Wage inequality and skill supplies in a globalised world

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This draft: December 2019

Abstract

We investigate empirically, and explain theoretically, how the relative wages of skilled and unskilled workers vary with their relative supplies in open economies. Our results combine the insights of simple labour market and trade models. In countries that trade, relative wages respond inversely to variation in skill supplies, but the response decreases with the degree of openness to trade and is small in very open countries. To reconcile our results with standard estimates of the elasticity of substitution between skilled and unskilled workers, we allow also for the influence of directed technical change and income elasticity of demand for skill-intensive goods.

Keywords: Wage inequality, labour markets, Heckscher-Ohlin, trade and wages, directed technical change.
JEL codes: F11, F16, J23, J31.

*We are grateful to a referee and the editor, Timur Kuran, for comments that enabled us to improve this article substantially. We received very useful comments also from Nicolas Berman and Marcelo Olarreaga, and from seminar participants at Oxford, Sussex, Birmingham, Louvain-la-neuve, RCEA workshop, LETC Slovenia, EEA meetings, DEGIT Geneva, Bari, LSE, Melbourne, UNSW, CEPII Paris, Adelaide, Marseille, Bank of Canada, St Andrews, WU Vienna, and Insted Workshop 2017, and Paris (IELM). Earlier versions of this paper were entitled 'Wages and endowments in a globalised world'.

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I Introduction

Concern about wage inequalities remains strong in many countries. The income share of the top one percent tends to grab the headlines, but among the "other 99 percent", most of the inequality still reflects differences in wages between workers of different skill levels (Autor, 2014). A commonly suggested policy response is to increase the relative supply of skilled workers by improving access to higher education and training. The hope is that such a supply shift would not only lower the proportion of lower-paid workers but also narrow the gap in wages between the skilled and the less-skilled. However, standard economic models offer differing views on the effects of changes in skill supplies on relative wages in countries open to international trade.

That a larger relative skill supply would narrow the wage gap, to a degree dependent on substitutability between workers with different skills, is predicted by standard models of the labour market. In the simplest Heckscher-Ohlin (HO) trade model, however, wages in an open economy are, as Freeman (1995) put it, "set in Beijing" – pinned down by world prices and trade costs, and insensitive to changes in skill supplies. In more complex models, this difference of predictions is blurred.[1] But there remains a basic tension between the labour market logic (a demand curve linking relative wages to skill supplies) and the trade logic (variation in skill supplies absorbed by changes in production structure).

Empirical resolution of this issue has been hindered by a shortage of panel data on wages and skill supplies in a wide spectrum of countries. A big step forward in this respect is the Socio-Economic Accounts of the World Input-Output Database (WIOD, 2013 release), which cover 40 countries during 1995-2009. What these data show at first sight is in the two panels on the left side of Figure 1, which plots the logged wages of college-educated relative to other workers against their logged relative employment for all the WIOD countries – more information on the variables is in section III.

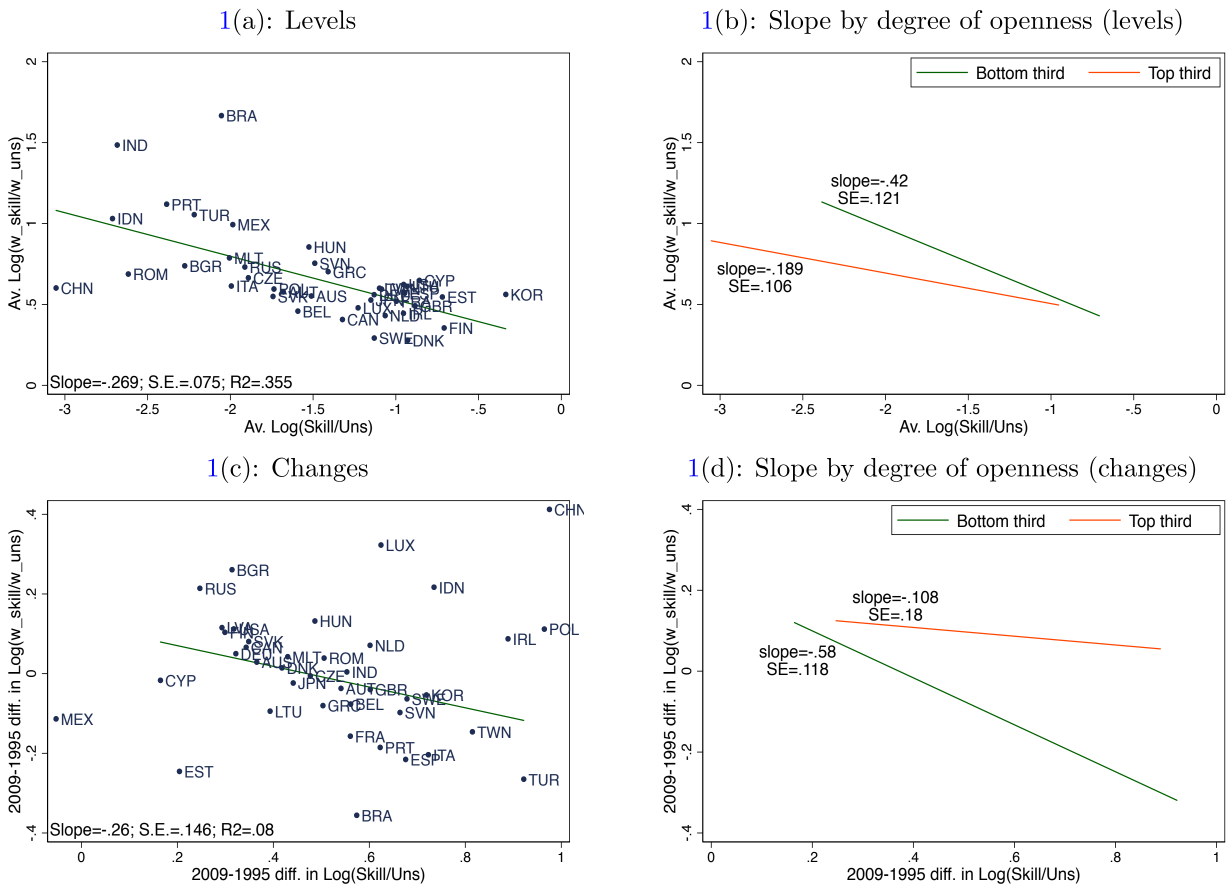
The upper panel 1(a) shows the relationship across countries in levels (after averaging the data over time). There is a clear downward slope, with an elasticity estimated at -0.27 (and consistently between -0.2 and -0.3 in individual years). The lower panel 1(c) shows the relationship across countries in changes. It is confused by outliers, but if we drop Mexico, whose employment data are suspect,[2] and the transition countries, whose labour

[1] Countries with widely differing relative skill supplies can have different wages because they produce different sets of goods, as in the "multi-cone" HO models of Markusen and Venables (2007) and Leamer (2012). Firm heterogeneity and labour market frictions (Helpman and Itskhoki, 2010) can also link relative wages with relative skill supplies in trade models, though not necessarily in the direction labour economists would expect (Trionfetti, 2015).

[2] The fall in the college-educated share of employment in Mexico is out of line with all other countries,

market institutions changed substantially, not least in China[3], there is a similar though less significant elasticity of -0.26.

Figure 1: Relative wages and skill supplies across countries



Notes: All regressions include a constant. Prediction line and statistics in Figures 1(c) and 1(d) are based on a regression excluding CHN, MEX, and POL. The regressions lines in Figures 1(b) and 1(d) are based the subsamples in the first tercile of trade openness ("bottom third") and in the third tercile of trade openness ("top third"). The split of countries by openness (as defined in section IV) is based on their average openness during 1995-2009.

These numerical values are puzzling. Their downward slope is inconsistent with the zero predicted by the simplest HO model, but far less steep than the -0.7 implied by the

and based on sources that changed during the period (`http://stats.oecd.org/mei/default.asp?lang=e&subject=10&country=MEX`). The regression reported in Figure 1(c) also excludes two other extreme outliers, China and Poland. If the other European transition countries are also dropped, the elasticity is -0.24 (p-value = 0.12).

[3]The relaxation of administrative control of wages in China was accompanied by rapid expansion of universities, which had been closed during the Cultural Revolution (Knight and Song, 2005). The combination of these influences puts China in the bottom left corner of Figure 1(a) and in the upper right corner of Figure 1(c).

often-quoted Katz and Murphy (1992) aggregate elasticity of substitution of 1.4 between college-educated and other labour in the US.[4] Nor is the observed pattern consistent with a more complex ('multi-cone') HO model.[5]

A clue to solving the puzzle is presented in the two panels on the right side of Figure 1, which show separately the slopes for more open countries and less open countries, where 'more open' refers to countries in the top third of trade-to-GDP ratios (averaged over time and adjusted for country size, as explained in section IV), and 'less open' to countries in the bottom third. There is a striking difference: in levels (Figure 1(b)), the downward slope for more open countries (-0.19) is less than half as steep as that for less open countries (-0.42); in changes (Figure 1(d)), the downward slope for more open countries (a statistically insignificant -0.11) is an even smaller fraction of that for less open countries (-0.58).[6]

The descriptive evidence in Figure 1 is validated by the more refined estimates in later sections of the paper. We find that relative wages in open economies vary with relative skill supplies, in line with simple labour market models and as Figures 1(a) and 1(c) suggest. But we also find that the response of wages to skill supplies is smaller in countries with lower barriers to trade, as Figures 1(b) and 1(d) illustrate, and in very open economies comes close to the simple trade economics view that wages are unaffected by skill supplies.

Theoretically, we explain these results by extending Samuelson's classic formalisation of the HO model to include elements of other models. One such element is the observed price inelasticity of sales and purchases of goods in world markets. A widely accepted explanation of this inelasticity, due to Armington (1969), is qualitative differences – and hence imperfect substitutability – among the varieties produced by different countries (or firms, as in Krugman (1979)) of what trade statistics classify as the same good. An

[4]The estimated elasticities in Figure 1 are at the other end of the (-0.3, -0.7) range reported by Katz and Autor (1999) in their review of the empirical evidence from different countries in the 1990s. For later years in the US, Blankenau and Cassou (2011) also estimate an elasticity of about -0.7, as do Acemoglu and Autor (2011, Table 6), though only with a non-linear time trend. Blum (2010) too estimates an elasticity of about -0.7 for 15-year changes in all countries, using data for 1973-90 on occupational (production vs non-production workers) rather than educational categories (with less negative values for shorter periods and more negative values for developed countries only).

[5]In section C of the Online Appendix, we convert the cross-country slope in Figure 1(a) into a step function congruent (apart from China) with a four-cone HO model. However, half of the countries stay in one cone throughout the period (Figure C.2). In theory their wages should have been insensitive to changes in skill supplies, but there is no clustering of relative wage changes around zero in Figure 1(c).

