External Instrument SVAR Analysis for Noninvertible Shocks

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IV in Macroeconomics

- **New and increasingly** popular method for **Macroeconometrics**

$$z_t = \alpha u_t^i + \eta_t \qquad \eta_t \sim \mathcal{WN}(0, \sigma_\eta^2)$$

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- Wealth of **new instruments** expanding Macro literature:
  - **Oil** – Hamilton 2003; Kilian, 2008, Känzig, 2021
  - **Government purchases** – Ramey, 2011, Ricco et al., 2016, Ramey and Zubairy, 2018
  - **Tax** – Romer and Romer, 2010, Leeper et al., 2013, Mertens and Ravn, 2012, Mertens and Montiel-Olea, 2018
  - **Conventional/Unconventional monetary policy** – Romer and Romer, 2004, Gürkaynak et al. 2005, Gertler and Karadi, 2015, Jarocinski and Karadi 2020, Swanson, 2020, Miranda-Agrippino and Ricco, forth.,
  - **Government asset purchases** – Fieldhouse et al. 2017, Fieldhouse et al. 2018
  - **Confidence** – Lagerborg et al. 2018
  - **Technology news** – Cascaldi-Garcia and Vukotić 2019

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$$z_t = \alpha u_t^i + \underbrace{(\ldots \qquad \ldots)}_{\text{contamination}} + \eta_t \qquad \eta_t \sim \mathcal{WN}(0, \sigma_\eta^2)$$

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Conditions for External Instrument SVAR

Stock (2008), Stock and Watson (2012, 2018) and Mertens and Ravn (2013)

Reduced-Form VAR

$$A(L)y_t = \varepsilon_t$$

Conditions – Global Invertibility

(i) $\mathbb{E}[u_t^1 z_t] = \alpha$ *(Relevance)*

(ii) $\mathbb{E}[u_t^{2:n} z_t] = 0$ *(Contemporaneous Exogeneity)*

(iii) $u_t = Proj(u_t | Y_t, Y_{t-1}, \ldots)$ *(Global Invertibility)*

Conditions for External Instrument SVAR

Stock (2008), Stock and Watson (2012, 2018) and Mertens and Ravn (2013), Miranda-Agrippino, Ricco (2023)

Reduced-Form VAR

$$A(L)y_t = \varepsilon_t$$

Conditions – Partial Invertibility

(i) $\mathbb{E}[u_t^1 z_t] = \alpha$ *(Relevance)*

(ii) $\mathbb{E}[u_t^{2:n} z_t] = 0$ *(Contemporaneous Exogeneity)*

(iii) $\mathbb{E}[u_{t-j}^{m+1:n} z_t^{\perp}] = 0$ *for all* $j \neq 0$ *for which* $\mathbb{E}[u_{t-j}^{m+1:n} \nu_t'] \neq 0$

(Limited Lead-Lag Exogeneity for partial invertibility)

What if the shocks of interest are not invertible?

1. Is IV identification still possible in SVAR?

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$\Longrightarrow$ Yes, internal instrument SVAR (Plagborg-Møller and Wolf, 2021)

- many additional parameters
- potentially very large information set
- IV and VAR sample have to align
- Lag order fixed by the VAR

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This Paper

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2. General Representation Result
   - invertible/fundamental (Lippi and Reichlin, 1994)
   - recoverable (Chahrour and Jurado, 2021)
   - non-recoverable

3. Tests for invertibility and recoverability

4. Validation in simulated environment & application to monetary policy

A Representation Result

The model

- The **structural representation** (SMA)

$$y_t = B(L)u_t \qquad u_t \sim \mathcal{WN}(0, I_q) \tag{1}$$

$B(L)$ is an $n \times q$ matrix of rational function in the lag operator L, $n \leq q$

- The **Wold representation**

$$y_t = C(L)\varepsilon_t \tag{2}$$

- The **VAR representation**

$$A(L)y_t = \varepsilon_t \tag{3}$$

- What is the relation between the structural shocks u_t and the VAR residuals ε_t?

