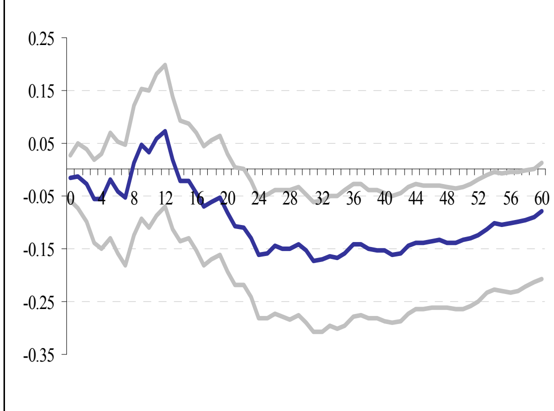


Panel B: Impulse LVIX, response RERA

Long-run restriction



Short-run restriction



Notes: Medians (blue lines) and 90% bootstrapped confidence intervals (grey lines) of the distribution of the estimated structural impulse-response functions for the model with 14 lags (selected by Akaike), based on 1000 replications. Panel A presents the response of LVIX to a one standard deviation shock to RERA. Panel B presents the response of RERA to a one standard deviation shock to LVIX. Panels on the left present results of the model with the long-run restriction, panels on the right present results of the model with the short-run restriction.

Table 3: Robustness to monetary policy measures

MP instrument	Impulse MP, response LVIX		Impulse LVIX, response MP	
	sign	significant from-to (month)	sign	significant from-to (month)
Real interest rate				
- reduced-form	+	15 – 17, 21 – 52, 57	–	23 - 59
- structural LR	+	36 – 53, 55 - 58	–	55 - 59
- structural SR	+	16-17, 21-44, 46-48, 51-52	–	23 - 58
Taylor rule				
- reduced-form	+	7 - 10, 12, 14 - 43	–	23 - 25, 31, 40 - 52
- structural LR	+	31 – 58, 60	–	--
- structural SR	+	12, 14 – 53	–	22 - 25, 31 - 34, 38 - 59
Fed funds Rate				
- reduced-form	+	18 - 29	–	2 - 18
- structural LR	+	24 – 25, 27	–	--
- structural SR	+	17 - 34	–	4 - 15
M1 growth				
- reduced-form	–	6 - 30	+	--
- structural LR	–	17 - 40	+	--
- structural SR	–	16 – 22	+	--

Notes: Table 3 summarizes results for the real interest rate (RERA) and three alternative measures of the monetary policy stance: Taylor rule deviations (Taylor rule), Fed funds rate, and growth of the monetary aggregate M1. It lists for how many months impulse-response functions (from the reduced-form VAR, and the structural VARs with long-run and short-run restrictions, respectively) were statistically significant within the 90% confidence interval in the direction indicated in the column "sign".

Table 4: Four-variable VAR results (RA, RERA, LJOB, UC)

Panel A: Lag-length selection

lag	AIC	HQIC	SBIC
1	0.0555	0.1639*	0.3231*
2	0.0643	0.2810	0.5995
3	-0.0216*	0.3034	0.7812
4	-0.0088	0.4246	1.0617
5	0.0131	0.5548	1.3511
6	0.1223	0.7723	1.7279
7	0.1942	0.9526	2.0674
8	0.2652	1.1319	2.4060
9	0.2559	1.2310	2.6643
10	0.3212	1.4046	2.9973

