What Impulse Response Do Instrumental Variables Identify?

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- Impulse response (IR) functions are dynamic causal effects
- IR analysis typically based on SVAR or LP

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  - A government spending shock: sum of sectoral spending shocks (Cox, Müller, Pasten, Schoenle, Weber, 2020; Bouakez, Rachedi and Santoro, 2020)

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  - A government spending shock: sum of sectoral spending shocks (Cox, Müller, Pasten, Schoenle, Weber, 2020; Bouakez, Rachedi and Santoro, 2020)
- IVs are often used as an important source of exogeneity to identify IRs to policy-relevant macro shocks
  - Proxy SVAR: Stock and Watson (2012), Mertens and Ravn (2013)
  - Local projection (Jordà, 2005) with instrumental variables (LP-IV): Stock and Watson (2018), Plagborg-Møller and Wolf (2021)

LP-IV

- LP-IV: Single equation linear model with endogeneity

$$y_{t+h} = x_t \beta_h + u_{t+h}$$

- y_t, x_t: macro variables, z_t: instrument
- LP-IV estimand:

$$\beta_h \equiv \frac{Cov(y_{t+h}, z_t)}{Cov(x_t, z_t)}$$

- θ_h: IR to the macro shock that changes x_t by one unit on y_{t+h}
- Stock and Watson (2018) showed $\beta_h = \theta_h$
- What if the shock is composite?

What We Do

- Show that β_h is an affine combination of the IRs to the components of the macro shock

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    - Sign restrictions on w_s
    - Granular data (e.g. sectoral spending as well as total spending data)
- Apply our identification strategies to revisit
    - Jarociński and Karadi (2020): IR to information shock/monetary policy shock
    - Ramey and Zubairy (2018): Estimating the government spending multipliers

Structural Vector Moving Average Model

$$\underbrace{\begin{pmatrix} x_t \\ \vdots \\ y_t \end{pmatrix}}_{\substack{n \times 1 \\ \text{observed} \\ \text{endogenous}}} = \Theta(L) \underbrace{\begin{pmatrix} \varepsilon_{1,t} \\ \varepsilon_{2,t} \\ \vdots \\ \varepsilon_{m,t} \end{pmatrix}}_{\substack{m \times 1 \\ \text{unobserved} \\ \text{structural shocks}}}$$

- $\varepsilon_{s,t}$'s are mutually uncorrelated, $E[\boldsymbol{\varepsilon}_t] = 0$, $E[\boldsymbol{\varepsilon}_t \boldsymbol{\varepsilon}_t'] > 0$
- $\Theta(L) = \Theta_0 + \Theta_1 L + \Theta_2 L^2 + \cdots$, L is the lag operator
- Θ_h: $n \times m$ matrix of impulse responses whose elements are

$$\theta_{h,ys} \equiv E[y_{t+h} | \varepsilon_{s,t} = 1] - E[y_{t+h} | \varepsilon_{s,t} = 0]$$

Impulse Response to a Composite Shock

- Impulse response of y_{t+h} to the macro shock ξ_t:

$$\theta_{h,y*} \equiv E[y_{t+h}|\xi_t = 1] - E[y_{t+h}|\xi_t = 0]$$

- ξ_t: an unobserved exogenous **composite** macro shock

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- example: government spending shock = non-defense (ε_1) + defense (ε_2)

$$\begin{array}{r} (\varepsilon_1 = \frac{1}{2}, \varepsilon_2 = \frac{1}{2}) \Rightarrow \\ (\varepsilon_1 = 1, \varepsilon_2 = 0) \Rightarrow \\ (\varepsilon_1 = 0, \varepsilon_2 = 1) \Rightarrow \end{array} \boxed{\xi = 1} \longrightarrow \boxed{\text{y}}$$

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- The response of y_{t+h} to $\xi_t = 1$ is heterogeneous to various shock combinations: **heterogeneous treatment**

Average Impulse Response

- If ξ_t were observed, $\theta_{h,y*}$ is the average of $\theta_{h,ys}$ wrt all possible combinations of $\varepsilon_{s,t}$ such that $\xi_t = 1$:

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- Since ξ_t is typically not observed, we use an instrument z_t
- z_t effectively *selects* a particular combination of $\varepsilon_{s,t}$'s based on $corr(z_t, \varepsilon_{s,t})$
- example: z_t is positively correlated with ε_1, but not correlated with ε_2

$$z_t \Rightarrow \quad \begin{array}{r} (\varepsilon_1 = \frac{1}{2}, \varepsilon_2 = \frac{1}{2}) \Rightarrow \\ (\varepsilon_1 = 1, \varepsilon_2 = 0) \Rightarrow \\ (\varepsilon_1 = 0, \varepsilon_2 = 1) \Rightarrow \end{array} \boxed{\xi = 1} \longrightarrow \boxed{\text{y}}$$

- Two different IVs may select different combinations of $\varepsilon_{s,t}$'s

  $\Rightarrow$ IR identified by an IV is instrument-specific!

LATE

Assumptions for IV

Assumption 1 (IV validity)

(i) $E[z_t \xi_t] \neq 0$ (relevance)

(ii) $E[z_t \varepsilon_{r,t}] = 0$ for all $r = S+1, S+2, ..., m$ (contemporaneous exogeneity)

(iii) $E[z_t \boldsymbol{\varepsilon}_{t+j}] = 0$ for $j \neq 0$ (lead-lag exogeneity)

- Identical to Stock and Watson (2018) when $S = 1$ where identification under homogeneity ($\xi_t = \varepsilon_{s,t}$) is established

Main Identification Result

To solve the scale indeterminancy of ξ_t, we measure the response of y_{t+h} wrt to the unit change in x_t.

Proposition 1

Under Assumption 1, for $h = 0, 1, 2, ...,$

$$\beta_h \equiv \frac{Cov(y_{t+h}, z_t)}{Cov(x_t, z_t)} = \sum_{s=1}^{S} w_s \theta_{h,ys},$$

under the unit effect normalization, where

$$w_s = \frac{Cov(z_t, \varepsilon_{s,t})}{Cov(x_t, z_t)}, \quad \sum_{s=1}^{S} w_s = 1$$

- LHS: LP-IV estimand for general (non-binary) z_t
- RHS: affine combination of structural impulse responses

LP-IV Estimand May Not Be Meaningful

- Suppose $S = 2$: $\zeta_t = \varepsilon_{1,t} + \varepsilon_{2,t}$
- Under Assumption 1 and the unit effect normalization

$$\beta_{IV} = w_1\theta_{h,y1} + w_2\theta_{h,y2}$$

where $w_s = Cov(z_t\varepsilon_{s,t})/(Cov(z_t\varepsilon_{1,t}) + Cov(z_t\varepsilon_{2,t}))$

- But we are not quite done yet, because the weight can be negative
- Why is this a problem?

$$\begin{array}{ccccccc} \beta_h & = & w_1 & \theta_{h,y1} & + & w_2 & \theta_{h,y2} \\ \uparrow & & \uparrow & \uparrow & & \uparrow & \uparrow \\ 0 & & 2 & 1 & & -1 & 2 \end{array}$$

- Negative weight arises in other literature:
  - TWFE: de Chaisemartin and D'Haultfoeuill (2020, AER)
  - 2SLS: Mogstad, Torgovitsky, and Walters (2021, AER)

What to do?

- β_h may not identify what we aim to recover with composite macro shocks unless we can make

  Assumption: Same-Sign

  For all $s = 1, 2, ..., S$, either $Cov(z_t, \varepsilon_{s,t}) \geq 0$ or $Cov(z_t, \varepsilon_{s,t}) \leq 0$.