Innovations and Shocks

- VAR residuals ε_t are linear combinations of the current and lagged structural shocks u_t

$$\varepsilon_t = A(L)y_t = A(L)B(L)u_t = Q(L)u_t \tag{4}$$

- Generally, the inverse map is not exact function of the ε_t

$$u_t = P(u_t|\mathcal{H}) + s_t = D'(F)\varepsilon_t + s_t \tag{5}$$

where P is the linear projection operator and $\mathcal{H} = \overline{\text{span}}(\varepsilon_{j,t-k}, j = 1, \ldots, n, k \in \mathbb{Z})$

The structural IRFs are linked to the Wold representation by

$$B(L) = C(L)Q(L) = C(L)\Sigma_\varepsilon D(L)$$

In particular, an IRF of interest

$$b_i(L) = C(L)q_i(L) = C(L)\Sigma_\varepsilon d_i(L)$$

Invertible shocks

Invertibility

A shock is invertible if it is a linear combination of the present and past values of the VAR variables, or, equivalently, a contemporaneous linear combination of the VAR residuals

Proposition – Structural shocks and VAR residuals

If u_{it} is fundamental for y_t, then $d_i(F) = d_{i0} = d_i$ and $q_i(F) = q_{i0} = q_i$, so that

$$u_{it} = d_i' \varepsilon_t = q_i' \Sigma_\varepsilon^{-1} \varepsilon_t. \tag{6}$$

Recoverable shocks

Recoverability

A shock is **recoverable** if it is a linear combination of the present, past and future values of the VAR variables, or, equivalently, it is a linear combination of the present and future values of the VAR residuals

Proposition – Structural shocks and VAR residuals

If u_{it} is recoverable with respect to y_t,

$$u_{it} = d_i'(F)\varepsilon_t = q_i'(F)\Sigma_\varepsilon^{-1}\varepsilon_t, \tag{7}$$

where $d_i(F) = d_{i0} + d_{i1}F + d_{i2}F^2 + \cdots$ is the i-th column of $D(F)$ and $q_i(F) = q_{i0} + q_{i1}F + q_{i2}F^2 + \cdots$ is the i-th column of $Q(F)$. Moreover

$$d_i'(F)\Sigma_\varepsilon d_i(L) = q_i'(F)\Sigma_\varepsilon^{-1}q_i(L) = 1.$$

A General Representation

Any vector process y_t with an SMA and VAR form can be represented as

$$\begin{aligned} y_t &= B^f(L)u_t^f + B^r(L)u_t^r + B^n(L)u_t^n \\ &= C(L)Q^f u_t^f + C(L)Q^r(L)u_t^r + C(L)Q^n(L)u_t^n \\ &= C(L)\Sigma_\varepsilon D^f u_t^f + C(L)\Sigma_\varepsilon D^r(L)u_t^r + C(L)\Sigma_\varepsilon D^n(L)u_t^n. \end{aligned} \tag{8}$$

where $C(L)$ the Wold representation coefficients and Σ_ε is the covariance of ε_t

- u_t^f the fundamental structural shocks
- u_t^r the recoverable (but nonfundamental) shocks
- u_t^n of the nonrecoverable ones
- $Q^h(L)u_t^h$, for $h = f, r, n$, is the projection of ε_t onto u_{t-k}^h, with $k \geq 0$;
- $D^h(F)\varepsilon_t$ is the projection of u_t^h onto ε_{t+k}, with $k \geq 0$

Moreover, the following properties hold:

(i) D^f and Q^f s.t $D^{f\prime}\Sigma_\varepsilon D^f = Q^{f\prime}\Sigma_\varepsilon^{-1}Q^f = I_{q_f}$, for q_f fundamental shocks;

(ii) $D^r(L)$ and $Q^r(L)$ s.t. $D^{r\prime}(F)\Sigma_\varepsilon D^r(L) = Q^{r\prime}(F)\Sigma_\varepsilon^{-1}Q^r(L) = I_{q_r}$, for q_r recoverable shocks