Panel B: Granger causality

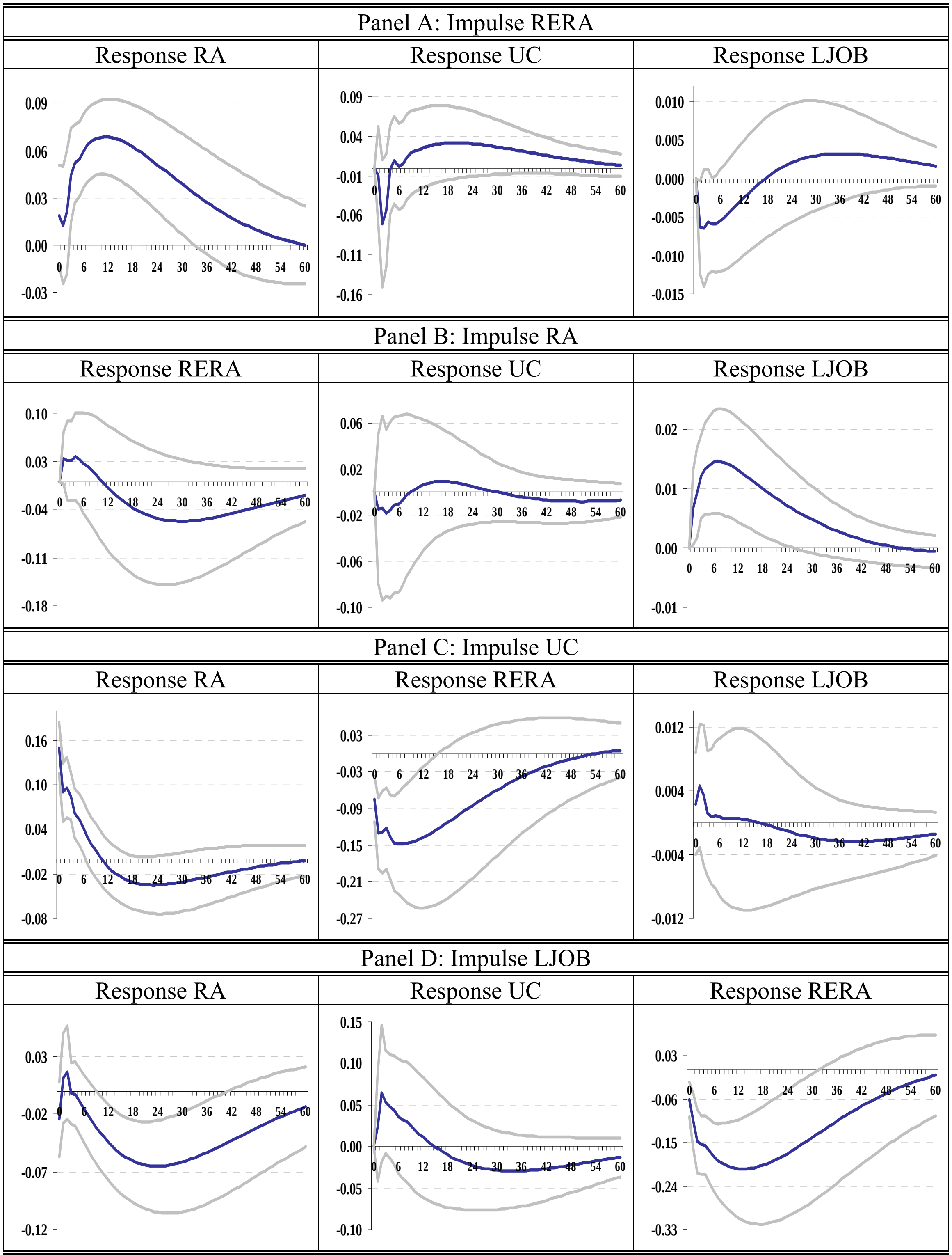
Equation	Excluded	chi2	df	p-value
RA	RERA	14.4460	3	0.0020
RA	LJOB	1.5888	3	0.6620
RA	UC	5.7468	3	0.1250
RA	ALL	24.8780	9	0.0030
RERA	RA	4.4763	3	0.2140
RERA	LJOB	13.7200	3	0.0030
RERA	UC	9.2123	3	0.0270
RERA	ALL	22.1440	9	0.0080
LJOB	RA	9.1933	3	0.0270
LJOB	RERA	6.4407	3	0.0920
LJOB	UC	5.5901	3	0.1330
LJOB	ALL	12.4980	9	0.1870
UC	RA	0.2420	3	0.9710
UC	RERA	4.6045	3	0.2030
UC	LJOB	0.9810	3	0.8060
UC	ALL	6.8800	9	0.6500