- Should be checked for each case, but may not hold in some major applications
- Not a LP-IV specific problem: Plagborg-Møller and Wolf (2021) show SVAR and LP yield asymptotically same IR
- So, what to do?
- Focus on identification of $\theta_{h,ys}$ by imposing reasonable restrictions

Monotonicity

Identification Strategy 1: Sign Restrictions

- Use the signs of the weight (w_s)
- WLOG assume $Cov(z_t, x_t) > 0$ then $sgn(w_s) = sgn(Corr(z_t, \varepsilon_{s,t}))$

$$w_s = \frac{Cov(z_t, \varepsilon_{s,t})}{Cov(z_t, x_t)}$$

- Consider restrictions such as $w_s > 0$ or $w_s < 0$
- Two components model:

$$\beta_h = w_1\theta_{h,y1} + w_2\theta_{h,y2}$$

  where $w_1 + w_2 = 1$

- Rearranging terms:

$$w_1 = \frac{\beta_h - \theta_{h,y2}}{\theta_{h,y1} - \theta_{h,y2}}, \quad w_2 = \frac{\theta_{h,y1} - \beta_h}{\theta_{h,y1} - \theta_{h,y2}}$$

Identified Set by Sign Restrictions

Proposition 2

Suppose that Assumption 1 holds. The identified set for $(\theta_{h,y1}, \theta_{h,y2})$ under the sign restriction of $\{w_1 > 0, w_2 > 0\}$ is

$$\Theta_{++} = \{(\theta_{h,y1}, \theta_{h,y2}) | \theta_{h,y1} > \beta_h > \theta_{h,y2} \text{ or } \theta_{h,y1} < \beta_h < \theta_{h,y2}\}.$$

And the identified set under $\{w_1 > 0, w_2 < 0\}$ is

$$\Theta_{+-} = \{(\theta_{h,y1}, \theta_{h,y2}) | \beta_h > \theta_{h,y1} > \theta_{h,y2} \text{ or } \beta_h < \theta_{h,y1} < \theta_{h,y2}\}.$$

Identified Set by Sign Restrictions

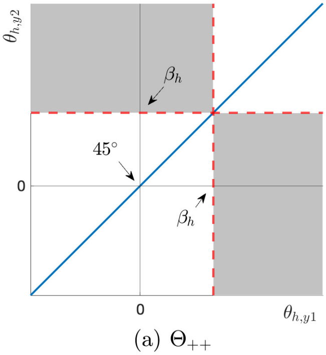

Figure: Identified Sets for Sign Restrictions on the Weight

Intersection of the Identified Sets

- Two instruments: z_t^A and z_t^B
- Two LP-IV estimands: β_h^A and β_h^B
- Three cases of sign restrictions:
  1. $\{w_1^A > 0,\ w_2^A > 0\}$ and $\{w_1^B > 0,\ w_2^B > 0\}$: $\Theta_{++}^A \cap \Theta_{++}^B$
  2. $\{w_1^A > 0,\ w_2^A < 0\}$ and $\{w_1^B > 0,\ w_2^B < 0\}$: $\Theta_{+-}^A \cap \Theta_{+-}^B$
  3. $\{w_1^A > 0,\ w_2^A > 0\}$ and $\{w_1^B > 0,\ w_2^B < 0\}$: $\Theta_{++}^A \cap \Theta_{+-}^B$
- Consider $\beta_h^A > \beta_h^B$ and $\beta_h^A < \beta_h^B$ for each case

Two IVs: $\Theta^A_{++} \cap \Theta^B_{++}$ and $\Theta^A_{+-} \cap \Theta^B_{+-}$