Identification

A general IV

The Instrument

The researcher can observe the proxy $\tilde{z}_t$, following the relation

$$\tilde{z}_t = \beta(L)\tilde{z}_{t-1} + \mu'(L)x_{t-1} + \underbrace{\alpha u_{it} + w_t}_{z_t}, \tag{9}$$

where w_t is an error orthogonal to $u_{j,t-k}$, $j = 1, ..., q$, for any integer k and to z_{t-k}, x_{t-k}, $k \geq 0$, and $\beta(L)$, $\mu(L)$ are rational functions in the lag operator L

- We consider the 'residual'

$$z_t = \alpha u_{it} + w_t. \tag{10}$$

The IRFs and the shock

Consider the projection of ε_t onto the present and past of the proxy:

$$\varepsilon_t = \psi(L) z_t + e_t. \tag{11}$$

Proposition – Relative IRFs

The coefficients of the projection (11) are related to $q_i(L)$ by the equation

$$\psi(L)\sigma_z^2 = q_i(L)\alpha \tag{12}$$

Hence the impulse-response functions fulfil the relation

$$b_i(L)\alpha = C(L)\psi(L)\sigma_z^2 \tag{13}$$

The IRFs and the shock

- **Invertible**: $\varepsilon_t = \psi' z_t + e_t$, and IRFs:

$$b_i(L) = \frac{C(L)\psi}{\sqrt{\psi' \widehat{\Sigma}_{\varepsilon}^{-1} \psi}} \tag{14}$$

- **Recoverable**: $\varepsilon_t = \psi(L) z_t + e_t$, and IRFs:

$$b_i(L) = \frac{C(L)\psi(L)}{\sqrt{\sum_{k=0}^{\infty} \psi_k' \Sigma_{\varepsilon}^{-1} \psi_k}} \tag{15}$$

- **Non-Recoverable** Upper and the lower bounds of α^2 (Plagborg-Møller and Wolf, 2022)

$$\begin{aligned} \alpha^2 &\leq \sigma_z^2 = \overline{\alpha}^2 \\ \alpha^2 &\geq \alpha^2 \sup_{\theta \in (0 \;\; \pi]} R_r^2(\theta) = \sigma_z^4 \sup_{\theta \in (0 \;\; \pi]} \psi'(e^{j\theta}) \Sigma_{\varepsilon}^{-1} \psi(e^{-j\theta}). \end{aligned} \tag{16}$$

Variance and historical decompositions

- Historical decomposition is easy once the shock is identified
- Variance is difficult...
  - The standard forecast error variance decomposition (**FVD**) only for invertible models
  - ... one cannot estimate the denominator without estimating the whole structural model
  - Plagborg-Møller and Wolf (2022): denominator with the forecast error variance (**FVR**)
  - Alternative: integral of the spectral density over a frequency band (**VD**)

$$\hat{c}_h(\theta_1, \theta_2) = \frac{\int_{\theta_1}^{\theta_2} \hat{b}_{ih}(e^{-j\theta})\hat{b}_{ih}(e^{j\theta})d\theta}{\int_{\theta_1}^{\theta 2} \widehat{S}_h(\theta)d\theta}. \tag{17}$$

Testing for recoverability and invertibility

- **Recoverability**:

$$z_t = \delta'(F)\varepsilon_t + v_t \tag{18}$$

  - If recoverable $\hat{u}_{it} = \hat{\delta}(F)\hat{\epsilon}_t$ (intuition: Plagborg-Møller and Wolf, 2022)
  - Ljung-Box Q-test to the estimated projection $\hat{\delta}(F)\hat{\epsilon}_t$
  - H_0 is recoverability (serial uncorrelation) vs H_1 nonrecoverability (serial correlation)

