Robots at Work

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Robots much improved & more prevalent over past 25 yrs

Modern robots are autonomous, flexible, versatile machines

- moving flexibly in 3 dimensions a hard problem, but solved

Robot density (#robots per million hours worked) has increased by 150 percent in developed countries

Growing interest in the impact of robots

- special report on robots in Economist (2014), NYT video series "Robotica" (2015)
- *The Second Machine Age* (Brynjolfsson & McAfee, 2014), "Polanyi's Paradox and the Shape of Employment Growth" (Autor, 2014)

But no hard evidence on robots' impact on the economy

No empirical research in economics on the impact of robots

- in contrast to large body of evidence on ICT

More broadly, macro literature concerned about future productivity growth ("secular stagnation"), role of robots unclear

What is the impact of industrial robots on growth, productivity and employment?

What we do

Investigate the impact of industrial robots on growth, productivity, employment

Construct country-industry panel data of **robot deliveries** (International Federation of Robotics, IFR), **value added**, **labor** and other **capital** inputs (EUKLEMS)

Regress long differences (1993-2007) in log of outcome variables on change in robot density

Instrument for change in robot density

- measure industry's "replaceability" of labor by comparing robot applications with titles of occupations

Preview of results

Positive effect of robots on value added and labor productivity

Robots contributed 0.36 percentage points to annual labor productivity growth 1993-2007

No significant aggregate effect on hours worked, but some evidence of crowding out of low and middle skill workers

Results are robust to large set of specification checks, controls, falsification exercises (IV)

Related literature

Effects of ICT on productivity

Solow (1987): "You can see the computer age everywhere but in the productivity statistics." Stiroh (2002), O'Mahony & Timmer (2009) find substantial aggregate impact of ICT, Acemoglu et al. (2014) find gains are concentrated in ICT-producing industries; firm-level evidence favourable: e.g. Basker (2012), Bloom et al. (2012).

Effects of ICT on skill demand

Bias of ICT against middle skill workers: Michaels et al. (2014), Goos et al. (2014), Goos & Manning (2007), Autor (2014)

Concerns about falling labor shares

Karabarbounis & Neiman (2014), Elsby et al. (2013)

Discussions of potential future effects of robots on employment

Fears that robots will have detrimental effects on employment: Brynjolfsson & McAfee (2013), Ford (2009), Frey & Osborne (2013)

Studies of earlier automation

Doms et al. (1997), Bartelsman et al. (1998)

Outline

Outline

A model of production using robots and workers

Two sectors, robots-using (R) and non-robots-using (N)

$$U = \left[Y_R^{\frac{\varepsilon-1}{\varepsilon}} + Y_N^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon-1}} \qquad Y_R = \left[R^{\frac{\sigma-1}{\sigma}} + L_R^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}, \quad Y_N = L_N$$

ε and σ are elasticities of substitution in consumption and production, respectively

Perfect competition, exogenous rental price of robots ρ, labor in fixed supply but mobile across sectors

If robots become cheaper (if ρ falls)

1. robot density R/L_R increases
2. labor productivity Y_R/L_R increases
3. robot-using sector sells more output at lower price
4. employment L_R increases (decreases) iff $\varepsilon > \sigma$ ($\varepsilon < \sigma$)

Intuition for prediction about hours

Firms substitute cheaper robots for workers

The supply curve of the robots-using sector shifts out

Moving along the demand curve, Y_R increases in equilibrium

If consumers' response to lower relative goods prices (measured by ε) is stronger than firms' response to cheaper robots (measured by σ), then hours in the robots-using sector increase

Allowing for choice of technology

Many sectors

$$U = \left[\int_0^1 Y(i)^{\frac{\varepsilon-1}{\varepsilon}} di \right]^{\frac{\varepsilon}{\varepsilon-1}}$$

$$Y^R(i) = \left[\alpha(i)^{\frac{1}{\sigma}} R(i)^{\frac{\sigma-1}{\sigma}} + (1-\alpha(i))^{\frac{1}{\sigma}} L(i)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}, \quad Y^N(i) = L(i)$$

Adopt robot-using technology at fixed cost

Motivating the replaceability IV

Share of replaceable tasks $\alpha(i)$ must be sufficiently large for robots to be adopted

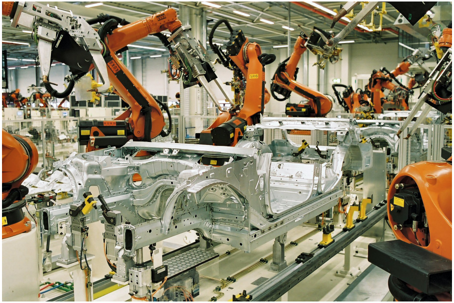
When prices fall, larger response the larger is $\alpha(i)$

Outline

What are industrial robots?