[6]The estimated slope for countries in the middle third is -0.26 (std. error=0.13) in Figure 1(b) and -0.02 (std. error=0.39) in Figure 1(d). The same pattern emerges if we compare countries above and below the median trade-to-GDP ratio. In levels, the slope is -0.34 (std. error=0.12) for countries below median openness, and -0.23 (std. error=0.11) for countries above. In changes, the slope is -0.40 (std. error=0.15) for countries below median openness, and insignificantly different from zero (equal to -0.16; std. error=0.17) for countries above.

additional, more recent explanation of this inelasticity is differences in efficiency and location among countries (Eaton and Kortum, 2002) and firms (Melitz, 2003).

Because the demand for labour is a derived demand, price inelasticity in the world market for goods creates inelasticity of demand in labour markets and helps to explain why relative wages vary with skill supplies in open economies. If world demand for goods were infinitely elastic, any change in skill supplies might (as in the simplest HO model) be fully absorbed by a change in the country's relative output of more and less skill-intensive goods, leaving goods prices and thus relative wages unaffected.

Our model includes two additional sources of labour demand inelasticity (drawn from Wood (2012)). First, the goods price elasticities faced by a country's firms depend also on its degree of openness: the bigger the share of home suppliers in the home market, as a result of higher trade barriers, the more do their sales depend on substitutability among goods, which is lower than substitutability among home and foreign varieties of the same good. Second, components of the relative total costs of different goods that do not vary in proportion to their relative labour costs (capital and materials, most obviously). By attenuating the response of relative prices to changes in relative wages, these other cost components reduce the scope for the output structure to absorb changes in skill supplies.

The relative elasticity of demand for skilled and unskilled workers in an open economy thus depends on all three of these elements– inelasticity of demand for goods in world markets, degree of openness to trade, and the size of costs that do not vary in proportion to labour costs. We set out a model that includes these three elements and provides the basis for our empirical investigation of the responsiveness of relative wages to variation in skill supplies using the WIOD data.

Reduced-form estimation is problematic: observed elasticities of the sort in Figure 1 are the outcome of several forces, including the three just mentioned, and there is not enough exogenous variation in the data to be able to identify their influence separately. However, we start by using reduced-form methods to check the prima facie consistency of our model with reality. Our results confirm the inverse relationship between the relative wages and relative supplies of skilled and unskilled workers found in many other studies (e.g. Katz and Murphy (1992); Robbins (1996); Blum (2010); Marshall (2012); Morrow and Trefler (2017)). As suggested by our model, moreover, the inverse relationship is weaker where countries are more open to trade and where the ratio of wages to other costs is higher.

These reduced-form inferences are supported by the results of structural estimation of our theoretical model – obtaining numerical values for its parameters and simulating the response of relative wages to the observed variation in relative skill supplies. The simulated changes in relative wages are correlated with actual changes in relative wages, both across countries and within countries over time, and the correlation is increased by incorporating the two novel elements of our model – degree of openness to trade and size of non-proportional non-labour costs.

The structural estimates of our baseline model, however, imply a wage-skill supply elasticity that is much lower (i.e. more negative) than in Figure 1 and in our reduced-form estimates. The difference can plausibly be explained by adding two other elements to the theoretical framework, drawing on Acemoglu (2007) and Caron et al. (2014). One is directed technical change: increases in the supply of a factor create an incentive to find new ways of using it more productively. The other is that increases in skill supply raise incomes and that the demand for skill-intensive goods is income-elastic. Adding these two elements brings the aggregate elasticity of substitution between skilled and unskilled workers implied by our structural results into line with generally accepted estimates of this parameter.

In addition to the work by others already noted, our paper relates and contributes to several areas of the literature. One is the role of variation in the sectoral structure of output in absorbing variation in factor supplies, documented for trade by Romalis (2004) and Chor (2010) and for immigration by Lafortune et al. (2015). That such variation in output requires variation in goods prices is a feature also of Costinot and Rodriguez-Clare (2014), and that price elasticities depend on trade shares is in the spirit of Rodrik (1997).[7] Non-proportional costs affect goods prices as in Alchian and Allen (1964) and Hummels and Skiba (2004).

Our paper also fits with studies showing that variation in output structure absorbs only part of the variation in skill supplies (Ciccone and Peri, 2005; Blum, 2010; Lewis, 2013), with the rest absorbed by variation in skill intensity (Davis and Weinstein, 2001; Schott, 2003). We combine these two absorption mechanisms in an extension of the "economy-wide elasticity of substitution" of Jones (1965).

Our paper complements studies of variation in relative wages across countries for reasons other than variation in their skill supplies, including labour market institutions, technology (Levchenko and Zhang, 2016; Morrow and Trefler, 2017), and market size (Epifani and Gancia, 2006). It also complements studies of the various ways in which openness can make a country's relative wages higher or lower than would be expected from its skill supply (e.g.

[7] Rodrik showed theoretically that greater international mobility of capital could increase the elasticity of demand for labour in an economy open to trade, and he conjectured that an increase in openness to trade would have a similar effect (Panagariya, 1999). His conjecture has been tested at plant, firm and industry level (but not for the whole economy) in later studies, most of which have found some relationship between these micro elasticities, especially for unskilled labour, and proxies for openness to trade, though in some cases not robust to controls for new technology or time trends (e.g., Slaughter (2001); Hijzen and Swaim (2010); Senses (2010)).

Wood (2002); Epifani and Gancia (2008); Harrison et al. (2011); Parro (2013); Burstein and Vogel (2017)).

The rest of the paper is organised as follows. Section II sets out the theory. Section III describes our empirical strategy and the WIOD data. Sections IV-VI present the results. Section VII concludes.

II Theoretical framework

For simplicity, we start with a model of a single country in which two sorts of labour, H (high-skilled) and L (low-skilled), produce two goods, B (biochemicals, which are H-intensive) and G (garments, which are L-intensive). Using the small-proportional-changes 'hat' algebra of Jones (1965), where $\widehat{x} = {}^{dx}/_{x}$ and $\widehat{x}_{1/2} = \widehat{x}_1 - \widehat{x}_2$, changes in the relative labour costs of the goods, $\widehat{c}_{B/G}$, are related to changes in relative wages, $\widehat{w}_{H/L}$, by

$$(1) \quad \widehat{c}_{B/G} = (\theta_{HB} - \theta_{HG})\, \widehat{w}_{H/L}$$

where θ_{ij} is the share of labour type i in the cost of good j. Since the greater skill intensity of B implies $\theta_{HB} > \theta_{HG}$, an increase in the relative wage of skilled workers raises the relative cost and price of the skill-intensive good. Labour-market clearing requires

$$(2) \quad \widehat{v}_{H/L} = -\left[1 - (\lambda_{HB} - \lambda_{LB})\,(\theta_{HB} - \theta_{LB})\right] \sigma \widehat{w}_{H/L} + (\lambda_{HB} - \lambda_{LB})\, \widehat{q}_{B/G}$$

where the economy-wide supply of a labour type is denoted by v (so $\widehat{v}_{H/L}$ is the change in the relative supply of skilled workers), the output of a good is denoted by q (so $\widehat{q}_{B/G}$ is the change in the relative output of good B), λ_{ij} is the share of the supply of labour type i used by good j (with the greater skill intensity of B implying $\lambda_{HB} > \lambda_{LB}$), and σ is the elasticity of substitution between H and L in production, assumed to be the same for both goods.

A rise (say) in the relative supply of skilled labour ($\widehat{v}_{H/L} > 0$) must be matched by a rise in the relative demand for skilled labour. This can be achieved by a fall in the relative skilled wage that induces a rise in the skill intensity of the techniques used in producing both goods (as in the first right-hand side (rhs) term in (2)) and/or by a shift in the composition of output towards the skill-intensive good B (as in the second term). The bigger the difference in skill intensity between the two goods, measured by $(\lambda_{HB} - \lambda_{LB})$, the larger is the proportion of the supply shift that can be absorbed by any given change in relative quantities, and so the smaller is the proportion that needs to be absorbed by changes in technique within sectors.

(a) Demand system

In an open economy, consumers buy both home-produced and imported varieties of goods. Their preferences among varieties are described, as in many other models (for example, Costinot and Rodriguez-Clare (2014)), by a constant-elasticity-of-substitution (CES) utility function

$$(3) \quad C_j = \left[\left(C_j^H \right)^{\frac{\beta_j - 1}{\beta_j}} + \left(C_j^M \right)^{\frac{\beta_j - 1}{\beta_j}} \right]^{\frac{\beta_j}{\beta_j - 1}}$$

where C_j^H and C_j^M are composites of home-produced and imported varieties in sector j, respectively, and β_j is the elasticity of substitution between the two composites, assumed to be finite (and to be equal to the elasticities of substitution within the composites, as found by Feenstra et al. (2018) for two-thirds to three-quarters of their sample of U.S. goods). The relative sales of goods B and G depend on the relative prices of the aggregate utility of each good (C_j from eq. (3)) according to a higher-level CES utility function

$$(4) \quad C = \left[\alpha C_B^{\frac{\gamma_{BG} - 1}{\gamma_{BG}}} + (1 - \alpha) \, C_G^{\frac{\gamma_{BG} - 1}{\gamma_{BG}}} \right]^{\frac{\gamma_{BG}}{\gamma_{BG} - 1}}$$

where α is a preference parameter and γ_{BG} is the elasticity of substitution between the goods. A crucial and plausible assumption of our model is that that γ_{BG} is lower than β_B or β_G, since there is normally far less substitutability among goods than among varieties of the same good.

For home producers, whose behaviour is what matters for clearing the domestic labour market in our model, the elasticity of their relative sales of B and G with respect to the relative prices they charge, denoted by ϵ_{BG}, is a weighted average of γ_{BG}, β_B and β_G, in which the weights depend on their shares of (and the relative sizes of) the various markets in which they sell. Where they have small shares, as in export markets open to all comers, their price elasticity is close to that among varieties, β. With bigger shares, as in home markets sheltered from imports by trade barriers, the relative price of the B and G aggregates is more dependent on the prices of home-produced varieties, so the relative sales of home producers are more dependent on consumer preferences among goods (γ) rather than among varieties (β). If home producers supply the entire market, as with a non-traded good, the only relevant elasticity is γ.