Panel C: Lagrange-multiplier test

lag	chi2	df	p-value
1	22.0339	16	0.1421
2	31.7639	16	0.0107
3	21.4902	16	0.1604

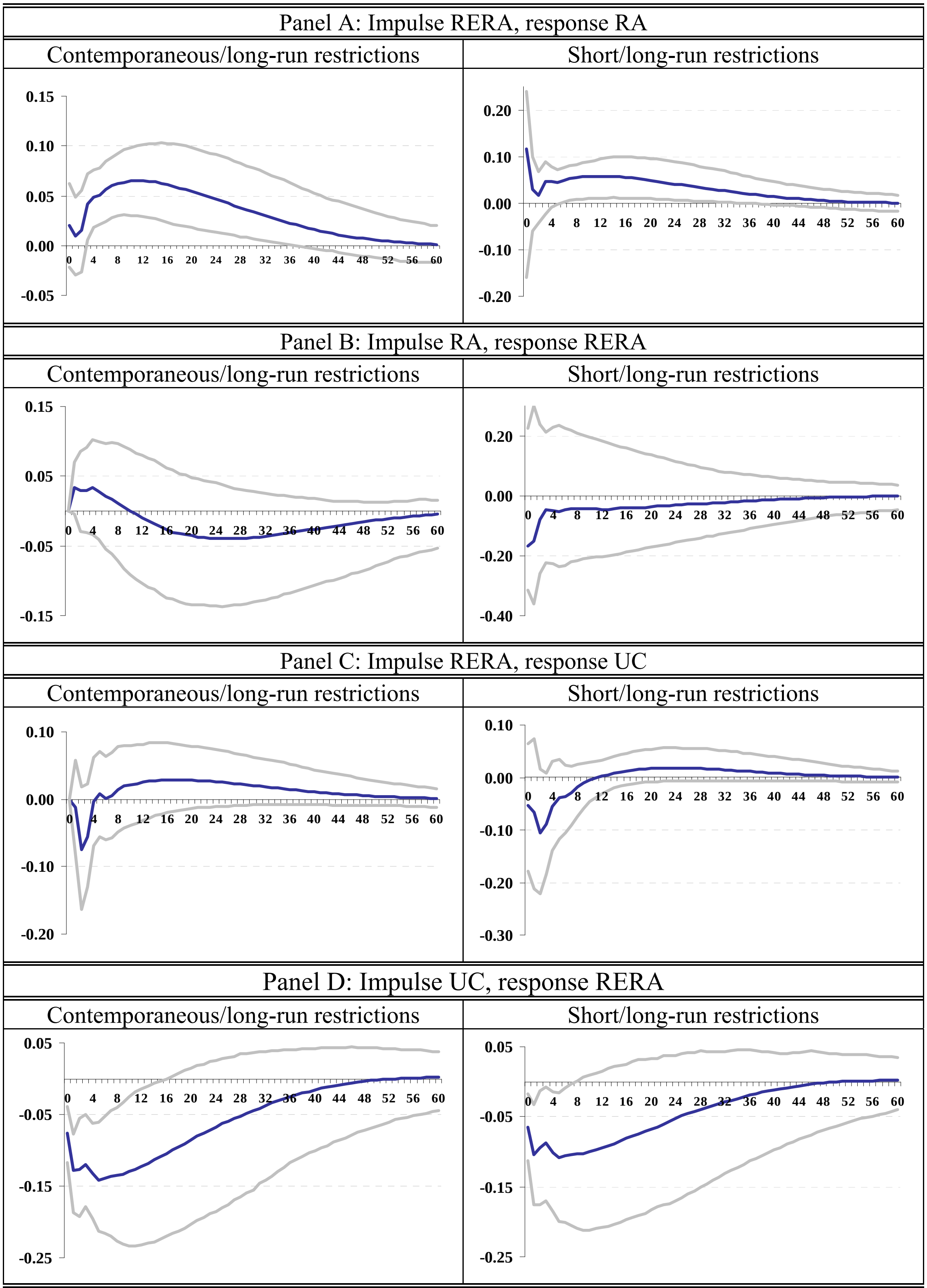
Notes: Four-variable VAR on the log of risk aversion (RA), the real interest rate (RERA), the log of jobless claims (LJOB) and the log of uncertainty (UC). Panel A presents lag-length selection results based on three criteria: Akaike (AIC), Hannan-Quinn (HQIC) and Schwarz (SBIC). The star indicates the lag chosen. Panel B presents Granger causality results for the model with 3 lags (selected by Akaike). Panel C presents Lagrange-multiplier specification tests for the model with 3 lags (selected by Akaike). The null hypothesis is that there is no autocorrelation at lag order j=1,2,3 and the degrees of freedom are given by the square of the number of equations in the VAR, as the test examines the null hypothesis that the residuals of lag j are not jointly significant in the VAR.

Figure 4: Orthogonalized reduced-form IRFs, UC LJOB RERA RA

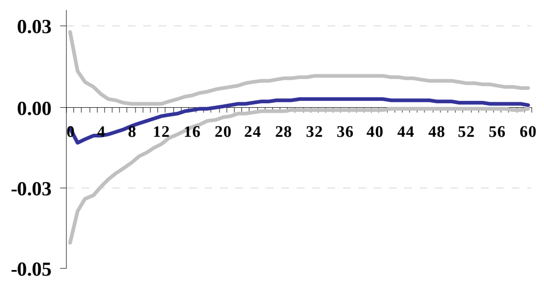
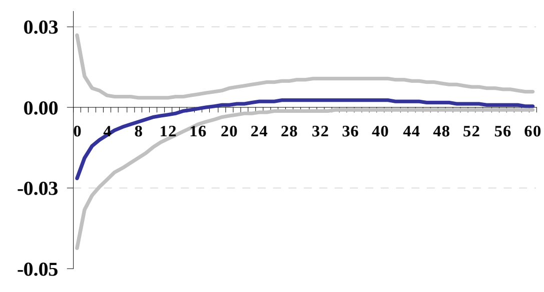


Notes: Medians (blue lines) and 90% confidence intervals (grey lines) of the estimated orthogonalized IRFs for the model with 3 lags (selected by Akaike). Order of variables in the VAR is UC LJOB RERA RA. Each panel presents the responses of three variables to a one standard deviation shock to the impulse variable.

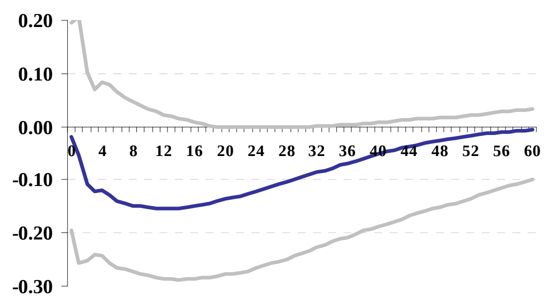
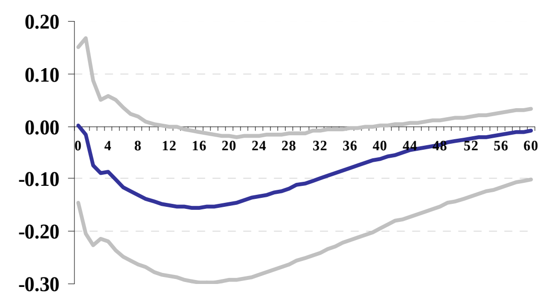
Figure 5: Structural-form IRFs for the 4-variable VAR (RERA, LJOB, UC, RA)