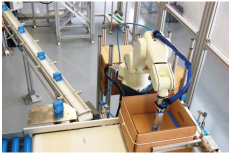
International Federation of Robotics (IFR) uses ISO definition of industrial robots

> *automatically controlled, reprogrammable, multipurpose manipulators, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications*



What are industrial robots? Examples

packaging



picking and placing

painting

welding

This paper is NOT about service robots

Constructing the data—the stock of robots

We calculate the number of robots in use from counts delivered each year as reported by IFR, using the perpetual inventory method

Robot density: stock of robots divided by million hours worked

Limitations of data: robots are heterogenous, quality rising

- aggregate price indices either from surveys (graph) or turnover

Constructing the data—cont'd

EUKLEMS variables

Real value added, hours, capital services, wage bill, TFP growth

Breakdown of capital (ICT, non-ICT) and labor (three skill groups)

Replaceability IV

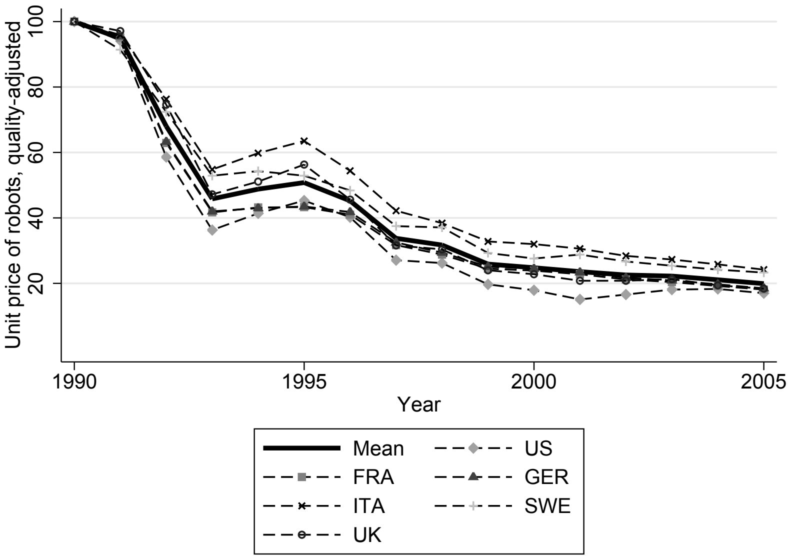
Use list of robot applications from IFR data, e.g. "welding", "processing", "assembling"

An occupation (2000 US census) has a replaceability value of one if its title contains a robot application

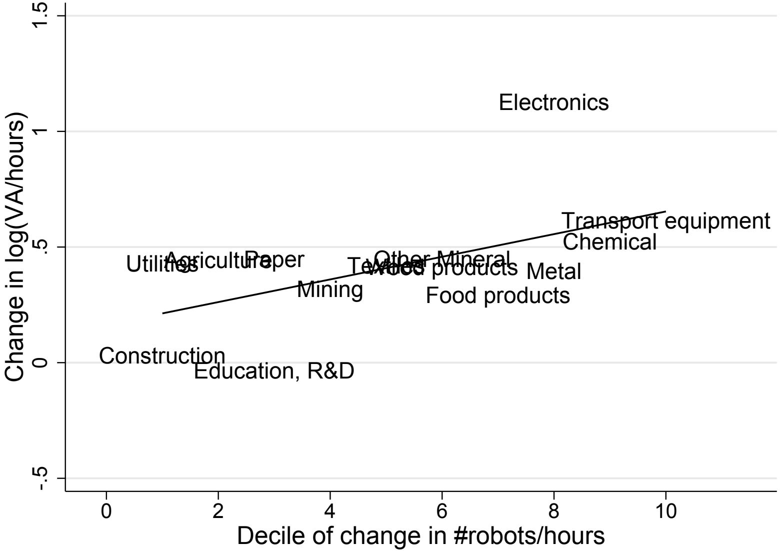
Map to 1980 US census occupations, compute fraction of replaceable hours in each industry using 1980 employment shares of occupations