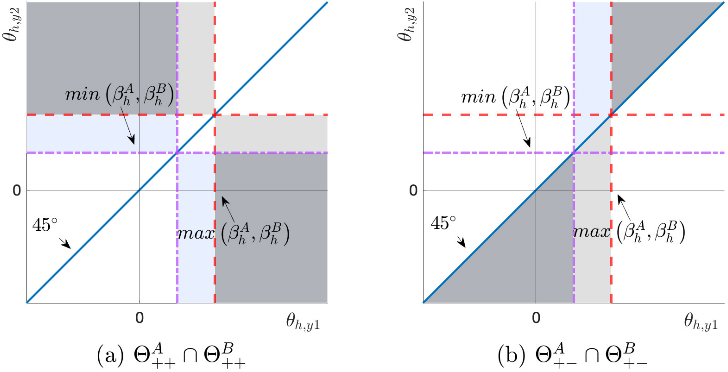

Figure: Intersection of Identified Sets

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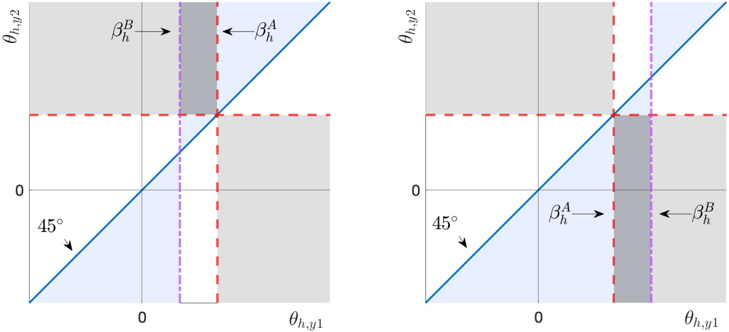


(c) $\Theta^{A}_{++} \cap \Theta^{B}_{+-}$, $\beta_h^A > \beta_h^B$ (d) $\Theta^{A}_{++} \cap \Theta^{B}_{+-}$, $\beta_h^A < \beta_h^B$

Figure: Intersection of Identified Sets (cont)

Jarociński and Karadi (2020)

- The US Federal Open Market Committee (FOMC) announcements are usually considered as monetary policy shocks
- Observes that the interest rate and stock price surprises often move in the same direction upon the FOMC announcements
- FOMC announcement:

$$\xi_t = \varepsilon_{mp,t} + \varepsilon_{cb,t}$$

- $\varepsilon_{mp,t}$: pure monetary policy shock
- $\varepsilon_{cb,t}$: the central bank information shock

IV and Sign Restrictions

- High-frequency financial market surprises (the change between 10 minutes before and 20 minutes after the announcements)
- Two IVs: z_t^{ff} and z_t^{sp}
- z_t^{ff}: high-frequency surprise in the fed funds futures
- z_t^{sp}: high-frequency surprise in the stock price
- Sign restrictions are

$$\begin{aligned} z_t^{ff}: &\quad Cov(z_t^{ff}, \varepsilon_{mp,t}) > 0, \quad Cov(z_t^{ff}, \varepsilon_{cb,t}) > 0 \quad \Rightarrow \Theta_{++}^{ff} \\ z_t^{sp}: &\quad Cov(z_t^{sp}, \varepsilon_{mp,t}) < 0, \quad Cov(z_t^{sp}, \varepsilon_{cb,t}) > 0 \quad \Rightarrow \Theta_{+-}^{sp} \end{aligned}$$

Identified Set for Componentwise IR

- Recall
$$\beta_h^j = w_{mp}^j \theta_{h,mp} + w_{cb}^j \theta_{h,cb}$$
where
$$w_s^j = \frac{Cov(z_t^j, \varepsilon_{s,t})}{Cov(z_t^j, x_t)}$$
for $j = ff, sp$ and $s = mp, cb$
- $\theta_{h,mp}$: response of y_{t+h} to the unit change in the pure monetary shock (corresponding to 25BP change in x_t)
- $\theta_{h,cb}$: response of y_{t+h} to the unit change in the central bank information shock (corresponding to 25BP change in x_t)
- Obtain the identified sets by $\Theta_{++}^{ff} \cap \Theta_{+-}^{sp}$

Data and Model

- Econometric model:

$$y_{t+h} = \mu_h + \beta_h x_t + \boldsymbol{\phi}_h(L)' \boldsymbol{R}_{t-1} + u_{t+h}$$

- y_t: macro variable of interest
- x_t: monthly average of the 1-year Treasury yield
- $\boldsymbol{R}_t$: all the macro var including y_t, x_t, and z_t
- $\boldsymbol{\phi}_h(L)$: a coeff vector of polynomial in the lag operator of order 12
- β_h: Responses to 25BP increase in 1-year government bond yield
- $\widehat{\beta}_h^{ff}$, $\widehat{\beta}_h^{sp}$: LP-IV est using z_t^{ff} and z_t^{sp} one at a time, respectively