Formally, with (3) and (4) being CES, the relevant average of the γ and β's in any particular market can be written precisely, following Sato (1967), as a weighted harmonic mean (which we use in the calculations in section V). For purposes of exposition, this average can temporarily be written more simply for the two goods B and G as a weighted arithmetic mean

$$(5) \quad \epsilon_{BG} = s_{BG}\gamma_{BG} + (1 - s_{BG})\,\beta_{BG}$$

where β_{BG} is an average of β_B and β_G and s_{BG} is the average across B and G of the shares of home producers in the market concerned (either the home market or the market of a foreign country). For each good in each market, the share of home producers, s_j, depends on the ratio of their sales to those of all foreign suppliers (denoted by an asterisk), which is determined through the CES demand system as

$$(6) \quad \frac{p_j q_j}{p_j^* q_j^*} = R\left(\frac{p_j}{p_j^*}\right)^{1-\beta_j} = R\left[\frac{c_j\,(1+\tau_j)}{c_j^*\,(1+\tau_j^*)}\right]^{1-\beta_j}$$

with p being price, R a measure of the selling country's economic size relative to that of the rest of the world, and τ the ratio of other production and trade costs per unit of output, t, to unit labour costs, c. Market share depends on country size and on comparative advantage (reflected in ${}^{c_j}/_{c_j^*}$), and it increases with the height of trade barriers to foreign suppliers (relative to those that affect home-country suppliers – which would be lower in the home market, but similar or higher in an export market).

The effect of relative prices on a country's relative outputs of B and G depends on the average ϵ_{BG} across all its markets, at home and abroad, weighted by the shares of its total sales in each market. This average elasticity – which for simplicity and with a slight abuse of notation we will also label ϵ_{BG}, and henceforth refer to as the 'price elasticity' – increases with exposure to trade for two reasons. Lower barriers to imports push s_{BG} down and thus increase ϵ_{BG} in its home market. Greater access to foreign markets increases the share of exports in its output and so the weight in the average ϵ_{BG} of the higher ϵ_{BG}'s in its foreign markets (where s_{BG}'s are small). The demand system in this two-good model can thus conveniently be summarised by

$$(7) \quad \widehat{q}_{B/G} = -\epsilon_{BG}\widehat{p}_{B/G}$$

in which a country's relative sales of the goods depends on their average relative prices, p, and on the average relative demand elasticity, across all markets.

(b) Price-cost elasticity

The elasticity of the relative wage with respect to relative skill supplies in our model depends not only on the price elasticity ϵ_{BG}, but also on the responsiveness of the relative prices of goods B and G to their relative unit labour costs, $c_{B/G}$, which we call the 'price-cost elasticity', δ_{BG}. This elasticity is a novel feature of our model and is implicitly assumed in most other models to be unity.[8]

In practice, δ_{BG} is normally less than unity (the relative prices of goods vary by proportionally less than their relative unit labour costs), because prices contain costs that do not vary in proportion to their unit labour costs, including per-unit trade costs (Alchian and Allen, 1964; Hummels and Skiba, 2004). Intuitively, the main determinant of the size of δ_{BG} is the share of labour costs in the prices of the goods concerned. The smaller is this share, as a result of larger other costs, the smaller is the effect of a proportional change in relative unit labour costs on relative prices (just as, for instance, with a single good for which labour was half the cost, a 10% rise in the unit labour cost would raise the price by only 5%).

Deriving an exact expression for $\delta_{BG} = \frac{\widehat{p}_{B/G}}{\widehat{c}_{B/G}}$ is complicated (section D of the Online Appendix), but for purposes of exposition its essential features can be conveyed by

$$(8) \qquad \delta_{BG} = \frac{1 + \eta_{BG}\tau_{BG}}{1 + \tau_{BG}}$$

where τ_{BG} is the geometric mean of τ_B and τ_G (defined as before as $\tau_i \equiv \frac{t_i}{c_i}$), and η_{BG} is the elasticity of $\frac{t_B}{t_G}$ with respect to $\frac{c_B}{c_G}$. If η_{BG} is zero, meaning that the relative other costs of the two goods are independent of their relative unit labour costs, this equation reduces to $\frac{1}{1+\tau_{BG}}$, which (in line with the intuition set out above) is the average share of labour costs in the prices of the two goods. If relative other costs vary with relative unit labour costs, for example because some trade costs are ad-valorem, η_{BG} will be positive, tending to increase δ_{BG} (and if η_{BG} were unity, as if for example non-labour costs consisted only of ad-valorem trade costs, δ_{BG} would be unity, too).

[8] Incomplete pass-through plays a similar role in models with imperfect competition (Krugman (1979); Dornbusch (1987); and, with heterogeneous firms, Berman et al. (2012)).

(c) Wage-skill supply elasticity

Combining eq. (1), (2), and (7) (with $\widehat{p}_{B/G} = \delta_{BG}\widehat{c}_{B/G}$), the effect of changes in the relative supply of skilled and unskilled workers on relative wages can be derived as

$$(9) \quad \widehat{w}_{H/L} = -\frac{1}{\left[1-(\lambda_{HB}-\lambda_{LB})(\theta_{HB}-\theta_{HG})\right]\sigma + (\lambda_{HB}-\lambda_{LB})(\theta_{HB}-\theta_{HG})\,\epsilon_{BG}\delta_{BG}}\widehat{v}_{H/L}$$

The denominator of the rhs ratio is what Jones (1965) first described as the "economy-wide elasticity of substitution between factors".[9] Its first term is an 'aggregate' intra-sectoral elasticity of substitution between H and L. It determines the extent to which changes in the skill mix of employment within sectors can absorb variations in relative skill supplies. The second term illustrates how shifts in the sectoral composition of output can offset changes in skill supplies. It is the product of four elasticities: of relative labour costs with respect to relative wages $(\theta_{HB} - \theta_{HG})$, of relative goods prices with respect to relative labour costs δ_{BG}, of relative outputs with respect to relative goods prices ϵ_{BG}, and of relative employment of skilled and unskilled workers with respect to relative outputs $(\lambda_{HB} - \lambda_{LB})$.

Another way to look at the denominator of (9) is as a weighted average of the elasticity of substitution in production (σ) and the elasticity of relative sales with respect to labour costs ($\epsilon_{BG}\delta_{BG}$). The weights depend on the difference in skill intensity between the goods: the greater is $(\lambda_{HB} - \lambda_{LB})(\theta_{HB} - \theta_{HG})$, the greater the scope for absorbing changes in skill supplies by changes in product mix, and the smaller the need for changes in skill intensity within sectors. The higher are σ, ϵ_{BG} and δ_{BG}, moreover, the less does a rise in the relative supply of skilled workers depress their relative wage.[10]

(d) Influence of openness to trade on wage-skill supply elasticity

Eq. (9) can be expanded to include n goods (indexed by j and with good 1 as the numeraire), as will be shown in section V. This expansion could enable the model to include trade in intermediate as well as final goods (though there are practical limits on doing so in our

[9] The form of the denominator of eq. (9) is also basically the same as the form of eq. (15) of Jones (1965), but with one simplification (the assumption of a common σ across sectors) and one important difference, which is that Jones derives his equation for a closed economy, where the elasticity of relative outputs with respect to relative prices is γ_{BG} rather than ϵ_{BG} (and δ_{BG} is implicitly assumed to be unity).

[10] In practice, because data on goods are always aggregated, the aggregate elasticity of substitution in production (the first term in the denominator of the rhs ratio) encompasses wage-induced changes in intra-sectoral product mix as well as in techniques of production (Davis and Weinstein, 2001; Schott, 2003). Within each sector is a relationship qualitatively similar to that across sectors described by eq. (9), including the effect of changes in the relative prices of products of differing skill intensity on their relative sales and hence their relative weight in the output of the sector.

analysis). 'Other costs' should then include traded intermediate inputs, and unit labour costs should include the labour embodied in non-traded intermediate inputs. Production also needs capital, which is assumed to be internationally mobile (for reasons explained in Wood (1994, section 2.2) and supported by the evidence in Caselli and Feyrer (2007)), and thus plays a role similar to that of traded intermediate inputs.

Openness to international markets affects the elasticity of relative wages with respect to relative skill supplies through the values of ϵ_{j1} and δ_{j1} (the n-good equivalents of ϵ_{BG} and δ_{BG} in eq. (9)). Both the ϵ_{j1} and the δ_{j1} are increased by lower trade costs, though in different ways. What matters for the ϵ_{j1}, elasticities of the relative sales of goods j and 1 by home producers with respect to their relative prices, are international trade barriers of all types, which affect market shares at home and abroad. What matters for the δ_{j1}, elasticities of the relative prices of domestic supplies of goods j and 1 with respect to their relative labour costs, is only trade costs that are not proportional to labour costs, but including internal as well as international trade costs (plus the costs of traded intermediates and mobile factors).

Closer integration with the world economy unambiguously lowers (the absolute value of) the wage-skill supply elasticity by raising the ϵ_{j1} via lower home-firm shares of the domestic market and higher shares of exports in home-firm sales. It has an ambiguous effect, however, via the δ_{j1}, whose value is increased by lower (per-unit) trade costs but reduced by more use of traded intermediates and internationally mobile capital.

(e) Demand-side influences on the wage-skill supply elasticity

The central argument of this paper is that the elasticity of relative wages with respect to relative skill supplies depends on the degree of openness of an economy through its effect on the responsiveness of relative goods supply to relative skill supplies. There are also, however, two mechanisms operating from the labour-demand side that can affect the relative wage-skill supply elasticity.

One is directed technical change, as in Acemoglu (2007), who argues that increases in the supply of a factor stimulate innovation to use it more productively. The other, established by Caron et al. (2014) and confirmed by Jaimovich et al. (2019), is that the relative demand for skill-intensive goods is income-elastic. Since a larger skill supply tends to raise income, this income elasticity implies that skill supply increases will be partly absorbed by income-induced shifts in demand.

Intuitively, both these mechanisms tend to reduce the wage-skill supply elasticity: if increases in the relative supply of skilled workers raise the demand for skilled workers, there must be less of a reduction in their relative wage than is implied by eq. (9) and its

n-dimensional equivalent (as shown formally in section F of the Online Appendix). Modifying the analysis to allow for these demand-side channels will be shown in section VI to be essential for reconciling our reduced-form estimates of wage-skill supply elasticities with our structural estimates and for linking our results with other evidence on relative wage elasticities.

(f) Other influences on relative wages

Other forces that influence the relative wages of skilled and unskilled workers in open economies can be thought of as extra terms on the rhs of (9). One such influence of special interest in any HO model is the Stolper-Samuelson mechanism, through which relative wages are affected by variation in the relative world prices and relative trade costs of different goods. We cannot estimate this mechanism for lack of data in WIOD on world prices or (a full enough set of) trade costs, but need to be alert to its existence in estimating the effect of openness on the elasticity of relative wages with respect to skill supplies.

It will also be important to recognise that many other possible influences on relative wages, including labour market institutions, are likely to cause eq. (9) (and its n-good equivalent) to fit the data imperfectly. As with world prices and trade costs, moreover, some of these other influences depend on openness, including economies of scale (Epifani and Gancia, 2008), offshoring (Grossman and Rossi-Hansberg, 2008), firm heterogeneity (Harrison et al., 2011; Burstein and Vogel, 2017), and transfer of skill-intensive technology or products to skill-scarce countries (Wood, 2002; Burstein et al., 2013).