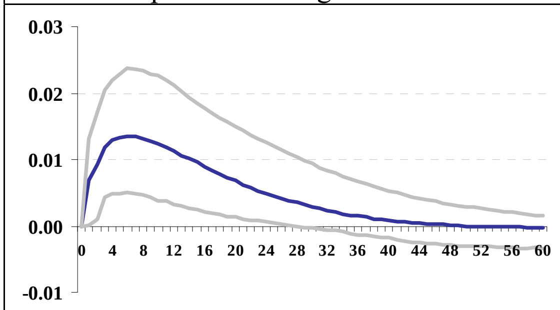
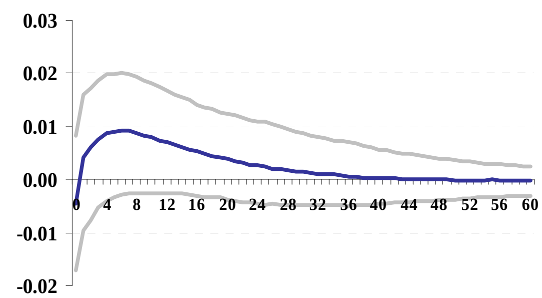
Panel E: Impulse RERA, response LJOB

Contemporaneous/long-run restrictions	Short/long-run restrictions
	

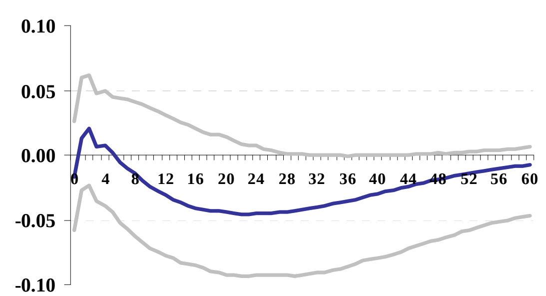
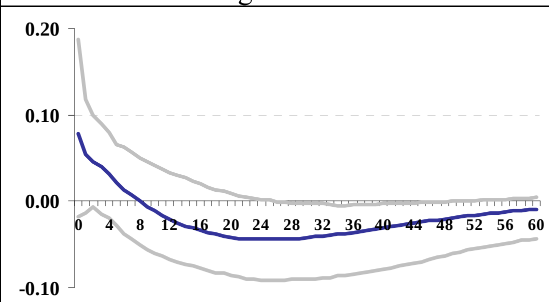
Panel F: Impulse LJOB, response RERA

Contemporaneous/long-run restrictions	Short/long-run restrictions
	

Panel G: Impulse RA, response LJOB

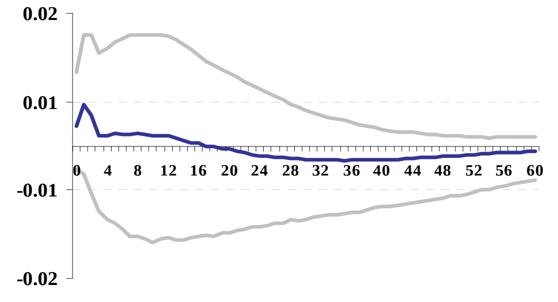
Contemporaneous/long-run restrictions	Short/long-run restrictions
	

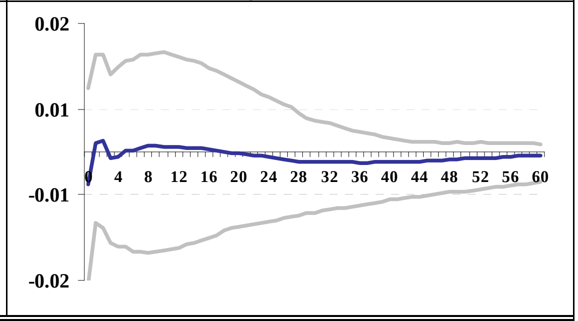
Panel H: Impulse LJOB, response RA

Contemporaneous/long-run restrictions	Short/long-run restrictions
	

Panel I: Impulse UC, response LJOB

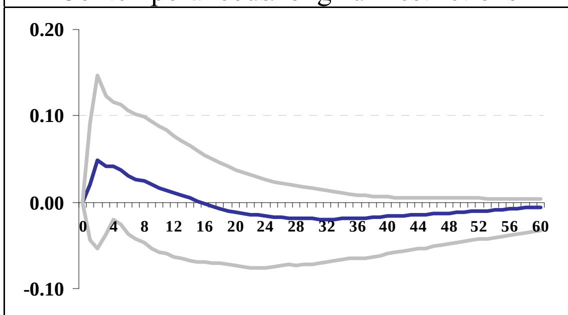
Contemporaneous/long-run restrictions | Short/long-run restrictions