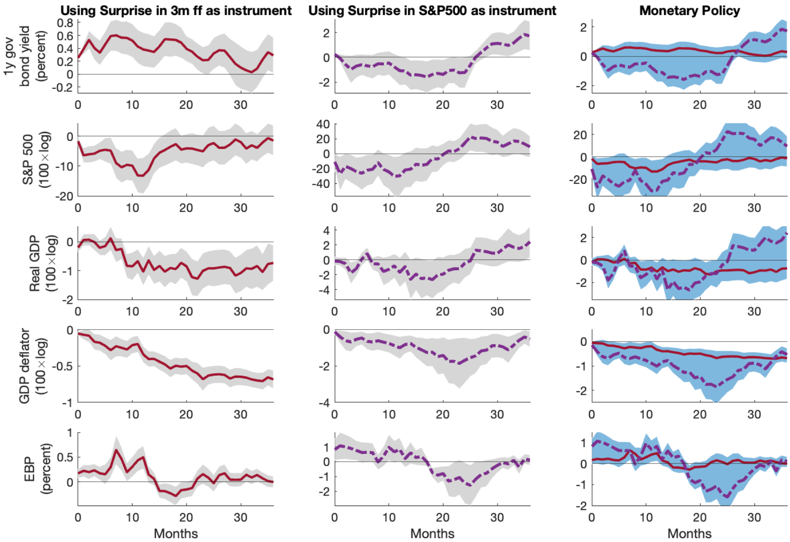


Figure: Responses to 25BP Increase in One-year Government Bond Yield

Identification Strategy 2: Granular Data

- Consider granular data $x_{s,t}$ which is a part of the augmented SVMA system:

$$
\begin{aligned}
x_{1,t} =& \varepsilon_{1,t} + \psi_{0,12}\varepsilon_{2,t} + \cdots + \{\boldsymbol{\varepsilon}_{t-1}, \boldsymbol{\varepsilon}_{t-2}, \cdots\} \\
x_{2,t} =& \psi_{0,21}\varepsilon_{1,t} + \varepsilon_{2,t} + \cdots + \{\boldsymbol{\varepsilon}_{t-1}, \boldsymbol{\varepsilon}_{t-2}, \cdots\}
\end{aligned}
$$

- Augmented SVMA:

$$
\underset{\substack{n \times 1 \\ \text{observed} \\ \text{endogenous}}}{\begin{pmatrix} x_{1,t} \\ x_{2,t} \\ \vdots \\ y_t \end{pmatrix}} = \Psi(L) \underset{\substack{m \times 1 \\ \text{unobserved} \\ \text{structural shocks}}}{\begin{pmatrix} \varepsilon_{1,t} \\ \varepsilon_{2,t} \\ \vdots \\ \varepsilon_{m,t} \end{pmatrix}}
$$

Identification Condition in the Augmented SVMA

Assumption 2 No contemporaneous inter-component causal effects:

$$0 = \psi_{0,12} = \psi_{0,21}$$

- Example: $x_{1,t}$: non-defense spending, $\varepsilon_{1,t}$: non-defense spending shock
- Similar to the recursive causal ordering in the triangular SVAR model
- Under Assumption 2, w_s is point-identified as

$$w_1 = \frac{Cov(x_{1,t}, z_t)}{Cov(x_t, z_t)}, \quad w_2 = \frac{Cov(x_{2,t}, z_t)}{Cov(x_t, z_t)}$$

Identified Set by Granular Data

Proposition 3

Suppose that Assumptions 1-2 hold. The identified set for $(\theta_{h,y1}, \theta_{h,y2})$ is

$$\Theta_L = \left\{(\theta_{h,y1}, \theta_{h,y2}) \,\middle|\, w_1\theta_{h,y1} + w_2\theta_{h,y2} = \beta_h \right\},$$

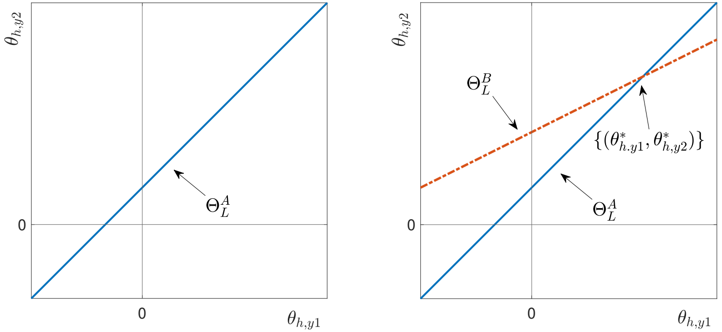
where β_h, w_1, and w_2 are functions of the observable moments.