- **Invertibility**:
  - If invertible $\delta_k = 0$ for all positive k
  - standard F-test for the joint significance of the coefficients of the leads in Eq. (18)
  - test H_0 of fundamentalness vs H_1 nonfundamentalness
  - If not invertibility, the degree of fundamentalness is

$$\hat{R}_f^2 = \hat{\delta}_0'\widehat{\Sigma}_\varepsilon\hat{\delta}_0 / \sum_{k=0}^{r} \hat{\delta}_k'\widehat{\Sigma}_\varepsilon\hat{\delta}_k.$$

Identification in Practice

IV Identification in practice

1. Regress $\tilde{z}_t$ onto its lags and a set of regressors x_t, to get z_t

$$\tilde{z}_t = \beta(L)\tilde{z}_{t-1} + \mu'(L)x_{t-1} + \alpha u_{it} + z_t \tag{19}$$

   If the F-test does not reject the null $H_0 : \beta(L) = 0$ & $\mu'(L) = 0$, step 1 can be skipped

2. Estimate a VAR(p) with OLS to obtain $\widehat{A}(L)$, $\widehat{C}(L) = \widehat{A}(L)^{-1}$, $\hat{\varepsilon}_t$ and $\widehat{\Sigma}_\varepsilon$

3. Regress $\hat{z}_t$ on the current value and the first r leads of the Wold residuals:

$$\hat{z}_t = \sum_{k=0}^{r} \hat{\delta}'_k \hat{\varepsilon}_{t+k} + \hat{v}_t = \hat{\delta}(F)\hat{\varepsilon}_t + \hat{v}_t$$

   Save the fitted value of the above regression, let us call it $\hat{\eta}_t$

   Test for invertibility

IV Identification in practice

4. **Invertible shock**: Estimate δ and the unit-variance shock. Estimate

$$\varepsilon_t = \psi' z_t + e_t$$

   and estimate IRFs according to (14). Estimate the variance decomposition

4′. **Invertibility is rejected**: Recoverability test

5. **Recoverable shock**: Estimate the unit-variance shock according. Estimate

$$\varepsilon_t = \psi(L) z_t + e_t$$

   and IRFs according to (15). Estimate the variance decomposition

5′. **Nonrecoverable shock**:
   - Either amend the VAR specification and repeat steps 2-4, or
   - Estimate

$$\varepsilon_t = \psi' z_t + e_t$$

     Estimate lower and upper bounds according and the corresponding variance contributions

A Simulated Economy with Fiscal Foresight

An economy with fiscal foresight

- Leeper et al. (2013) RBC model with log preferences and inelastic labor supply
- Two iid shocks: technology, $u_{a,t}$, and tax $u_{\tau,t}$

$$
\begin{aligned}
a_t &= u_{a,t} \\
\tau_t &= u_{\tau,t-2},
\end{aligned}
$$

  Tax shocks are announced before implementation: fiscal foresight
- In deviations from the SS capital accumulation is

$$
k_t = \alpha k_{t-1} + a_t - \kappa \sum_{i=0}^{\infty} \theta^i E_t \tau_{t+i+1} \tag{20}
$$

An economy with fiscal foresight

- Equilibrium MA representation for capital and taxes:

$$\begin{pmatrix} \tau_t \\ k_t \end{pmatrix} = \begin{pmatrix} L^2 & 0 \\ \frac{-\kappa(L+\theta)}{1-\alpha L} & \frac{1}{1-\alpha L} \end{pmatrix} \begin{pmatrix} u_{\tau,t} \\ u_{a,t} \end{pmatrix} = B(L)u_t. \tag{21}$$

- Nonfundamental shocks (matrix vanishes for $L = 0$)
- They are recoverable! (The system is square)
- Tax shock is equal to tax two periods ahead: $u_{\tau,t} = \tau_{t+2}$