Outline

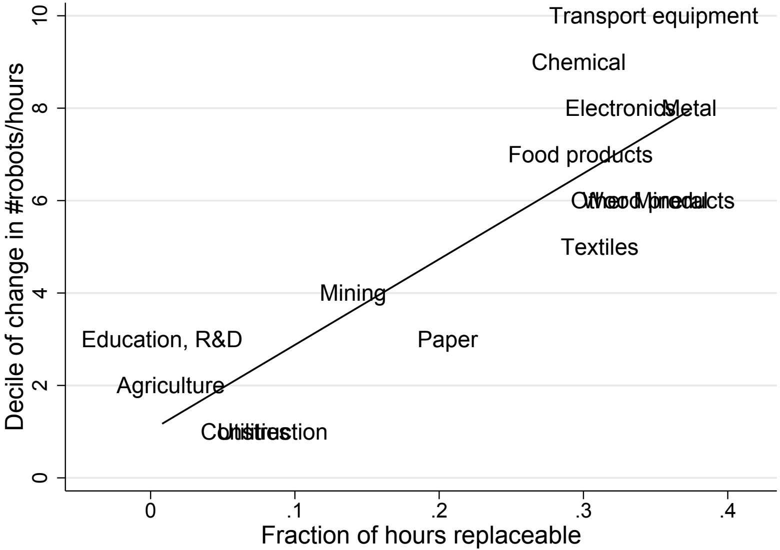
Robot prices over time in six countries, quality adjusted



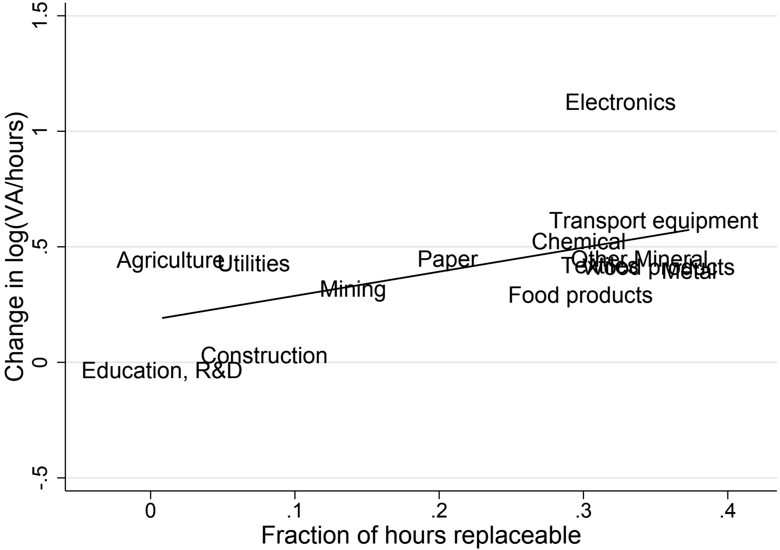
Productivity & robots at industry level (OLS)



Robots & replaceability at industry level (first stage)



Productivity & replaceability at industry level—red. form



Econometric specification

Long-differences between 1993-2007 for country c and industry i; outcome Y_{ic} (value added, VA/hours...)

OLS for various functional forms of the change in robot density $\Delta robots_{ci}$ and sets of controls

$$\Delta Y_{ci} = \gamma_1 + \gamma_2 \Delta robots_{ci} + \gamma_3 controls_{ci} + \varepsilon_{ci}$$

IV: using measure of replaceability to instrument for change in robot density

Main OLS and IV results

	Δ ln(VA/H)		Δ ln(VA)		Δ ln(H)	
A. OLS						
Pctile of Δ(R/H)/100	0.36	0.57	0.34	0.60	-0.02	0.03
	(0.13)	(0.12)	(0.14)	(0.13)	(0.10)	(0.11)
B. IV, replaceable hours						
Pctile of Δ(R/H)/100	0.88	0.91	0.58	0.64	-0.30	-0.28
	(0.12)	(0.13)	(0.13)	(0.14)	(0.12)	(0.13)
First-stage F statistic	122	109	122	109	122	109
Country trends	No	Yes	No	Yes	No	Yes
$N = 238$						