- Θ_L is a hyperplane in R^2 (a line)
- Intersecting two lines gives a point
- For z_t^A and z_t^B,

$$\Theta_L^A = \left\{(\theta_{h,y1}, \theta_{h,y2}) \,\middle|\, w_1^A\theta_{h,y1} + w_2^A\theta_{h,y2} = \beta_h^A \right\}$$
$$\Theta_L^B = \left\{(\theta_{h,y1}, \theta_{h,y2}) \,\middle|\, w_1^B\theta_{h,y1} + w_2^B\theta_{h,y2} = \beta_h^B \right\}$$

- $\Theta_L^A \cap \Theta_L^B = \{(\theta_{h,y1}^*, \theta_{h,y2}^*)\}$

Two IVs: $\Theta_L^A \cap \Theta_L^B$



(a) Θ_L^A (b) $\Theta_L^A \cap \Theta_L^B$

Figure: Identified Sets using Granular Data

Ramey and Zubairy (2018)

- Government spending multiplier
  - The effect of an extra dollar of government purchases on total economic output
- Long debate on the magnitude of the government spending multiplier
- Most focus on the *aggregate* spending multiplier
- Two sectors: non-defense (s=1) and defense (s=2)
- Our focus: Non-defense spending multiplier

Multiplier Estimates in the Literature

- Barro (1984): around **0.6**, US defense spending in WWI, WWII, Korean War
- Blanchard and Perotti (2002): **0.9-1.3**, VAR
- Romer and Bernstein (2009): around **1.6**
- Ramey (2011): **0.6-1.2**, US defense spending, VAR
- Barro and Redlick (2011): **0.4-0.8**, US defense spending
- Auerbach and Gorodnichenko (2012): **0-0.5** in expansions and **1-1.5** in recessions, Smooth Transition VAR
- Nakamura and Steinsson (2014): **1.5**, open economy relative multiplier, panel
- Ramey and Zubairy (2018): around **0.6**, 1889-2015, LP-IV

Data

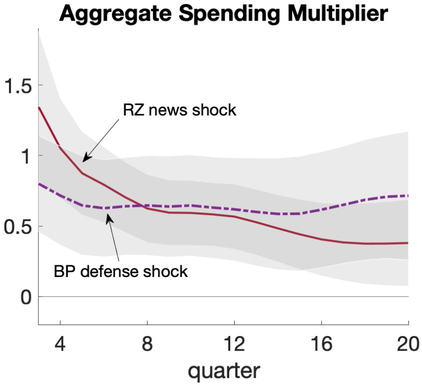
- y_t: De-trended real US GDP
- x_t: Real total government spending divided by trend GDP
- $x_{1,t}$: Real total non-defense spending divided by trend GDP
- $x_{2,t}$: Real total defense spending divided by trend GDP
- $(y_t, x_t, x_{1,t}, x_{2,t})$ are quarterly data from 1947Q1 to 2015Q4, obtained from FRED at St Louis FED
- z_t^{RZ}: Narrative military news series of Ramey and Zubairy (2018), "RZ news shock"
- z_t^{BP}: Defense spending shock of Blanchard and Perotti (2002), "BP defense shock"

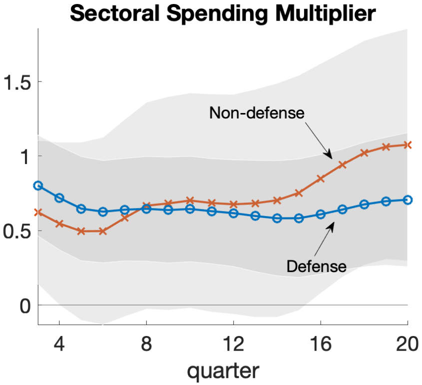
Estimation of Non-Defense Spending Multiplier

$$\sum_{j=0}^{h} y_{t+j} = \mu_h + \beta_h \sum_{j=0}^{h} x_{t+j} + \boldsymbol{\phi}_h(L)' \boldsymbol{R}_{t-1} + u_{t+h}$$