III Empirical strategy and data

The empirical analysis in the rest of this paper has two objectives. The first is to assess whether and how much the relative wage-skill supply elasticity varies with openness to trade among countries and periods in the ways suggested by our theory. The second is to assess whether the set of determinants of this elasticity discussed in the theory section provides a good explanation of the size of the observed average elasticities in Figure 1.

Sections IV and V address the first objective. They examine how variation in trade shares and in price-cost elasticities across countries and over time is related to variation in the strength of the inverse relationship between relative wages and relative skill supplies, using multi-country panel data. Section IV explores reduced-form relationships, as a check on the prima facie consistency of the data with theory. Section V applies a more stringent structural estimation approach to isolate and quantify the role of the price and price-cost elasticities. The second objective is addressed in Section VI, which compares the results of Sections IV and V and augments the structural estimates to include directed technical change and income elasticity of demand. The augmented estimates imply an economy-wide elasticity of substitution between skilled and unskilled workers that is consistent both with agreed values in the literature and with the observed average size of the wage-skill supply elasticity (in Figure 1 and in our reduced-form estimates).

Our data are from the World Input-Output Database (WIOD, release 2013), described in Timmer (2012). The core of WIOD is annual international input-output tables for 1995-2009 and 35 industries connecting 40 countries that produce 85% of world GDP, plus a composite rest of the world. Trade flows are computed from these tables, which include information on internal and international trade and transport margins. Price deflators can be computed from the same tables valued at previous-year prices.

WIOD also provides information on employment and wages for three skill categories of workers in each country, industry and year. Skill is measured by schooling, using the International Standard Classification of Education (ISCED). 'Low skilled' workers are ISCED categories 0, 1 and 2 (below completed upper secondary). 'Medium skilled' are ISCED categories 3 and 4 (complete upper secondary and tertiary below a college degree), and 'high skilled' are categories 5 and 6 (a 2-4 year college degree, or its vocational equivalent, and above). As in Timmer et al. (2014) and Morrow and Trefler (2017), we reduce the three WIOD skill categories to two by combining 'low-skilled' and 'medium-skilled' into 'unskilled' (those with less than a college degree).

WIOD wage and employment data were assembled from national labour force surveys and censuses, not previously collated in this form. We derive wage rates for each skill level, country and year as labour compensation divided by hours worked.

An important maintained assumption of our analysis is that WIOD data on economy-wide employment by skill category are a good proxy for skill supplies (or endowments). Differences in participation rates, unemployment rates and working hours (the unit of employment in WIOD) create differences across countries and periods in the relationship between total employment at specified levels of education and the numbers of adults with those levels of education (arguably the best measure of skill supplies). This raises identification issues, since variation in relative employment of skilled and unskilled workers arises not only from supply shocks but also from demand shocks and institutional influences on relative wages. However, the strong correlation with variation in the corresponding population ratios in Barro and Lee (2013) suggests that the variation in skilled employment ratios in WIOD is mainly due to variation in skill supplies.[11]

[11]The correlation between the Barro-Lee adult population measure of relative skill supply and the WIOD

In the reduced-form analysis we add controls for average income, additional factors of production, and labour market institutions. Table B.1 in the Online Appendix reports summary statistics and Table B.2 is a correlation matrix for the main variables used in the regressions.

IV Reduced-form relationships

Our theoretical framework makes two novel testable predictions about variation among countries and over time in the wage-skill supply elasticity:

1. This elasticity is reduced (brought closer to zero) by more openness to trade, which increases the influence of substitutability among varieties relative to substitutability among goods and thus diminishes the size of the relative price changes needed to achieve skill-supply absorbing variations in output mix.

2. It is also reduced by a higher price-cost elasticity – greater responsiveness of relative prices of goods to relative labour costs as a result of lower non-labour costs – which enables the relative price changes needed for skill supply-absorbing responses in output mix to be achieved with smaller changes in relative wages.

To explore in reduced form the implications of the first prediction, we use the commonest measure of openness: the ratio of a country's total trade (exports plus imports) to its total output. We adjust this measure for country size by using the residuals of a cross-section regression of the trade ratio on population (both in logs) for each year in the sample. This openness measure is clearly related to the theoretical construct summarised in eq. (5), since it is higher import and export shares that give substitutability among varieties more influence on the elasticity of demand.

The country size adjustment is also theory-based. Trade ratios are higher in smaller countries mainly because they produce in fewer sectors (due to less scope for realising scale economies and less diverse natural resources) and therefore need to import a wider range of goods. The elasticity of demand in our model depends on the share of domestic producers in markets in which they produce and thus compete: these shares rise with the height of barriers faced by foreign suppliers, which may be no lower in smaller countries, even if their overall

employment measure of relative skill supply is about 0.7, but it depends mainly on cross-country variation. Replacing the (annual) employment measure with the Barro-Lee (five-yearly) measure in reduced-form panel regressions yields weak results.

ratios of imports (and of the exports needed to finance imports) to output are higher.[12]

To assess the second prediction, we estimate the price-cost elasticity from the relative size of labour costs and other costs that do not vary in proportion to wages. The higher the ratio of labour costs to other costs, the more responsive are relative prices to changes in relative wages (though the price-cost elasticity also depends on the degree, η, to which the relative other costs of goods vary with their relative labour costs, on which we lack information). In relation to eq. (8), our simple measure of the price-cost elasticity, $\widetilde{\delta}$, is thus $1/(1+\tau)$, with τ defined as the ratio of other costs to labour costs, and is calculated for the economy as a whole.

A key issue is how to measure τ at country level. We confidently put internal trade costs and net taxes into other costs, since they drive a wedge between unit labour costs and goods prices, whatever the location of the purchaser. For each country and year we sum across sectors internal transport margins and net product taxes in WIOD's national Supply-and-Use tables. Given the assumption in this paper that capital is internationally mobile, we also assign WIOD's "capital compensation" to other costs, since it too creates a wedge between unit labour costs and prices regardless of where products are sold.

To calculate τ for each country and year, we then divide the sum of these other-cost elements by the total national wage bill (our proxy for economy-wide labour costs). In principle, the other costs should also include foreign trade costs and traded intermediate inputs, but the only information in WIOD on foreign trade costs is the international transport margin, and there was no practical way of isolating traded intermediates (which include domestically supplied inputs that are import-competing or exportable). In the reduced-form analysis, the influence of the omitted per-unit foreign trade costs and traded intermediates on the wage-skill supply elasticity should be at least partly picked up by our measure of openness.

Though related to the theory, as well as being easy to interpret, the trade-to-output and price-cost variables do not correspond exactly with the specification of the equations in section II. We choose them to check that the insights from the model are supported by the data. We further show in section E and Table E.1 of the Online Appendix that using measures based more precisely on the theoretical model yields qualitatively similar reduced-form results. To assess the theoretical predictions in reduced form, we employ the

[12]Because population size is correlated with land area, longer internal distances could create higher barriers in bigger countries, but not necessarily (Ramondo et al., 2016). Gravity-based measures of trade barriers control for internal distance (e.g., Anderson and Yotov (2010)).

following intuitive linear specification:

$$\text{(10)} \quad \ln(w) = \alpha + \beta_1 \ln(v) + \beta_2 \ln(o) + \beta_3 (\ln(v) \times \ln(o)) + \beta_4 \widetilde{\delta} + \beta_5 \left(\ln(v) \times \widetilde{\delta}\right) + \varepsilon$$

where w is the relative wage of skilled workers, v is their relative supply, and o is openness. Our two theoretical predictions suggest positive signs on the coefficients β_3 and β_5 on the v-o and v-$\widetilde{\delta}$ interactions, since higher o and $\widetilde{\delta}$ make the negative wage-skill supply elasticity less negative. The variables are transformed into deviations from their means, so that the coefficient on each variable alone (β_1, β_2, and β_4) measures its effect evaluated at the sample mean of the other interacted variable – e.g., β_2 is the wage-openness elasticity evaluated at the average skill supply ratio.

A limitation of this specification is that a positive β_3 could pick up more than the effect of greater openness on the wage-skill supply elasticity, as explained in section II. In particular, it could also reflect the effect of greater openness on relative goods prices, which according to the Stolper-Samuelson mechanism would tend to raise the skilled wage premium in a high-v country, but lower it in a low-v country. Nor does this specification identify the influence of directed technical change and income elasticity of demand.

Other mechanisms that are outside our theoretical framework (e.g., reverse causality from skill premia to skill supplies: Atkin (2016); Blanchard and Olney (2017)) could also bias the OLS estimate of the wage-skill supply elasticity from regression (10). In the absence of an exogenous shifter of skill supplies,[13] we refrain from a causal interpretation of our reduced-form estimates and interpret them as merely suggestive of the empirical association between skill supplies and skill premia.

In this spirit, we use the general regression framework in (10) in three different ways: across countries in levels (with variables averaged over time for each country, as in Figure 1(a)); across countries in full-period changes, as in Figure 1(b) (with $\ln(o)$ and $\widetilde{\delta}$ at their initial 1995 values); and as a panel with annual data, including country fixed effects and year dummies. The panel approach reduces bias from unobserved country-specific and time-invariant influences and global trends, and increases the sample size from 40 to 600, making it possible to control for other potentially confounding influences.

Table 1 presents the results. For each type of variation in relative wages and skill supplies, we report estimates of the wage-skill supply elasticity alone (columns (1), (3), and (5)), as

[13] Although for long-period changes, the sign and size of the wage-skill supply elasticity estimated with OLS are confirmed when using exogenous net migration flows as an instrument for changes in skill supplies. Figure A.1 in the Online Appendix portrays the results and the notes provide details on the identification strategy.

well as the specification in (10) with the v-o and v-$\widetilde{\delta}$ interaction terms (columns (2), (4), and (6)). For the panel specification only, we also report results including six other control variables, both on their own (column (7)) and interacted with v (column (8)).

The coefficient on v is negative in all specifications, confirming the inverse relationship between relative wages and skill supplies in Figure 1. Its size and significance vary across specifications, but the significant values are never far from those in Figure 1 (between -0.17 and -0.35). The coefficient is small and insignificant in the first panel regression (column (5)), which includes only the fixed effects and year dummies, but becomes much larger and significant with the controls for openness and the price-cost elasticity in column (6).

The coefficients on the openness variable alone, which measure its relationship with w at the sample average of v, vary widely among specifications: the significant but opposite-signed values in the small-sample cross-country and long-change results are more likely to reflect the influence of omitted variables than to shed light on the accuracy of alternative theories of trade and wages.