Falsification tests for the IV

	Δ ln(VA/H)	Δ ln(VA)	Δ ln(H)
A. Growth in outcome 1993-2007 (benchmark)			
Share of hours replaceable	1.13	0.80	-0.34
	(0.21)	(0.22)	(0.16)
Observations	238	238	238
B. Growth 1993-2007, non-adopters (1993)			
Share of hours replaceable	0.85	0.77	-0.08
	(0.87)	(0.82)	(0.51)
Observations	76	76	76
C. Growth 1979-1993, non-adopters (1993)			
Share of hours replaceable	-0.11	-0.17	-0.06
	(0.63)	(0.80)	(0.36)
Observations	72	72	72
D. Growth 1993-2007, non-adopters (2007)			
Share of hours replaceable	-0.37	-0.36	0.01
	(1.11)	(1.00)	(0.17)
Observations	27	27	27
p-value of test for equality, A versus C	0.03	0.20	0.41
p-value of test for equality, A versus D	0.01	0.04	0.87

Robustness checks

Controlling for industry trends results

Non-parametric specification results

Alternative functional forms results

In paper: alternative instruments, controlling for other capital and the composition of labor, controlling for prior changes in outcomes, dropping one industry or country at a time, ...

Further outcomes

Negative effect on output prices, positive effect on TFP results

Positive effect on wages, imprecisely estimated effect on labor share results

Negative effect on hours and wage bill of lower skill workers results

Magnitudes

How large would value added and labor productivity have been if robot densities had stayed at their 1993 levels? details

- VA and VA/H would have been 5.2% and 5.1% lower
- amounts to 0.37 and 0.36 percentage points of annual growth, which was 3.14 and 2 percent on average

Robots' contribution similar to that of ICT, post-war US road construction, steam engine

Conclusion

We analyze for the first time the economic impact of industrial robots using novel data

Positive impact of robots on value added and productivity

Contribute 0.37 percentage points to annual growth

- How soon will diminishing returns set in?

Contribution should be larger when robots spread to other industries

- signs that service robots are improving

Thank you!

Appendix: Outline

Counterfactual exercise to calculate magnitudes

Percentile of changes in robot density that corresponds to no change: q_0

Actual percentile: q_{ci}

For $Y \in \{VA/H, VA\}$ calculate counterfactual log change as

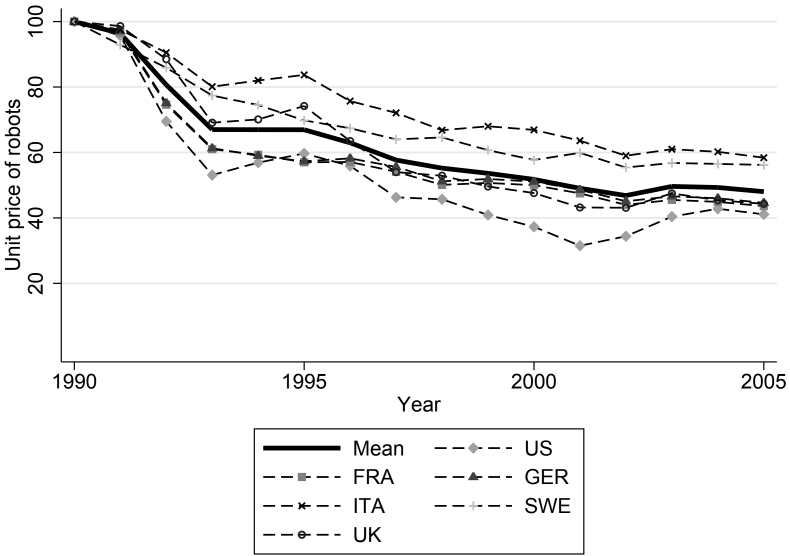
$$(\Delta \ln Y_{ci})^{cf} = \Delta \ln Y_{ci} - \widehat{\beta}_Y (q_{ci} - q_0)$$

Compute the counterfactual levels of productivity and value added in 2007 for each country-industry, aggregate to the country level, obtaining $Y^{cf}_{c,2007}$