- β_h is estimated by IV method (LP-IV)
- $\widehat{\beta}_h^{RZ}$: LP-IV estimate using the RZ news shock
- $\widehat{\beta}_h^{BP}$: LP-IV estimate using the BP defense shock
- Using sectoral data (granular data) and two IVs, we obtain point identification of the sectoral spending multipliers

Estimated Multipliers with 90% CI





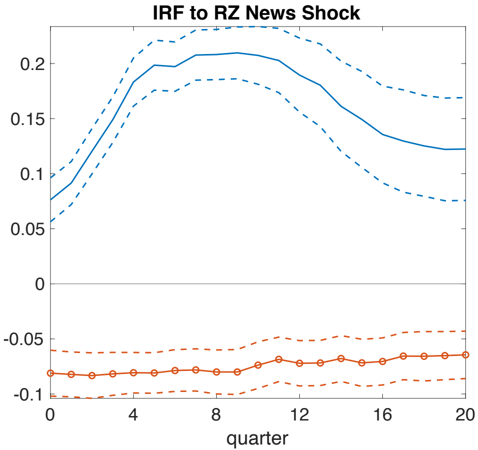
Negative Weight for Non-Defense Multiplier

- Non-defense spending multiplier is > 1 even when the aggregate and the defense spending multipliers are < 1
- Due to a negative weight for non-defense spending multiplier
- Consider the decomposition of $\widehat{\beta}_h^{RZ}$ for $h = 18$ (18 quarters):

$$\begin{array}{ccccccccc} \widehat{\beta}_h^{RZ} & = & \widehat{w}_{h,1}^{RZ} & \times & \text{non-defense} & + & \widehat{w}_{h,2}^{RZ} & \times & \text{defense} \\ 0.37 & & -0.87 & & 1.02 & & 1.87 & & 0.68 \end{array}$$

- RZ news shock is **negatively** correlated with non-defense spending
- Suggests a violation of the same-sign condition

IR of Sectoral Spending: RZ News Shock



- Defense spending: blue
- Non-defense spending: red

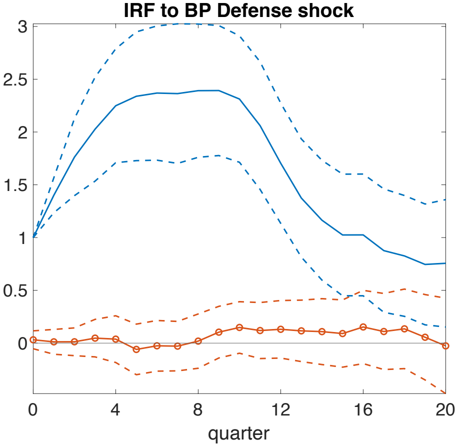
BP Defense Shock

- Likewise, $\widehat{\beta}_h^{BP}$ for $h = 18$ is decomposed into

$$\begin{array}{ccccccccc} \widehat{\beta}_h^{BP} & = & \widehat{w}_{h,1}^{BP} & \times & \text{non-defense} & + & \widehat{w}_{h,2}^{BP} & \times & \text{defense} \\ 0.69 & & 0.03 & & 1.02 & & 0.97 & & 0.68 \end{array}$$

- BP defense shock as an IV (almost) only affects the defense spending
- As a result, the BP-identified multiplier is very similar to the defense spending multiplier

IR of Sectoral Spending: BP Defense Shock



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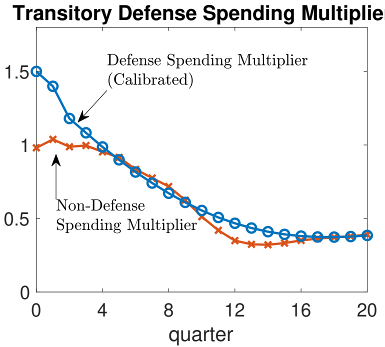
What can we do with only one IV?