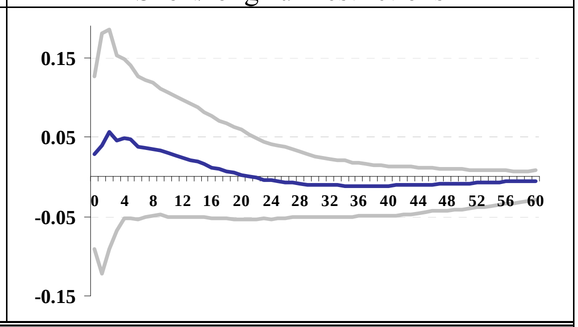




Panel J: Impulse LJOB, response UC

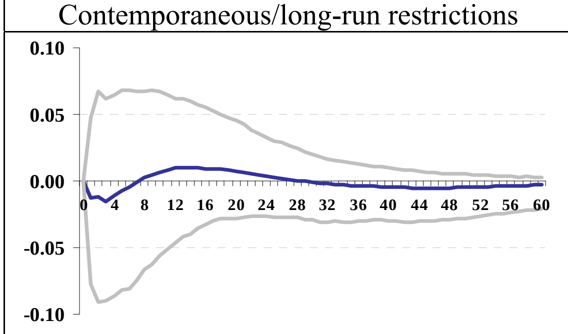
Contemporaneous/long-run restrictions | Short/long-run restrictions

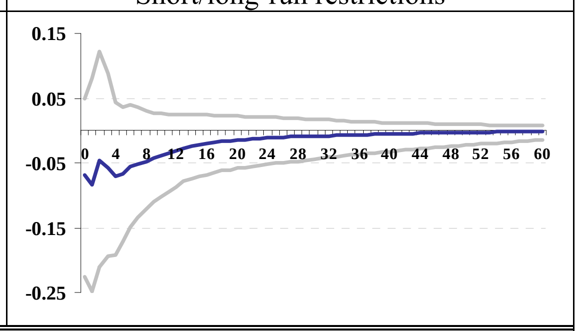




Panel K: Impulse RA, response UC

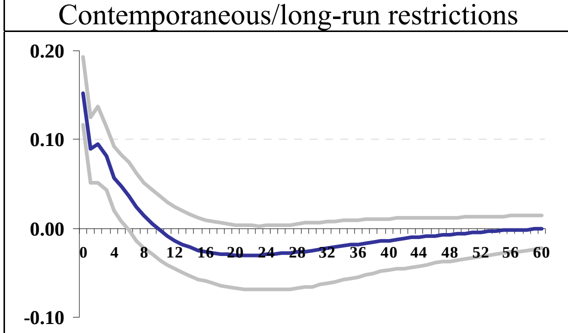
Contemporaneous/long-run restrictions | Short/long-run restrictions

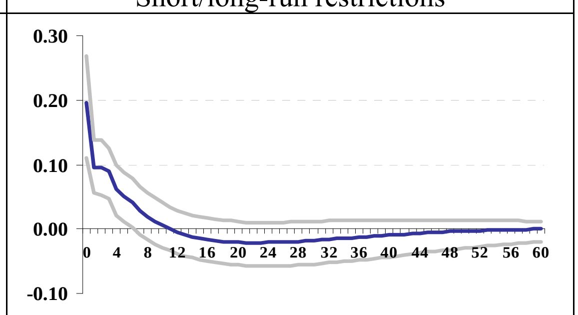




Panel L: Impulse UC, response RA

Contemporaneous/long-run restrictions | Short/long-run restrictions





Medians (blue lines) and 90% bootstrapped confidence intervals (grey lines) of the distribution of the estimated structural impulse-response functions for the model with 3 lags (selected by Akaike), based on 1000 replications. Panels on the left present results of the model with contemporaneous/long-run restrictions, panels on the right present results of the model with short/long-run restrictions.

Table 6: Channels, real interest rate – risk aversion pair

Channel	Impulse RERA, response RA		Impulse RA, response RERA	
	sign	significant from-to (month)	sign	Significant from-to (month)
Repo growth				
- reduced-form	+	3 – 39	–	--
- structural CLR	+	3 – 41	–	--
- structural SLR	+	5 – 20	–	--
(M2-M1) growth				
- reduced-form	+	4 – 36	–	--
- structural CLR	+	6 – 36	–	--
- structural SLR	+	16 – 23	–	--
Credit growth				
- reduced-form	+	3 – 39	–	--
- structural CLR	+	3 – 40	–	--
- structural SLR	+	8 – 15	–	--
Credit/GDP				
- reduced-form	+	3 – 39	–	--
- structural CLR	+	3 – 42	–	--
- structural SLR	+	9 – 22	–	--

Notes: Table 6 summarizes results for the interaction between monetary policy (as represented by the real interest rate) and risk aversion (RA) in the four-variable model with RERA, RA, UC and a Channel variable. The Table lists the corresponding Channel variable (left column) and for how many months impulse-response functions (from the reduced-form VAR, and the structural VAR with contemporaneous/long-run and short/long-run restrictions, respectively) were statistically significant within the 90% confidence interval in the direction indicated in the column “sign”.