Comparing to actual 2007 levels: calculate the percentage loss

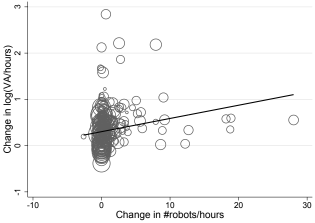
$$100 \times (1 - Y^{cf}_{c,2007}/Y_{c,2007})$$

Robot prices over time in six countries

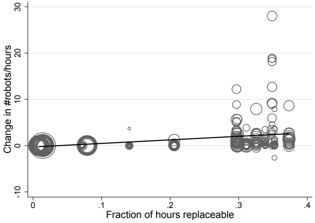


Productivity, robots, & replaceability—using robots/hours

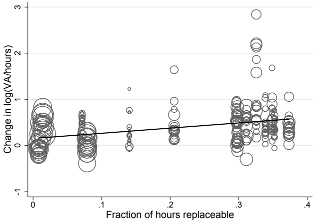
(a) OLS



(b) First stage



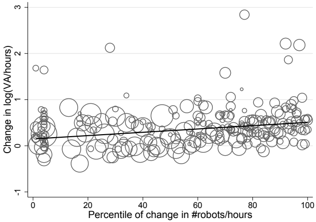
(c) Reduced form



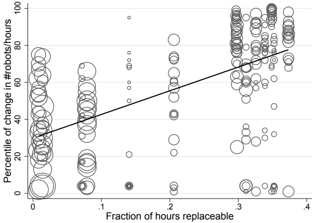
Note: all slope coefficients are statistically significant

Productivity, robots, & replaceability—percentile of change

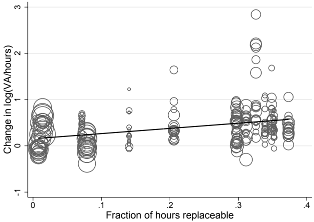
(a) OLS



(b) First stage



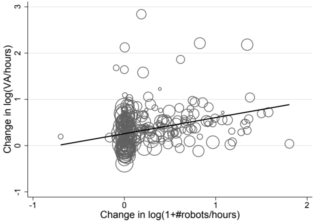
(c) Reduced form



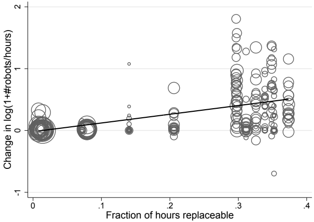
Note: all slope coefficients are statistically significant

Productivity, robots, & replaceability—using $\ln(1 + R/H)$

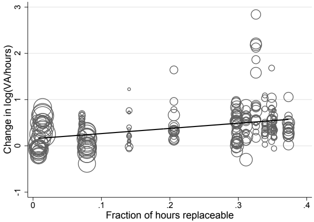
(a) OLS



(b) First stage



(c) Reduced form



Note: all slope coefficients are statistically significant

Summary statistics for robot densities

Note: all results reported are weighted using baseline employment shares of industries within a country (countries receive equal weights)

Robots per million hours worked were on average 0.58 in 1993

- Top three *countries*: Germany (1.7), Sweden (1.4), Belgium (1.2); US: 0.41
- No or almost no robots: Australia, Greece, Hungary, Ireland
- Top *industry* was Transport Equipment (5.4)

Robots per million hours worked increased by 0.90 (150 percent) on average 1993-2007

- Top three countries: Germany (2.7), Denmark (1.6), Italy (1.4); US: 0.97
- All countries and industries employed robots in 2007

Increased adoption likely due to fall in prices

Robustness to controlling for industry trends

	Δ ln(VA/H)		Δ ln(H)	
B. OLS				
Pctile of Δ(R/H)/100	0.57	0.35	0.03	0.01
	(0.12)	(0.15)	(0.11)	(0.10)
C. IV, replaceable hours				
Pctile of Δ(R/H)/100	0.91	0.93	-0.28	-0.02
	(0.13)	(0.38)	(0.13)	(0.64)
First-stage F statistic	109.0	4.5	109.0	4.5
Country trends	Yes	Yes	Yes	Yes
Industry trends	No	Yes	No	Yes
$N = 238$				