The v-o interaction terms support our theoretical predictions. The estimated interaction coefficients are consistently positive, suggesting that higher trade openness weakens the otherwise negative wage-skill supply elasticity. They are mostly about 0.4, though less precisely estimated across countries and in long changes.[14]

Table 1: Wage-skill supply elasticity and trade openness in reduced form

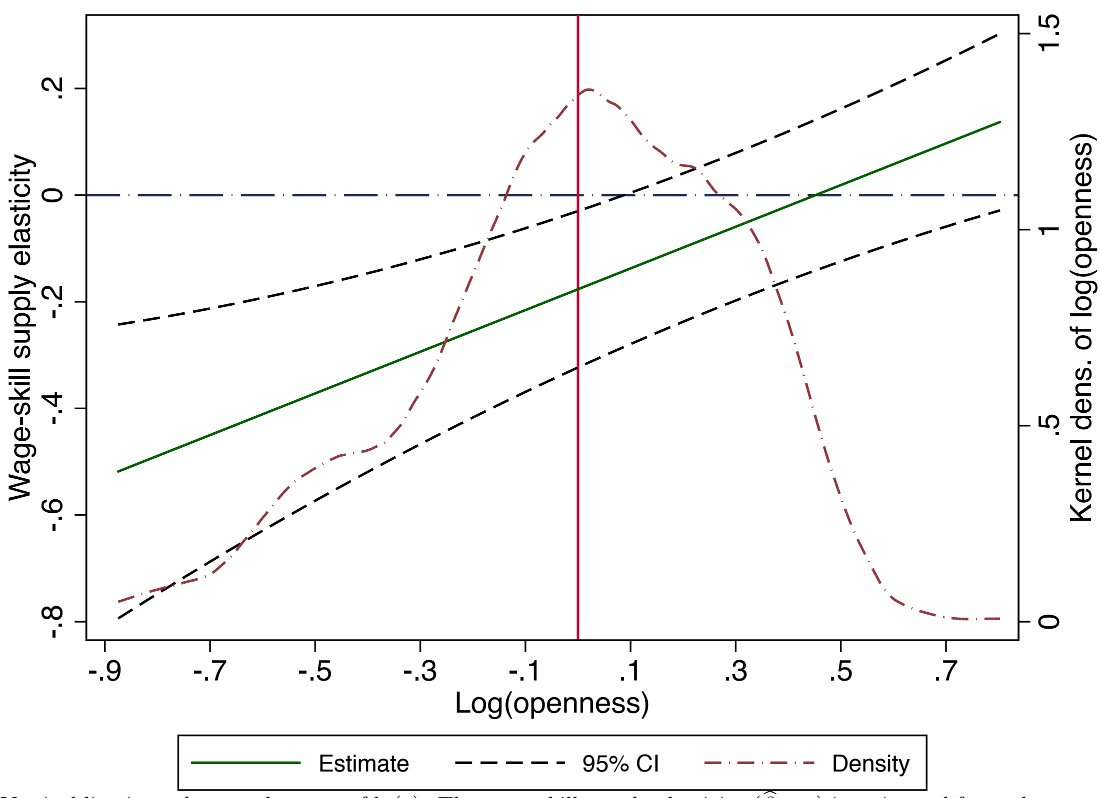
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Cross-country		14-year changes		Panel			
$\ln(v)$	-0.269***	-0.275***	-0.260*	-0.352**	-0.0781	-0.177**	-0.178**	-0.117
	(0.0751)	(0.0704)	(0.146)	(0.155)	(0.0976)	(0.0744)	(0.0788)	(0.0912)
$\ln(o)$		-0.294**		0.0163***		-0.0461	-0.0200	-0.0469
		(0.150)		(0.00543)		(0.0645)	(0.0661)	(0.0546)
$\ln(v) \times \ln(o)$		0.386		0.825		0.391***	0.396***	0.376***
		(0.334)		(0.518)		(0.103)	(0.105)	(0.0748)
$\widetilde{\delta}$		-0.879		-1.70e-05		-0.587**	-0.689*	-0.472
		(0.598)		(0.0202)		(0.256)	(0.413)	(0.298)
$\ln(v) \times \widetilde{\delta}$		1.671*		-0.987		0.745**	0.745***	0.790*
		(0.935)		(1.748)		(0.301)	(0.263)	(0.428)
Obs	40	40	37	37	600	600	600	600
R^2	0.355	0.535	0.106	0.373	0.069	0.332	0.353	0.408

Notes: All variables are within-country averages in columns (1) and (2). In columns (3) and (4), $\ln(w)$ and $\ln(v)$ are in 2009-1995 differences, whereas values for $\ln(o)$ and $\widetilde{\delta}$ are for the year 1995. Country fixed effects and year dummies are included in columns (5) to (8). Column (7) includes control variables (see text and Table A.1), and column (8) further adds interactions of each control variable with $\ln(v)$. Heteroskedasticity-robust standard errors are reported in parentheses in columns (1) and (3), standard errors bootstrapped with 500 replications are in parentheses in columns (2) and (4), and clustered-bootstrapped standard errors are in parentheses in columns (5) to (8). Significant at: *10%, **5%, ***1% level.

[14] Standard errors are clustered at the country level and bootstrapped because the openness variable is a "generated regressor" (the residuals of cross-section regressions of the trade-output ratio on population).

The panel estimates in column (6) are used in Figure 2 to show graphically how the wage-skill supply elasticity varies with trade openness, holding the level of $\widetilde{\delta}$ at its average value. In a low-trade economy (such as Brazil: average $\ln(o) = -0.51$), a 10 percent increase in relative skill supply is associated with a 3.8 percent drop in the skill premium, and in a hypothetical almost-closed economy with a striking (but very inaccurately estimated) drop of 20 percent. By contrast, countries in the upper quartile of openness (such as Germany: average $\ln(o) = 0.25$) exhibit relative wage insensitivity – no significant variation in the skill premium with skill supplies. The cross-country and long-change regressions (columns (2) and (4)) suggest even greater variation of the elasticity with trade openness: their smaller samples reduce precision without altering the economic implications. These patterns confirm the illustrative flattening of the wage-skill supply relationships in Figure 1.

Figure 2: Wage-skill supply elasticity and openness at average $\widetilde{\delta}$



Notes: Vertical line is at the sample mean of $\ln(o)$. The wage-skill supply elasticity ($\widehat{\beta}_{w-v}$) is estimated for each country c and year t from the reduced-form regression (10): $\widehat{\beta}_{w-v} = \widehat{\beta}_1 + \widehat{\beta}_3 \times \ln(o)$; where the 'hat' denotes the 'estimated' coefficients. Note that $\widehat{\beta}_1$ gives the elasticity at the means of $\widetilde{\delta}$ and $\ln(o)$.

These elasticity-reducing effects of greater openness are not materially altered if the trade ratio is calculated on a value-added rather than gross basis. Nor, as shown in Table B.3 of the Online Appendix, are they much altered if the numerator excludes trade in intermediates, trade with China (which has been found to have strong effects on local wages and labour markets (Autor et al., 2016)), or trade in equipment proxying for transfers of technology (Burstein et al., 2013).

The coefficients on the price-cost elasticity variable alone, which measure its relationship with w at the sample average of $\ln(v)$, are mainly negative (though zero in the long-changes specification), perhaps because of capital-skill complementarity – since capital is assumed to be mobile and payments to capital reduce $\widetilde{\delta}$. As predicted by our model, the v-$\widetilde{\delta}$ interaction coefficients are mainly positive and significant, but are twice as large in the cross-country as in the panel specification and insignificantly negative in the long-change specification. These differences may partly reflect the omission of international trade costs and traded intermediates, whose effect (and relationship with the openness variable) could differ across specifications.

As well as being less robust, the role of variation in price-cost elasticities is smaller than that of trade openness, as shown in Figure A.2 of the Online Appendix. The wage-skill supply elasticity rises more slowly with the price-cost elasticity than with openness. Even so, if for example Turkey had average openness and increased its price-cost elasticity from the low actual average value of 0.35 (10th percentile) to 0.55 (90th percentile), the relative wages of its skilled workers would no longer be sensitive to changes in skill supplies.

Other observable determinants of relative wages may be correlated with skill supplies, openness or price-cost elasticities, and could thus bias our estimates of the v-o and v-$\widetilde{\delta}$ interaction coefficients. To check this, we add to our panel regression six more variables (defined more precisely in the notes to Table A.1): the share of low-skilled workers in the unskilled (low + medium) aggregate, and the share with no education in the low category (computed from Barro and Lee (2013)); the ratio of a country's land area to its unskilled labour supply; the ratio of the capital rental rate to the average wage; GDP per capita; and an EU membership dummy (because EU countries are over-represented in our sample).[15]

As can be seen from columns (7) and (8) of Table 1 (the difference between which is that the latter includes also the interactions of the six control variables with v), the addition of these other determinants of relative wages has no substantial effect on the sizes of the v-o and v-$\widetilde{\delta}$ interaction coefficients (the coefficients on the extra variables in the column (7) regression are in Table B.4 in the Online Appendix).[16]

[15] We experimented also with measures of labour market rigidity, including unionisation, the Employment Protection Legislation index from the OECD (2013) and the "Labour Freedom' index from the Heritage Foundation, but all of them substantially reduced our sample size in non-random ways. For example, the differences between columns (6) and (7) in Table A.3 arise mainly from the change in sample rather than from adding the unionisation variable.

[16] The small samples in the cross-country and long-change regressions made the addition of more variables

In summary, our reduced-form evidence is consistent with the predictions of our theoretical framework concerning the wage-skill supply relationship. Both greater trade openness (which increases price elasticities) and higher price-cost elasticities attenuate the inverse relationship between the skilled wage premium and the relative skill supply – and with high openness and high price-cost elasticities relative wages vary only slightly or even not at all with respect to skill supplies.

V Structural relationships

In this section we further evaluate our openness and price-cost mechanisms by 'structural estimation' – that is, by inserting numerical values for the parameters of our theoretical relationship between relative wages and skill supplies. To bring the model to the data, we extend the two-good framework in eq. (9) to include n goods, indexed by j and with good 1 as the numeraire, as in eq. (11):

(11)

$$\widehat{w}_{H/L} = -\frac{1}{\left[1 - \sum_{j=2}^{n} \left(\lambda_{Hj} - \lambda_{Lj}\right)\left(\theta_{Hj} - \theta_{H1}\right)\right]\sigma + \sum_{j=2}^{n} \left(\lambda_{Hj} - \lambda_{Lj}\right)\left(\theta_{Hj} - \theta_{H1}\right)\epsilon_{j1}\delta_{j1}}\widehat{v}_{H/L}$$

whose rhs denominator, the economy-wide elasticity of substitution between skilled and unskilled workers, is again a weighted average of the intra-sectoral σ and inter-sectoral $\epsilon\delta$ terms.[17] Intuitively, greater variation of skill intensity across sectors, which enlarges $\sum_{j=2}^{n} \left(\lambda_{Hj} - \lambda_{Lj}\right)\left(\theta_{Hj} - \theta_{H1}\right)$, gives inter-sectoral substitution more weight. The underlying demand system should in principle be elaborated to accommodate input-output linkages (demand for intermediate goods in each sector depending on the output of other sectors), but for the sake of simplicity we do not attempt to do so.[18]

Our focus in this section is on the second term of the denominator, which contains the

less informative, but neither individually nor together did the six extra variables affect substantially the interaction coefficients (columns (1) to (4) of Table B.4).