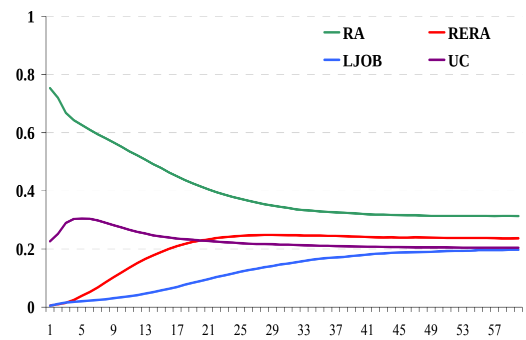
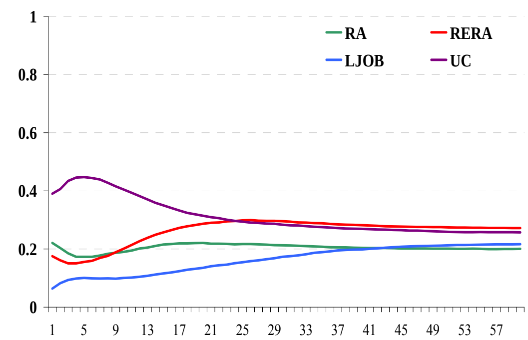
Table 7: Channels, real interest rate - uncertainty pair

Channel	Impulse RERA, response UC		Impulse UC, response RERA	
	sign	significant from-to (month)	sign	Significant from-to (month)
Repo growth				
- reduced-form	+	--	–	0 – 34
- structural CLR	+	--	–	0 – 41
- structural SLR	+	--	–	0 – 41
(M2-M1) growth				
- reduced-form	+	--	–	0 – 19
- structural CLR	+	--	–	0 – 23
- structural SLR	+	--	–	4
Credit growth				
- reduced-form	+	--	–	0 – 30
- structural CLR	+	--	–	0 – 37
- structural SLR	+	--	–	14 – 28
Credit/GDP				
- reduced-form	+	--	–	0 – 31
- structural CLR	+	--	–	0 – 38
- structural SLR	+	--	–	--

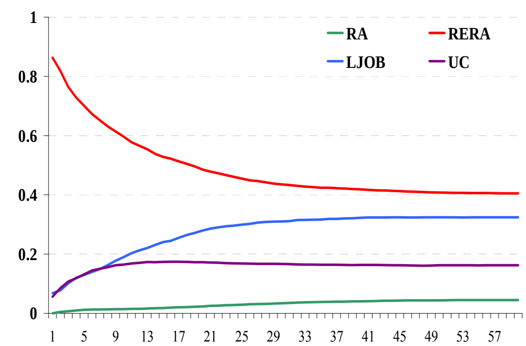
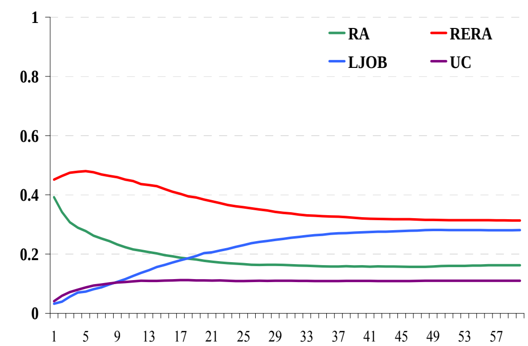
Notes: Table 7 summarizes results for the interaction between monetary policy (as represented by the real interest rate) and uncertainty (UC) in the four-variable model with RERA, RA, UC and a Channel variable. The Table lists the corresponding Channel variable (left column) and for how many months impulse-response functions (from the reduced-form VAR, and the structural VARs with contemporaneous/long-run and short/long-run restrictions, respectively) were statistically significant within the 90% confidence interval in the direction indicated in the column "sign".

Figure 6: Structural Variance Decompositions

Panel A: Variance decomposition of RA

Contemporaneous/long-run restrictions	Short/long-run restrictions
	

Panel B: Variance decomposition of RERA

Contemporaneous/long-run restrictions	Short/long-run restrictions
	

Notes: Medians of the distribution of the estimated structural variance decompositions from the four-variable model RA, RERA, LJOB and UC with 3 lags (selected by Akaike), based on 1000 replications. Panels on the left present results of the model with the contemporaneous/long-run restrictions, panels on the right present results of the model with the short/long-run restrictions.

Appendix 1: The VIX, Uncertainty and Risk Aversion

It may not be immediately obvious how the VIX is related to the actual ("physical") expected variance of stock returns and to risk aversion. In this appendix, we consider a particularly simple discrete state economy to clarify these relations.

Imagine a stock return distribution with three different states x_i, as follows:

Good state: $x_g = \mu + a$ with probability $(1-p)/2$,

Bad State : $x_b = \mu - a$ with probability $(1-p)/2$,

Crash state: $x_c = c$ with probability p,

where $\mu > 0$, $a > 0$ and $c < 0$ are parameters to be determined. We set them to match statistics in the data for the US stock market, the mean, the variance (standard deviation) and the skewness, while fixing the crash probability at an empirically plausible number.