Results from non-parametric specification

	Δ ln(VA/H)		Δ ln(VA)		Δ ln(H)	
Δ(R/H), quartile 2	-0.06	0.12	0.01	0.23	0.07	0.11
	(0.07)	(0.09)	(0.11)	(0.15)	(0.12)	(0.14)
Δ(R/H), quartile 3	0.04	0.20	0.00	0.20	-0.04	0.00
	(0.08)	(0.08)	(0.08)	(0.12)	(0.09)	(0.11)
Δ(R/H), quartile 4	0.27	0.45	0.28	0.49	0.01	0.05
	(0.10)	(0.10)	(0.12)	(0.12)	(0.10)	(0.12)
Country trends	No	Yes	No	Yes	No	Yes
$N = 238$						

Alternative functional forms

	Δ ln(value added/hours)		Δ ln(value added)	
A1. OLS				
Δ(#robots/hrs)	0.029	0.032	0.029	0.037
	(0.012)	(0.012)	(0.014)	(0.014)
A2. IV, replaceable hours				
Δ(#robots/hrs)	0.146	0.151	0.096	0.106
	(0.036)	(0.037	(0.030)	(0.032)
First-stage F statistic	32.1	30.2	32.1	30.2
B1. OLS				
Δ ln(1 + #robots/hours)	0.348	0.406	0.317	0.385
	(0.119)	(0.108)	(0.145)	(0.147)
B2. IV, replaceable hours				
Δ ln(1 + #robots/hours)	0.794	0.808	0.521	0.563
	(0.148)	(0.155)	(0.139)	(0.149)
First-stage F statistic	68.1	57.3	68.1	57.3
C1. OLS				
Δ(1,000 × robot services/wage bill)	0.121	0.116	0.109	0.116
	(0.083)	(0.065)	(0.106)	(0.105)
C2. IV, replaceable hours				
Δ(1,000 × robot services/wage bill)	1.414	1.445	0.928	1.008
	(0.762)	(0.798)	(0.540)	(0.600)
First-stage F statistic	3.3	3.1	3.3	3.1
Country trends	No	Yes	No	Yes
$N = 238$				

Effects on output prices & TFP

	$\Delta \ln(P)$		$\Delta \ln(TFP)$	
A. OLS				
Pctle of $\Delta(\#R/H)/100$	-0.38	-0.35	0.26	0.39
	(0.07)	(0.11)	(0.13)	(0.11)
B. IV, replaceable hours				
Pctle of $\Delta(\#R/H)/100$	-0.55	-0.54	0.62	0.67
	(0.12)	(0.12)	(0.11)	(0.12)
First-stage F statistic	122	109	95	91
N	238	238	210	210
Country trends	No	Yes	No	Yes

Effects on wages & labor share

	$\Delta \ln(\text{wage})$		$\Delta(\text{lab. share})$	
A. OLS				
Pctile of $\Delta(R/H)/100$	-0.01	0.04	-0.07	-0.06
	(0.03)	(0.01)	(0.11)	(0.08)
B. IV, replaceable hours				
Pctile of $\Delta(R/H)/100$	0.07	0.08	-0.15	-0.13
	(0.02)	(0.02)	(0.13)	(0.13)
First-stage F statistic	122	109	122	109
Country trends	No	Yes	No	Yes
$N = 238$				

Effects on hours and wage bill by skill group

	high skill		middle skill		low skill	
A. Hours, OLS						
Pctile of $\Delta(R/H)/100$	0.01	0.14	-0.15	-0.08	-0.23	-0.16
	(0.12)	(0.09)	(0.16)	(0.09)	(0.07)	(0.06)
B. Hours, IV						
Pctile of $\Delta(R/H)/100$	0.15	0.23	-0.13	-0.04	-0.26	-0.21
	(0.17)	(0.17)	(0.13)	(0.10)	(0.08)	(0.08)
First-stage F statistic	122	109	122	109	122	109
C. Wage bills, OLS						
Pctile of $\Delta(R/H)/100$	-0.11	0.10	-0.26	-0.13	-0.23	-0.18
	(0.13)	(0.12)	(0.19)	(0.10)	(0.08)	(0.07)
D. Wage bills, IV						
Pctile of $\Delta(R/H)/100$	0.08	0.17	-0.19	-0.08	-0.28	-0.21
	(0.19)	(0.19)	(0.16)	(0.11)	(0.09)	(0.13)
First-stage F statistic	122	109	122	109	122	109
Country trends	No	Yes	No	Yes	No	Yes
$N = 238$						