[17] In a multi-country setting and with γ's and β's varying by destination country, the overall elasticity of relative sales with respect to relative prices, ϵ_{j1}, is a weighted average of the bilateral elasticities (the approximated ϵ_{BG} in eq. (5), without country superscripts), where the weights are output shares averaged across sectors j and 1, as explained in section E of the Online Appendix.

[18] To model input-output linkages explicitly would require adding to eq. (3) and (4) another level at which labour and intermediate inputs are combined to produce final output (as for example in eq. (2) of Morrow and Trefler (2017)). Nor, for the same practical reason as in the reduced-form estimates, do we attempt to add traded intermediates to the numerators of the price-cost elasticities or the labour content of non-traded intermediates to their denominators.

price elasticity and price-cost elasticity parameters. They determine the effect of openness to trade on the size of the skill-supply-absorbing response of sectoral output mix. To the extent that the output mix response falls short of absorbing the whole of a change in skill supply, the first term in the denominator fills the gap through intra-sectoral adjustments of technique or detailed output mix, as in standard labour market models.

To simulate the rhs of eq. (11), we need numerical values for the parameters, with the n goods being the 35 WIOD sectors. The skill intensity parameters (θ's and λ's) are calculated from the sectoral employment data in the WIOD SEA, while the demand elasticities (β's and γ's) are estimated using the method of Feenstra (1994), as explained in section E of the Online Appendix. For the intra-sectoral elasticity of substitution, σ, we initially impose the value of 1.67 estimated by Morrow and Trefler (2017) from the same WIOD data. We run sensitivity checks by varying σ within the range of 1 to 3 that Katz and Autor (1999) consider plausible.

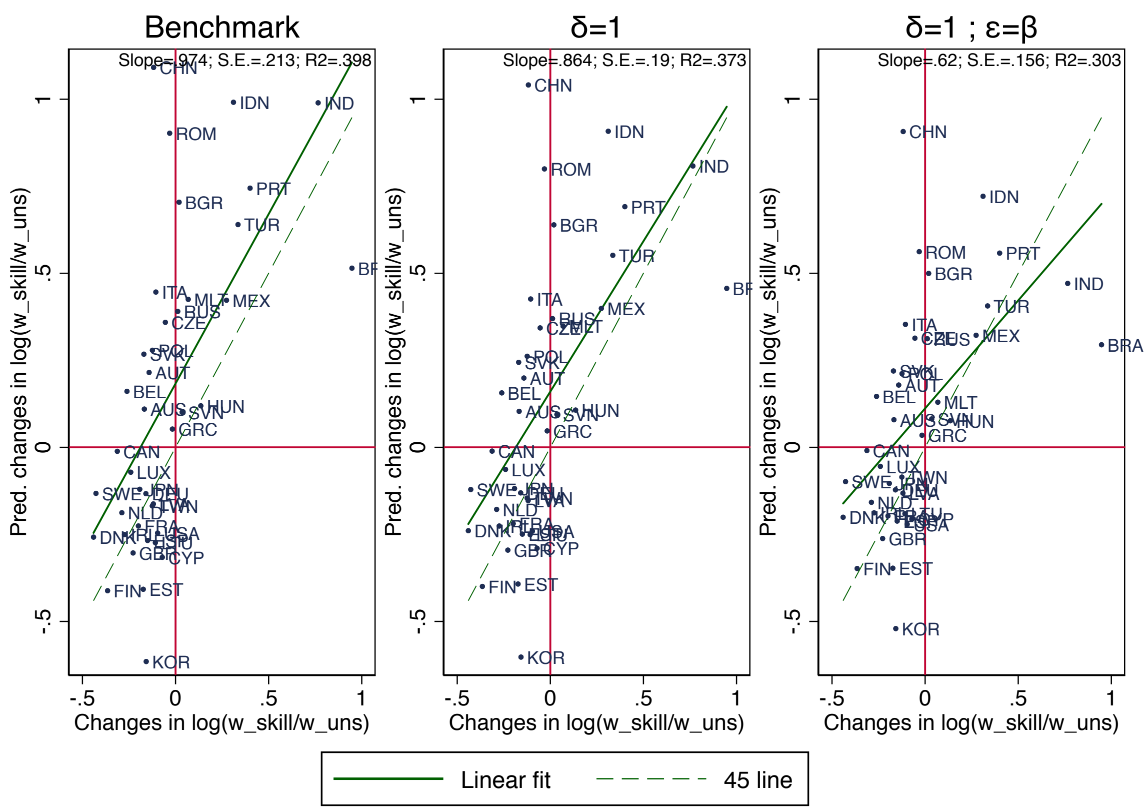
Our simulations then use eq. (11) to predict the variation of relative wages in response to observed variation in skill supplies. We assess how closely these predictions match observed variation in wages in both cross-country and panel data by applying two tests: a slope test, regressing predicted changes in relative wages on actual changes in relative wages; and a variance-ratio test (Trefler, 1995; Blum, 2010), dividing the variance of predicted changes in relative wages by the variance of actual changes in relative wages.

(a) Cross-country evidence

Figure 3 portrays the results of the cross-country slope tests (with 'changes' referring to individual-country deviations from world means, averaged across years). The left-hand panel is the "benchmark" case, including both the price-elasticity (ϵ_{j1}) terms and the price-cost elasticity (δ_{j1}) terms of eq. (11). The slope is almost equal to one and precisely estimated, implying that the model broadly explains how variation in skill supplies across countries affects the relative wages of skilled workers. The fit is also good by the standards of this sort of estimation (R2=0.40), though far from perfect as a result of errors in the data and omission from our model of all influences on relative wages other than skill supplies. For example, ten countries in the north-west quadrant, including China, have below-average actual skilled wage premia despite above-average predicted skill premia (reflecting their below-average skill abundance).

The other two panels of Figure 3 disentangle the mechanisms by using more restricted specifications. The "$\delta = 1$" case in effect drops the price-cost elasticity by forcing the values of all δ_{j1} terms to unity, which makes the slope slightly shallower and leaves the fit almost unchanged. The "$\delta = 1; \epsilon = \beta$" case drops the openness mechanism, too, by forcing the values of all the price-elasticity (ϵ_{j1}) terms to equal the elasticities of substitution among different varieties of the goods involved. This modification nullifies the influence of elasticities of substitution among different goods and hence of trade shares.[19] The resulting slope is 40% shallower than in the benchmark case. These comparisons suggest that variation in openness is crucial to explaining how skill premia vary with skill abundance across countries, and more important than variation in price-cost elasticities.

Figure 3: Slope tests – Cross-country estimates



Notes: All regressions include a constant. Standard errors are heteroskedasticity-robust. In the "benchmark" panel, the relative wage predictions are based straightforwardly on eq. 11. In the "$\delta = 1$" panel, the relative wage predictions assume that all the δ_{j1} terms in eq. 11 are equal to unity. In the "$\delta = 1; \epsilon = \beta$" panel, in addition to setting the δ_{j1} terms equal to one, the relative wage predictions assume that each ϵ_{j1} term in eq. 11 is the weighted harmonic mean of the relevant β_j and β_1 (modifying eq. (9) of the Online Appendix).

Both predicted and actual changes in wages must be measured with error. In such a situation, Klepper and Leamer (1984) show that bounds of the true slope coefficient are given by the estimated slopes of the 'direct' ($\widetilde{w}$ on w) and 'reverse' (w on $\widetilde{w}$) regressions. The upper

[19] This case corresponds to setting $s_{BG} = 0$ in the two-good simplified formula for the price elasticity (eq. (5)). It is equivalent to a one-level CES specification, standard in recent quantitative trade models (Costinot and Rodriguez-Clare, 2014) and related gravity applications (Anderson, 2011).

panel of Table 2 shows these bounds. In the benchmark case, the reverse regression yields a far smaller (0.4), though still positive and significant, slope than the direct regression. This difference is amplified by the ten countries where the skill premium is unusually low. Without them, the estimated slope is between 0.58 and 1.06, with a much better fit (R^2=0.62). The bounds of the slope parameter in the other two specifications are narrower, and the 'reverse' slopes are similar in all three cases.

The lower panel of Table 2 shows the results of the cross-country variance-ratio tests. The predicted variance of relative wages across countries in the benchmark case is over twice as large as the actual variance. The ratio is about two also for the "$\delta = 1$" case, though it is not far above unity with the "$\delta = 1; \epsilon = \beta$" specification (which generates a lower wage-skill supply elasticity). A plausible explanation for this over-prediction is that cross-country differences in actual skilled wage premia are narrowed by the influence of labour market and social security institutions.

Table 2: Bounds and Variance-ratio tests – Cross-country

	Benchmark		$\delta = 1$		$\delta = 1, \epsilon = \beta$	
Bounds:	$\tilde{w}$ on w	w on $\tilde{w}$	$\tilde{w}$ on w	w on $\tilde{w}$	$\tilde{w}$ on w	w on $\tilde{w}$
	0.974***	0.409***	0.864***	0.431***	0.620***	0.489***
	(0.213)	(0.106)	(0.190)	(0.117)	(0.156)	(0.144)
Obs	40	40	40	40	40	40
R^2	0.382	0.382	0.356	0.356	0.285	0.285
Variance ratio: $\frac{Var(\tilde{w})}{Var(w)}$						
	2.383		2.002		1.268	

Notes: All regressions include a constant. Heteroskedasticity-robust standard errors are in parentheses. In the "benchmark" columns, the relative wage predictions are based straightforwardly on eq. 11. In the "$\delta = 1$" columns, the relative wage predictions assume that all the δ_{j1} terms in eq. 11 are equal to unity. In the "$\delta = 1; \epsilon = \beta$" columns, in addition to setting the δ_{j1} terms equal to one, the relative wage predictions assume that each ϵ_{j1} term in eq. 11 is the weighted harmonic mean of the relevant β_j and β_1 (modifying eq. (9) of the Online Appendix). Significant at: *10%, **5%, ***1% level.

These results survive several robustness checks.[20] To see if they are driven by specific time periods, we apply the slope test to each year in the sample between 1995 and 2009. As shown in Figure A.3 of the Online Appendix, the slope increases slightly over time in all three specifications, although not significantly. We also replicate the slope test with different choices of the numeraire sector 1, as reported in Figure A.4 of the Online Appendix: the slopes do not vary much and they preserve the ordering across specifications, with the benchmark case generating a higher 'direct' slope than the two alternatives.