The mean is given by:

$$\overline{X} = \frac{1-p}{2}x_g + \frac{1-p}{2}x_b + pc = (1-p)\mu + pc\,.$$

The variance is given by:

$$V \equiv \sigma^2 = \frac{1-p}{2}(\mu + a - \overline{X})^2 + \frac{1-p}{2}(\mu - a - \overline{X})^2 + p(c - \overline{X})^2$$

and the skewness (Sk) by:

$$V^{\frac{3}{2}}Sk = \frac{1-p}{2}(\mu + a - \overline{X})^3 + \frac{1-p}{2}(\mu - a - \overline{X})^3 + p(c - \overline{X})^3\,.$$

Consider a one-period world in which the investor has a utility function over wealth that is power utility and that in equilibrium she invests her entire wealth in the stock market:

$$U(\widetilde{W}) = E\left[\frac{(W_0\widetilde{R})^{1-\gamma}}{1-\gamma}\right],$$

where $\widetilde{R}$ is the gross return on the stock market, W_0 is initial wealth and γ is the coefficient of relative risk aversion.

The "pricing kernel" in this economy is given by the marginal utility, denoted by m, and is proportional to $\widetilde{R}^{-\gamma}$. Hence, the stochastic part of the pricing kernel moves inversely with the return on the stock market. When the stock market is down, marginal utility is relatively high and vice versa.

The physical variance of the stock market is exogenous in this economy, and simply given by V. In other words, the variance is computed using the actual probabilities. What does the VIX measure? It measures the "risk-neutral" conditional variance. That is, it uses the so-called "risk-neutral probabilities", which are simply probabilities adjusted for risk.

In particular, for a general state probability π_j for state j, the risk neutral probability is:

$$\pi_j^{RN} = \pi_j \frac{m_j}{E[m]} = \pi_j \frac{R_j^{-\gamma}}{E[m]}.$$

So, for a given γ, we can easily compute the risk-neutral probabilities since $R_j = x_j + 1$.

Then, in general, the risk-neutral variance is given by:

$$VIX^2 = \sum_{j=1}^{K} \pi_j^{RN} (x_j - \overline{X})^2$$

and the variance premium is:

$$VP = VIX^2 - V = \sum_{j=1}^{K} (\pi_j^{RN} - \pi_j)(x_j - \overline{X})^2$$

Because the risk-neutral probability puts more weight on the crash state and the crash state induces plenty of additional variance, the variance premium is positive in this case. The higher is risk aversion, the more weight the crash state will get, and the higher the variance premium will be.

For our economy, the variance premium has a particularly simple form:

$$VP = (\pi_g^{RN} - \frac{1-p}{2})(x_g - \overline{X})^2 + (\pi_b^{RN} - \frac{1-p}{2})(x_b - \overline{X})^2 + (\pi_c^{RN} - p)(x_c - \overline{X})^2$$

where $\pi_g^{RN} = \frac{1-p}{2} \frac{(\mu + a + 1)^{-\gamma}}{E[m]}$, $\pi_b^{RN} = \frac{1-p}{2} \frac{(\mu - a + 1)^{-\gamma}}{E[m]}$ and $\pi_c^{RN} = p \frac{(c+1)^{-\gamma}}{E[m]}$.

Suppose the statistics to match are as follows: $\overline{X}$ = 10 % on an annualized basis, $\sigma = 15\%$ on an annualized basis, $Sk = -1$ and $p = 0.5\%$. The implied crash return is then given by $c =$ -25.0995 %. Table 8 below provides, for different values of the coefficient of relative risk aversion γ, the values for the VIX on an annualized basis in percent (VIX), the log of the VIX on a monthly basis (LVIX), i.e., $\log(\text{VIX}/\sqrt{12})$, the annualized variance premium (VP), and our risk aversion proxy computed on a monthly basis (RA), i.e., $\log(\text{VIX}^2/12 - \sigma^2/12)$.

Table 8: Numerical examples

Parameter	VIX	LVIX	VP	RA
$\gamma = 2$	15.9891	1.5295	0.0031	0.9377
$\gamma = 4$	17.6206	1.6266	0.0085	1.9634
$\gamma = 6$	20.1642	1.7615	0.0182	2.7169

Notes: Table 8 presents values of the VIX on an annualized basis in percent (VIX), the log of the VIX on a monthly basis (LVIX), the annualized variance premium (VP), and our proxy for risk aversion on a monthly basis (RA) for different values of the coefficient of relative risk aversion γ, while keeping the probability of the crash state fixed at $p = 0.5\%$.

Appendix 2: Alternative Identification Schemes

To ensure that our main results in the four-variable model, [RERA, LJOB, UC, RA]', are not sensitive to the identification scheme, we tried alternative schemes, while always preserving a structure that satisfies necessary and sufficient conditions for global identification. Table 9 below provides the order of variables in the system, together with identifying restrictions on the left and summarizes main results on the right hand side. We first list the contemporaneous/long-run model and the short/long-run model we described in the main text. We then present other models we estimated.