An economy with fiscal foresight

- 1000 simulations T=240
- IV simulated as

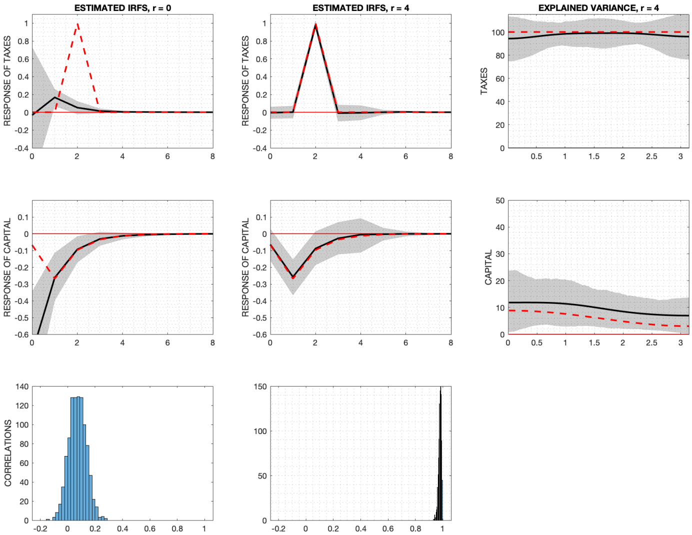
$$\tilde{z}_t = u_{\tau,t} + 0.5z_{t-1} + 0.4k_{t-1} - 0.6\tau_{t-1} + v_t,$$

  where $v_t \sim iid\,\mathcal{N}(0,1)$
- For each dataset, we test for invertibility and recoverability, and estimate the tax shock

$$p = m = 2 \qquad r = 0 \qquad p = m = 2 \qquad r = 4$$

- Invertibility is correctly rejected in all cases
- Recoverability is (wrongly) rejected at the 5% level in 10% of the cases (test is oversized)

An economy with fiscal foresight



A comparison with the Internal-Instrument SVAR

- Same model, same IV
- 1000 simulations T=240
- The instrument is preliminarily ‘cleaned’ by setting $x_t = y_t$ and the number of lags m according to the BIC
- For the Internal-Instrument method, VAR for the vector $(\tilde{z}_t \quad y_t')'$
- Estimation error measured as

$$100 \times \frac{\sum_{h=1}^{n} \sum_{k=0}^{K} (\hat{\mu}_{hk} - \mu_{hk})^2}{\sum_{h=1}^{n} \sum_{k=0}^{K} \mu_{hk}^2}. \tag{22}$$

sum of the squared errors divided by the sum of the squared coefficients of the true IRFs

A comparison with the Internal-Instrument SVAR

		External IV					
VAR order	Internal IV	$r = BIC$	$r = 3$	$r = 4$	$r = 5$	$r = 6$	$r = 7$
$p = 1$	410.8	**4.3**	**4.3**	**5.0**	**6.4**	**7.9**	**9.4**
$p = 2$	34.8	5.2	5.2	5.9	**6.4**	**7.9**	**9.4**
$p = 3$	**7.6**	6.0	6.0	6.8	7.3	8.0	9.5
$p = 4$	9.5	7.1	7.1	7.8	8.4	9.1	9.6
$p = 5$	11.2	8.0	8.0	8.8	9.3	10.0	10.6
$p = 6$	12.9	8.9	8.9	9.6	10.2	10.9	11.5
$p = BIC$	**7.6**	**4.3**					

A comparison with the Internal-Instrument SVAR

- **3 dynamic relations**:
  - the IV equation
  - the VAR model
  - the equation linking VAR residuals and the proxy
- Internal IV approach: they are all fixed at the same lag order
- External-Instrument: they can be independently set optimally

Monetary policy shocks

Monthly VAR and High Frequency IV

- **Specification I**: 1-year gov't bond rate, IP and CPI
- **Specification II**: Specification I + Gilchrist and Zakrajšek (2012)'s excess bond premium
- **Specification III**: Specification II + mortgage spread and the commercial paper spread

  CPI and IP in differences

- **Samples**: 1983:1–2008:12 (robustness 1979:7/1987:8/1990:1 – 2012:6/2019:6)