[20] The variance of predicted wage changes, and hence the slope of their regression on actual wage changes, decreases mechanically with the chosen value of σ (which is 1.67 in the results reported). With the benchmark specification of our model, raising σ from 1 to 3 reduces the slope from 1.5 to 0.5, though the R^2 remains at 0.40 (results available upon request).

(b) Panel evidence

To measure changes in relative wages and skill supplies within countries over time, we follow Blum (2010) and use annualised differences (in logs) over windows of 5, 10 and 14 years. The quantified value of the wage-skill supply elasticity (the ratio term on the rhs of eq. (11)) at the start of each window is combined with actual skill supply changes to predict wage changes, which are then regressed on actual differences in wages and, in the 5- and 10-year regressions, also on country fixed effects and time dummies. Table 3 reports the results of the (direct and reverse) slope and variance-ratio tests.

In the benchmark column, the estimated slope is positive and significant in both the 5- and 10-year windows, and is greater in the longer window, though still well below unity. The same is true of the reverse regressions, whose slopes are much closer to those of the direct regressions than in the cross-country test. In the longest possible window of 14 years, the slope estimated on the full sample is near zero. When three extreme outliers are omitted, as with Figure 1(b), the slope is positive and close to those in the shorter windows, though less precisely estimated. The variance ratios are similar across the time windows. These ratios are also all below unity, suggesting that changes over time in actual skill premia are amplified by forces omitted from eq. (11), in contrast to the cross-country damping suggested by Table 2.

As in the cross-country tests, the direct slopes in the "$\delta = 1; \epsilon = \beta$" columns of Table 3 are lower than in the benchmark and "$\delta = 1$" columns, suggesting that variation in openness is important for matching the predictions with actual variation in relative wages (though the reverse-regression slopes go the other way). In all three time windows, moreover, the variance ratios are closer to unity in the benchmark case than with the "$\delta = 1$" and "$\delta = 1; \epsilon = \beta$" specifications. The slopes are steeper for the 10-year than for the 5-year window, while for the 14-year window the slopes are insignificantly different from zero in the full sample, but positive in the restricted sample. These findings are again robust to the choice of the numeraire sector, as shown in Figures A.5-A.7 of the Online Appendix.[21,22]

[21] We also performed the slope and variance-ratio tests on manufacturing and services separately, treating their labour forces as specific to (and immobile between) them. Cross-section and panel results available upon request are qualitatively similar to the ones obtained on the full sample. They also do not reveal any systematic and robust difference across the two broad sectors. The wage-skill supply relationship seems to fit better the manufacturing sector in the cross-section specifications, but this difference is not confirmed in the within-country specifications.

[22] As in the cross-country analysis, the slope of the regression of predicted values on actual values decreases with the chosen value of σ (1.67 in the results reported). In our benchmark specification, raising σ from 1 to 3 reduces the slope from 0.48 to 0.19 with a 5-year window, from 0.79 to 0.30 with a 10-year window, and from 0.50 to 0.19 with a 14-year window (omitting outliers). The R^2's do not vary with σ.

Table 3: Slope and variance-ratio tests – Panel estimates

	Benchmark		$\delta = 1$		$\delta = 1; \epsilon = \beta$	
Bounds:	$\tilde{w}$ on w	w on $\tilde{w}$	$\tilde{w}$ on w	w on $\tilde{w}$	$\tilde{w}$ on w	w on $\tilde{w}$
5-year changes						
	0.314***	0.291***	0.286***	0.316***	0.224***	0.392***
	(0.0779)	(0.108)	(0.0698)	(0.119)	(0.0531)	(0.157)
Obs	400	400	400	400	400	400
Within R^2	0.221	0.221	0.215	0.221	0.195	0.218
Variance ratio: $\frac{Var(\tilde{w})}{Var(w)}$						
	0.855		0.712		0.455	
10-year changes						
	0.514***	0.482***	0.480***	0.525***	0.380***	0.641***
	(0.121)	(0.138)	(0.111)	(0.152)	(0.0819)	(0.202)
Obs	200	200	200	200	200	200
Within R^2	0.338	0.310	0.335	0.314	0.314	0.306
Variance ratio: $\frac{Var(\tilde{w})}{Var(w)}$						
	0.662		0.556		0.378	
14-year changes						
	0.0690	0.0758	0.0384	0.0496	-0.0256	-0.0445
	(0.189)	(0.207)	(0.176)	(0.227)	(0.152)	(0.262)
Obs	40	40	40	40	40	40
R^2	0.005	0.005	0.002	0.002	0.001	0.001
14-year changes, without outliers						
	0.319*	0.433**	0.280*	0.467**	0.185	0.416
	(0.163)	(0.201)	(0.145)	(0.227)	(0.124)	(0.265)
Obs	37	37	37	37	37	37
R^2	0.138	0.138	0.130	0.130	0.077	0.077
Variance ratio: $\frac{Var(\tilde{w})}{Var(w)}$						
	0.736		0.599		0.444	

Notes: All 5- and 10-year regressions include country fixed effects and year dummies. Standard errors clustered at the country-level (for 5- and 10-year regressions) and heteroskedasticity-robust (for 14-year regressions) are in parentheses. The bottom panel excludes CHN, MEX and POL from the regressions. In the "benchmark" columns, the relative wage predictions are based straightforwardly on eq. 11. In the "$\delta = 1$" columns, the relative wage predictions assume that all the δ_{j1} terms in eq. 11 are equal to unity. In the "$\delta = 1; \epsilon = \beta$" columns, in addition to setting the δ_{j1} terms equal to one, the relative wage predictions assume that each ϵ_{j1} term in eq. 11 is the weighted harmonic mean of the relevant β_j and β_1 (modifying eq. (9) of the Online Appendix). Significant at: *10%, **5%, ***1% level.

Overall, the results of these tests suggest that our extensions of the HO model play an important role in explaining the observed variation in skill premia across countries and within countries over time. The explanatory power of the theoretical framework seems to derive from variation more in openness to trade (through the influence of market shares on price elasticities) than in price-cost elasticities. This asymmetry may reflect the theoretically more clear-cut effect of openness than of price-cost elasticities (discussed in section II), or the crudity of our estimates of price-cost elasticities (discussed in section IV and section E of the Online Appendix). The structural tests also confirm that skill supplies affect wages through channels not mediated by trade shares or per-unit costs and that variation in skill supplies is by no means the only cause of variation in relative wages.

VI Comparing reduced-form and structural elasticities

Both the reduced-form and the structural analysis suggest that variation in openness and in price-cost elasticities contributes importantly to explaining how the elasticity of the relative wages of skilled workers with respect to skill supplies varies across countries and periods. The two sets of estimated elasticities are also strongly correlated: across all 600 country-year observations (the reduced-form ones being based on the panel estimates in column (6) of Table 1), the correlation coefficient is 0.35 (standard error = 0.04).[23]

(a) Accommodating supply-induced demand shifts

The reduced-form and structural elasticities, however, are measuring different things. The reduced-form estimates rely on proxies (trade-output ratio and labour share in total costs) for the theoretical mechanisms and can potentially encompass all determinants of the wage-skill supply elasticity. The structural estimates cover only the effects of price elasticities and price-cost elasticities (in the denominator of eq. (11)).

In particular, the structural estimates omit influences from the labour demand side, namely directed technical change and the income elasticity of demand, which as explained in section II are bound to make the wage-skill supply elasticity less negative than implied by eq. (11). The reduced-form estimates should thus be (absolutely) smaller than the structural estimates, to a degree that reflects the strength of these omitted demand-side (and possibly other) mechanisms.

Figure 4(a), which plots the kernel densities of the two sorts of elasticity estimates, with vertical lines denoting their means, confirms this theoretical expectation.[24] The structural elasticities are both much larger (i.e. more negative) and less dispersed than the reduced-form ones, with the mean of the reduced-form estimates being -0.18 (the coefficient on $\ln(v)$ in column (6), Table 1) and that of the structural ones being -0.67.[25]

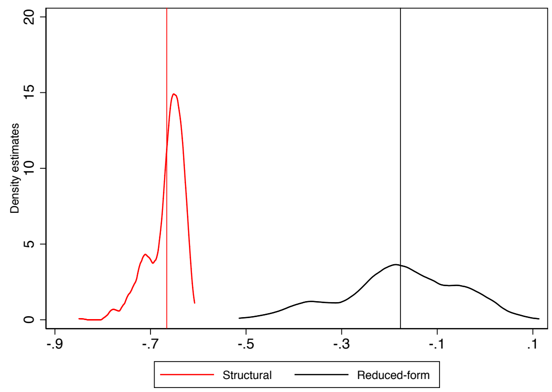
[23] The estimated wage-skill supply elasticity for each country c and year t is: $\widehat{\beta}_{w-v} = \widehat{\beta}_1 + \widehat{\beta}_3 \times \ln(o) + \widehat{\beta}_5 \times \widetilde{\delta}$; where the 'hat' denotes the 'estimated' coefficients.

[24] The structural elasticity for each country and year is the median of elasticities across all possible reference sectors.

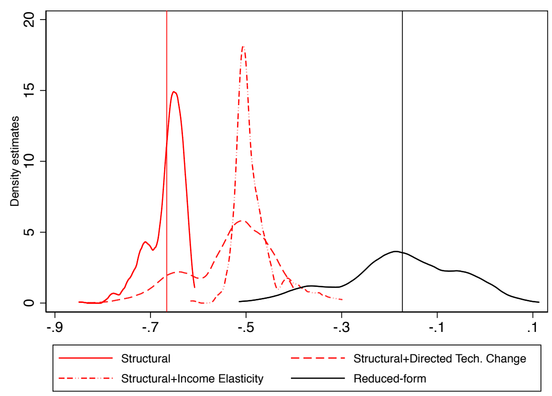
[25] We do not isolate elasticities that are not statistically different from zero. In the reduced-form estimates, 32% of the sample has insignificant elasticities at the 10% level. If we restrict our sample only to significant

Figure 4: Distributions of estimated wage-skill supply elasticities

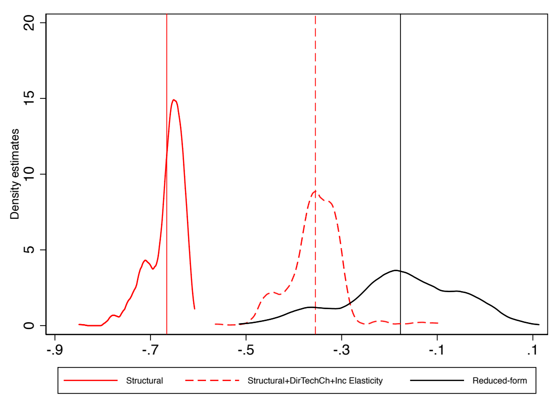
4(a): Structural vs. reduced-form



4(b): Adding demand-side influences separately



4(c): With demand-side influences combined



Notes: Vertical lines are at the mean elasticities. "Structural" refers to the wage-skill supply elasticities calculated on the basis of eq. (11). "Reduced-form" refers to the wage-skill supply elasticities estimated from the regression model in (10) (see footnote n.23. "Structural+Income Elasticity" refers to elasticities calculated on the basis of eq. (18) in the Online Appendix but omitting the directed technical change term $((\phi_{HL}-1)(\widetilde{\sigma}-1))$. "Structural+Directed Tech. Change" refers to elasticities calculated on the basis of eq. (18) in the Online Appendix but omitting the income elasticity term $(\left[\widetilde{\omega}+\sum_{j=2}^{n}\left(\lambda_{Hj}-\lambda_{Lj}\right)(\mu_j-\mu_1)\right]\pi_v)$. "Structural+DirTechCh+Inc Elasticity" refers to elasticities calculated on the basis of the full eq. (18) in the Online Appendix.

elasticities, the average reduced-form elasticity is -0.24.