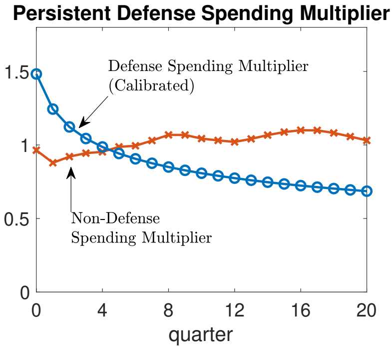
- Only one IV (RZ news shock) and the sectoral data
- LP-IV estimates:

$$\widehat{\beta}_h^{RZ} = \widehat{w}_{h,1}^{RZ} \times \text{non-defense} + \widehat{w}_{h,2}^{RZ} \times \textit{defense}[\textit{calibrated}]$$

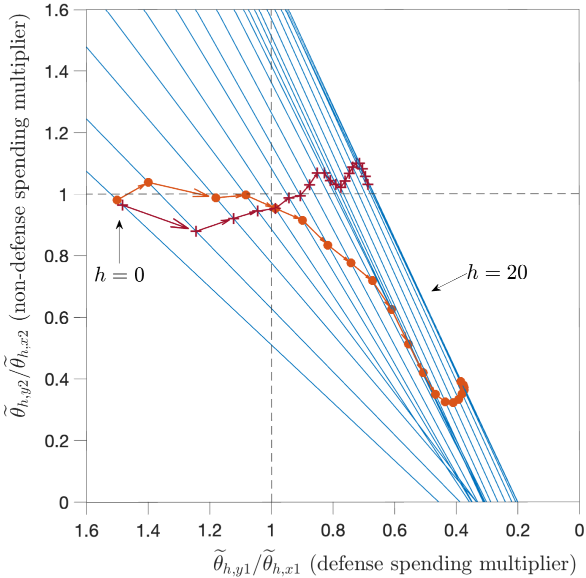
- We use Auerbach and Gorodnichenko (2012) and Barro and Redlick (2011) to calibrate the defense spending multiplier (more estimates available in the literature)

Sectoral Spending Multipliers using Calibration





Identified Set for Sectoral Spending Multipliers



Summary

- IR analysis using LP-IV when the macro shock is composite
- LP-IV estimand is an affine combination of componentwise IR (non-negative weights under the same-sign condition)
- Main intuition is that the IV may be heterogeneously correlated with the macro shock elements, which generates heterogeneous treatment
- LP-IV estimand should be carefully interpreted as a structural IR
- Simple to implement identification strategies for componentwise IR are proposed

Thank you!

Comparison with LATE

- Potential outcome framework with binary treatment D_i
  - $Y_i(0)$: potential outcome without treatment
  - $Y_i(1)$: potential outcome with treatment
- Individual treatment effect: $Y_i(1) - Y_i(0)$
- Average treatment effect: $E[Y_i(1) - Y_i(0)]$
- Potential outcomes framework: Heterogeneous *treatment effects* and homogeneous treatment D_i for the treated
- Our framework: Combinations of $\varepsilon_{s,t}$ makes $\xi_t = 1$

  $\Rightarrow$ Treatment is heterogeneous

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Monotonicity and Same-Sign

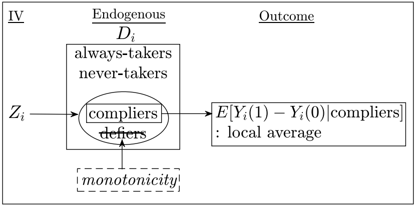

Figure: Monotonicity

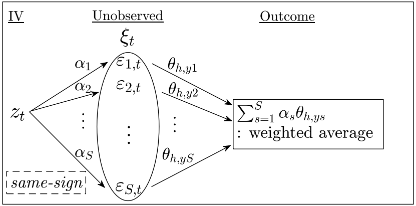

Figure: Same-Sign

- Imbens and Angrist (1994): $E[Y_i(1) - Y_i(0)|\text{compliers}]$ (LATE)
- Both LATE and LP-IV estimand identify IV-specific structural parameter
- Monotonicity: A cross-person restriction on the potential treatment status
- Same-sign: A cross-shock restriction on the sign of correlation

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