- **IV**: Fed Funds futures (FF4) surprises

  ... likely to capture both conventional shocks and forward guidance

  'Clean' the IV onto its lags and 6 lags variables of Specification I

Fundamentalness and recoverability

	Number of leads r					
	$r=4$	$r=5$	$r=6$	$r=7$	$r=8$	$r=9$
Specification I						
$p=6$	0.008	0.028	0.002	0.003	0.001	0.001
$p=9$	0.016	0.051	0.003	0.003	0.002	0.001
$p=12$	0.011	0.045	0.003	0.002	0.001	0.000
Specification II						
$p=6$	0.080	0.195	0.027	0.001	0.000	0.000
$p=9$	0.180	0.351	0.034	0.002	0.000	0.000
$p=12$	0.221	0.457	0.059	0.003	0.000	0.000
Specification III						
$p=6$	0.060	0.184	0.089	0.003	0.001	0.002
$p=9$	0.184	0.362	0.220	0.020	0.002	0.003
$p=12$	0.215	0.353	0.250	0.060	0.031	0.027

(a) Fundamentalness test

	Number of leads r					
	$r=4$	$r=5$	$r=6$	$r=7$	$r=8$	$r=9$
Specification I						
$p=6$	0.619	0.662	0.251	0.469	0.037	0.060
$p=9$	0.350	0.571	0.114	0.435	0.050	0.042
$p=12$	0.880	0.944	0.324	0.820	0.466	0.285
Specification II						
$p=6$	0.441	0.473	0.308	0.777	0.394	0.357
$p=9$	0.119	0.186	0.104	0.517	0.222	0.193
$p=12$	0.472	0.558	0.269	0.913	0.701	0.575
Specification III						
$p=6$	0.034	0.315	0.446	0.608	0.738	0.546
$p=9$	0.005	0.064	0.148	0.046	0.391	0.103
$p=12$	0.032	0.037	0.065	0.057	0.343	0.022

(b) Recoverability test

Small VAR specification: Monetary policy shocks

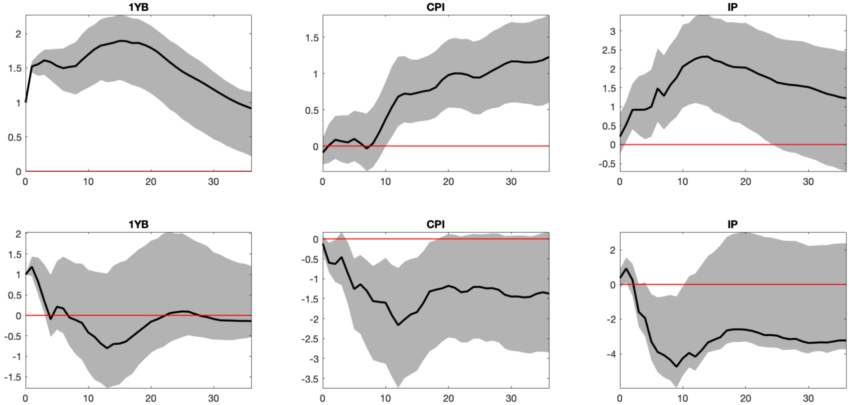


Figure 1: *VAR results: Specification I, $p = 12$, GK instrument. Top panels: estimated response functions with $r = 0$ (standard method). Bottom panels: estimated response functions with our proposed method $r = 6$. Black line: point estimate. Grey area: 68% confidence bands.*