Table 9: Estimated alternative identifying restrictions

Restrictions		Impulse - response	sign	significant from-to (month)
ra *mp* *bc* *uc*	$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ 0 & a_{22} & a_{23} & a_{24} \\ 0 & a_{32} & a_{33} & a_{34} \\ 0 & 0 & 0 & a_{44} \\ d_{11} & d_{12} & d_{13} & d_{14} \\ d_{21} & d_{22} & d_{23} & d_{24} \\ d_{31} & 0 & d_{33} & d_{34} \\ d_{41} & d_{42} & d_{43} & d_{44} \end{bmatrix}$	RERA - RA RA - RERA RERA - UC UC – RERA	+ – + –	3 – 36 -- -- 0 – 16
mp *bc* *ra* *uc*	$\begin{bmatrix} \phi_{11} & \phi_{12} & \phi_{13} & \phi_{14} \\ \phi_{21} & \phi_{22} & \phi_{23} & \phi_{24} \\ \phi_{31} & 0 & \phi_{33} & \phi_{34} \\ 0 & 0 & 0 & \phi_{44} \\ d_{11} & d_{12} & d_{13} & d_{14} \\ 0 & d_{22} & d_{23} & d_{24} \\ d_{31} & d_{32} & d_{33} & d_{34} \\ 0 & d_{42} & d_{43} & d_{44} \end{bmatrix}$	RERA - RA RA - RERA RERA - UC UC – RERA	+ – + –	6 – 35 -- -- 0 – 7
mp *bc* *uc* *ra*	$\begin{bmatrix} \phi_{11} & \phi_{12} & \phi_{13} & \phi_{14} \\ \phi_{21} & \phi_{22} & \phi_{23} & \phi_{24} \\ \phi_{31} & 0 & \phi_{33} & \phi_{34} \\ 0 & 0 & 0 & \phi_{44} \\ d_{11} & d_{12} & d_{13} & d_{14} \\ 0 & d_{22} & d_{23} & d_{24} \\ 0 & d_{32} & d_{33} & d_{34} \\ d_{41} & d_{42} & d_{43} & d_{44} \end{bmatrix}$	RERA - RA RA - RERA RERA - UC UC – RERA	+ – – –	6 – 37 -- 2 – 3 --

$\begin{array}{c} mp \\ bc \\ uc \\ ra \end{array} \begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} \\ 0 & d_{22} & d_{23} & d_{24} \\ 0 & 0 & d_{33} & d_{34} \\ 0 & 0 & 0 & d_{44} \end{bmatrix}$	RERA - RA RA - RERA RERA - UC UC – RERA	+ + + –	13 – 39 0 – 26 -- 4 – 22
$\begin{array}{c} mp \\ bc \\ ra \\ uc \end{array} \begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} \\ 0 & d_{22} & d_{23} & d_{24} \\ 0 & 0 & d_{33} & d_{34} \\ 0 & 0 & 0 & d_{44} \end{bmatrix}$	RERA – RA RA – RERA RERA – UC UC – RERA	+ + + –	12 – 39 0 – 27 -- --
$\begin{array}{c} mp \\ ra \\ bc \\ uc \end{array} \begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} \\ 0 & d_{22} & d_{23} & d_{24} \\ 0 & 0 & d_{33} & d_{34} \\ 0 & 0 & 0 & d_{44} \end{bmatrix}$	RERA - RA RA - RERA RERA - UC UC – RERA	+ + + –	14 – 42 0 – 27 -- --
$\begin{array}{c} mp \\ bc \\ ra \\ uc \end{array} \begin{bmatrix} \phi_{11} & \phi_{12} & \phi_{13} & \phi_{14} \\ \phi_{21} & \phi_{22} & \phi_{23} & \phi_{24} \\ \phi_{31} & 0 & \phi_{33} & \phi_{34} \\ \phi_{41} & 0 & 0 & \phi_{44} \\ d_{11} & d_{12} & d_{13} & d_{14} \\ 0 & d_{22} & d_{23} & d_{24} \\ 0 & d_{32} & d_{33} & d_{34} \\ 0 & d_{42} & d_{43} & d_{44} \end{bmatrix}$	RERA - RA RA - RERA RERA - UC UC – RERA	+ + + –	14 – 41 0 – 14 -- --
$\begin{array}{c} mp \\ bc \\ uc \\ ra \end{array} \begin{bmatrix} \phi_{11} & \phi_{12} & \phi_{13} & \phi_{14} \\ \phi_{21} & \phi_{22} & \phi_{23} & \phi_{24} \\ \phi_{31} & 0 & \phi_{33} & \phi_{34} \\ \phi_{41} & 0 & 0 & \phi_{44} \\ d_{11} & d_{12} & d_{13} & d_{14} \\ 0 & d_{22} & d_{23} & d_{24} \\ 0 & d_{32} & d_{33} & d_{34} \\ 0 & d_{42} & d_{43} & d_{44} \end{bmatrix}$	RERA – RA RA – RERA RERA – UC UC – RERA	+ + + –	14 – 41 0 – 12 -- 0 – 11

Notes: Table 9 summarizes the main results for the interaction between monetary policy (as represented by the real interest rate, RERA), risk aversion (RA) and uncertainty (UC) in the four-variable model with RERA, LJOB, UC and RA under various identification schemes. The Table lists the corresponding identification assumptions for the structural VAR (left column) and for how many months impulse-response functions were statistically significant within the 90% confidence interval in the direction indicated in the column "sign".