To allow a more informative comparison of the reduced-form and structural elasticities, we extend our theoretical model and structural estimation to include directed technical change (Acemoglu, 2007) and the income elasticity of demand (Caron et al., 2014), as explained in section F of the Online Appendix. Conveniently, the addition of these demand-side influences alters only the numerator of (11), reducing it, as intuition would suggest, below unity. To use the modified equation, we also need to obtain values for some new parameters, particularly the income elasticity of demand for each good and the elasticity of per capita income with respect to economy-wide skill supply.

Figure 4(b) plots the kernel densities of the structural elasticities, after adjustment for these demand-side influences, alongside the unadjusted structural and reduced-form densities. Directed technical change and income elasticity both shift the structural distribution to the right by similar amounts. Directed technical change also widens the dispersion of the structural distribution.[26] Together, as shown in Figure 4(c), the two adjustments greatly narrow the gap between the reduced-form mean (-0.18) and the structural mean (now -0.35), as well as creating a substantial overlap between the two distributions.

(b) Effects of openness on reduced-form and structural distributions

Even after both demand-side adjustments, the dispersion of the structural distribution in Figure 4(c) is smaller than that of the reduced-form distribution. This difference may reflect inaccuracies in opposite directions in the estimated effect of variation in openness to trade on the reduced-form and structural elasticities.

The reduced-form dispersion is probably amplified by overestimation of the openness interaction. According to our model, the coefficient on this interaction should capture how lower home market shares and greater export sales increase the weights of β's relative to γ's in the determination of ϵ's (eq. (5), and (9) in the Online Appendix), strengthening the role of shifts in output structure in absorbing changes in skill supplies and thus reducing the need for changes in relative wages. In practice, however, this coefficient may be biased upward by the Stolper-Samuelson mechanism, as explained in section IV. Non-HO mechanisms may amplify this bias: for example, Burstein and Vogel (2017, figure 3) show how lower trade costs can raise the skilled wage premium by more in countries with more skilled workers.

[26] This is because, as explained in section F of the Online Appendix, the influence of directed technical change varies across countries and over time with the economy-wide elasticity of substitution. The apparent lack of effect of income elasticity on the dispersion of the structural distribution may reflect our simplifying assumption of a common elasticity of per capita income with respect to skill supply in all countries and periods.

Conversely, the effect of variation in openness on the structural dispersion may be understated by the specification of the demand system in our theoretical model or by the way we estimate its parameters. Our two-level CES demand system is standard, and we estimate the elasticity parameters at each level in a standard way. But this approach may not capture the full effect of the difference between substitutability among goods and substitutability among varieties on which the effect of openness on the relative wage-skill supply elasticity depends. Our income-elasticity adjustment probably also underestimates the effect of openness on the structural dispersion by failing to allow for the likelihood that income gains from inward transfers of technology (through trade) increase with labour force skills.

In Figure 4(c), moreover, there is still a non-negligible gap between the means of the reduced-form and structural elasticities. An obvious possible way of closing this gap is to raise the assumed value of the intra-sectoral elasticity of substitution (σ), which brings the wage-skill supply elasticity closer to zero both by making it easier to substitute skilled for unskilled labour within sectors and by amplifying the directness of technical change.[27] The result of experimenting with different values of σ is depicted in Figure A.8 of the Online Appendix. Without directed technical change, no value of σ could eliminate the gap. But with directed technical change, this gap could be eliminated by raising the assumed value of σ from 1.67 to 1.92.

(c) Substitutability between skilled and unskilled labour

More instructive than arbitrarily varying σ is to use the structural model to estimate its value, given the other parameter values and our data on relative wages and skill supplies. The first row of Table 4 reports non-linear least squares (NLS) estimates of σ using cross-country data (similar results using panel data are in Table B.5 of the Online Appendix). The columns refer to different specifications of the model, starting with the extended Heckscher-Ohlin (EHO) framework of eq. (11), and then adding income elasticity (IE) and directed technical change (DTC) as in eq. (18) of the Online Appendix.

[27] Another possible explanation for this gap is our assumption in the structural calculations that $\eta_{j1} = 0$, which is likely to underestimate all the δ_{j1} and thus to overestimate the wage-skill supply elasticity. However, we made the same assumption in the reduced-form estimation, the results of our structural tests were not greatly altered by setting $\delta_{j1} = 1$, and the effects on the mean of including or excluding the price-cost elasticity term are much the same for the reduced-form and the simulated distributions (results available upon request).

Table 4: Non-linear least squares (NLS) estimates of σ

	EHO	EHO+IE	EHO+DTC	EHO+IE+DTC
σ	4.326***	2.814***	2.058***	1.775***
	(1.159)	(0.722)	(0.0694)	(0.0824)
Ave. ϕ_{HL} (std. dev.)	3.69 (0.23)	2.44 (1.4)	1.82 (0.1)	1.59 (0.08)
Ave. $w-v$ elasticity (std. dev.)	0.27 (0.02)	0.3 (0.03)	0.24 (0.1)	0.29 (0.06)
Obs	40	40	40	40
R^2	0.401	0.387	0.486	0.455

Notes: All NLS regressions include a constant term. Heteroskedasticity-robust standard errors are in parentheses under the σ coefficients. The EHO column corresponds to eq. (11). The EHO+IE column fits a version of eq. (18) in the Online Appendix that omits the DTC term $((\phi_{HL}-1)(\widetilde{\sigma}-1))$. The EHO+DTC column fits a version of eq. (18) in the Online Appendix that omits the IE term $(\left[\widetilde{\omega}+\sum_{j=2}^{n}\left(\lambda_{Hj}-\lambda_{Lj}\right)(\mu_j-\mu_1)\right]\pi_v)$. The EHO+IE+DTC column fits the full relationship in eq. (18) of the Online Appendix. In estimating eq. (11) and eq. (18) of the Online Appendix, the terms $\sum_{j=2}^{n}\left(\lambda_{Hj}-\lambda_{Lj}\right)\left(\theta_{Hj}-\theta_{H1}\right)$ and $\sum_{j=2}^{n}\left(\lambda_{Hj}-\lambda_{Lj}\right)\left(\theta_{Hj}-\theta_{H1}\right)\epsilon_{j1}\delta_{j1}$ are taken at the beginning of each 5-, 10-, or 14-year window. The 'Other non-metallic minerals' sector is chosen as the reference sector 1. Significant at: *10%, **5%, ***1% level.

The estimates of σ (in the top row of the Table) are all significantly greater than one, confirming the widespread presumption of gross substitutability within sectors between skilled and unskilled workers. The fit of the regression is improved by adding directed technical change to the model, but reduced by adding income elasticity of demand. Adding the demand-side mechanisms, especially directed technical change, also reduces the estimated value of σ, which at 1.78 with both mechanisms together in the last column is less than half the 4.33 in the first column and very close to the 1.67 estimated by Morrow and Trefler (2017) and imposed in our estimations.

We then combine these estimates of σ with the other elements of the relevant models to calculate the economy-wide elasticity of substitution between skilled and unskilled labour (the denominator of eq. (11), summarised as ϕ_{HL}) and its reciprocal, the wage-skill supply elasticity.[28] The lower rows of Table 4 report the means and standard deviations of these two elasticities for each model specification, again using country data (and again with similar panel data results in Table A.6).

These results reconcile our reduced-form (and Figure 1) estimates of the wage-skill supply elasticity, which are consistently between 0.2 and 0.3, with standard estimates of the aggregate elasticity of substitution between skilled and unskilled labour – a key parameter for economy-wide analysis of labour market policies. In all the columns of Table 4, the estimated wage-skill supply elasticity is in the observed range, but with our baseline model (in the EHO column), this entails a rather high (3.7) economy-wide elasticity of substitution.

[28] Our empirical approach resembles the one of Acemoglu and Autor (2011) and of much of the macro empirical literature on the labour market determinants of the skill premium. In those papers, estimates from regressions of relative wages on relative skill supplies (plus controls for technological change through time trends) are used to back out the value of the elasticity of substitution between skilled and unskilled workers (in the standard framework, the reciprocal of the estimated coefficient on relative skill supplies)

Adding directed technical change and income elasticity of demand lowers the estimated economy-wide elasticity of substitution, and with both demand-side mechanisms in the model its value of 1.59 is squarely within the generally accepted 1 - 3 range.

VII Concluding remarks

We have analysed how the relative wages of skilled and unskilled workers in economies open to trade vary with their relative supplies. Our empirical results have shown that, as intuition and much other evidence suggests, wages in open economies vary systematically with skill supplies across countries and over time, but also that, as trade theory suggests, wages are less sensitive to skill supplies where exposure to trade is higher.

We have also been able to explain why the average (across countries and periods) wage-skill supply elasticity is about -0.25. That it is negative, rather than zero (as in simple trade theory), is the result of imperfect substitutability between home and foreign goods, trade barriers, and non-proportional costs, which make changes in relative wages necessary to absorb changes in skill supplies. That its size is not much greater (in absolute value), as suggested by standard estimates of the aggregate elasticity of substitution between skilled and unskilled workers, is partly because trade allows more of a change in skill supply to be absorbed by changes in output structure, and partly because directed technical change and income elasticity in consumption cause increases in the supply of skilled workers also to increase the demand for skilled workers.

These results are of practical importance, because they make clearer both the scope for and the limitations of policy initiatives to reduce inequality between skilled and unskilled workers by expansion of education and training. As ever, however, there is scope for future improvement of our analysis, especially by using better measures of trade barriers and of per-unit trade and production costs, and by fuller investigation of the effects of trade in intermediate inputs and of payments to capital.

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