Medium VAR specifications: Monetary policy shocks

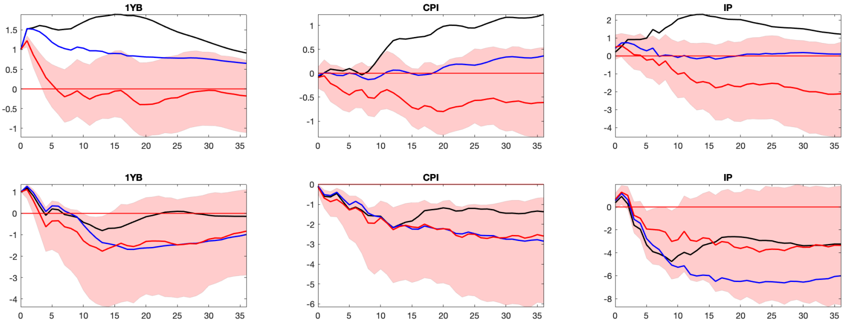


Figure 2: *Red line: point estimates for Specification III; blue line: point estimates for Specification II; black line: point estimates for Specification I. Top panels: estimated response functions with* $p = 12$, $r = 0$ *(standard method). Bottom panels: estimated response functions with our proposed method,* $p = 12$, $r = 6$. *Pink shaded area: 68% confidence bands for Specification III.*

Variance decomposition

	Waves of periodicity		
	2 – 18 months	18 – 96 months	2+ months
Specification I			
CPI inflation	19.2	27.6	20.8
	(13.5—29.1)	(12.8—64.2)	(16.2—35.1)
IP growth	27.7	33.8	28.3
	(19.1—36.4)	(13.1—55.4)	(20.0—37.6)
Specification II			
CPI inflation	12.3	12.9	13.2
	(10.4—23.1)	(9.7—45.1)	(13.4—26.8)
IP growth	20.3	29.5	22.5
	(15.8—28.2)	(11.4—51.5)	(16.7—31.3)
Specification III			
CPI inflation	12.5	10.3	12.5
	(10.2—19.5)	(6.9—34.2)	(11.2—21.5)
IP growth	16.1	5.2	13.0
	(12.2—22.2)	(4.2—22.0)	(11.2—20.7)

Table 1: *Percentage of variance accounted for by the monetary policy shock, for waves of periodicity 2-18 months (short run), 18-96 months (business cycle), 2+ months (overall variance). 68% confidence bands in brackets.*

Variance decomposition

	FVR Horizon					VD
	impact	3 months	6 months	12 months	24 months	2+ months
CPI inflation						
Specification I	0.5	7.2	15.3	18.4	20.7	20.8
Specification II	0.2	4.7	9.1	13.3	13.4	13.2
Specification III	0.3	5.6	7.4	12.5	12.4	12.5
CPI index in levels						
Specification I	0.5	4.2	9.9	20.0	21.5	
Specification II	0.2	2.6	5.3	13.7	22.5	
Specification III	0.3	4.4	7.1	13.8	18.5	

Table 2: *Percentage of variance of CPI inflation and prices accounted for by the monetary policy shock, according to the FVR measure of Plagborg-Møller and Wolf (2022), on impact and at 3,6, 12, 24 months horizons.*

Variance decomposition – Subsamples

	VD: waves of periodicity			FVR: horizon
Time span	2 – 18 months	18 – 96 months	2+ months	24 months
1983:1–2008:12	10.4	22.0	16.1	15.5
1990:1–2012:6	6.3	15.5	8.0	8.1
1987:1–2008:12	7.3	15.4	11.3	10.6
1983:1–2012:6	10.0	24.6	12.7	12.8
1979:7–2012:6	17.2	19.3	17.4	17.5
1979:7–2019:6*	15.7	18.2	15.3	15.1

Table 3: *Variance decomposition of inflation for different time spans, Specification IV: FFR, CPI inflation, IP growth, EBP. VD: percentage of inflation variance accounted for by the monetary policy shock, for waves of periodicity 2-18 months (short run), 18-96 months (business cycle), 2+ months (overall variance). FVR: percentage of forecast error variance of inflation accounted for by the monetary policy shock at the 2-year horizon. For the sample 1979:7–2019:6 in place of the EBP series we use three financial variables: the 10-year treasury bond rate, the BAA corporate bond yield and the S&P500 stock price index.*

Conclusions

- New estimation procedure for structural VARs with an external instrument
- Test for invertibility and a test for recoverability
- The method works well in simulation
- HFI IV policy shocks are not invertible but recoverable
- Standard method produces puzzling results ...
- ... new procedure results in line with textbook effects
- Variance decomposition indicates that monetary policy has sizeable effects