ELSEVIER

Journal of International Economics 71 (2007) 389 – 409

Journal of INTERNATIONAL ECONOMICS

www.elsevier.com/locate/econbase

Technology, endowments, and the factor content of bilateral trade ☆

Huiwen Lai [a], Susan Chun Zhu [b,*]

[a] Economics Group, Wachovia Corporation, 301 South College Street, DC-7, Charlotte, NC 28288, USA
[b] Department of Economics, Michigan State University, Marshall-Adams Hall, East Lansing, MI 48824, USA

Received 25 July 2005; received in revised form 12 July 2006; accepted 12 July 2006

Abstract

We derive testable restrictions relating the factor content of *bilateral* trade to bilateral differences in technology and endowments. This departs from the Heckscher–Ohlin–Vanek theorem which compares the factor content of *net* trade with factor abundance. We test the theoretical restrictions using a unique dataset that covers 41 developed and developing countries with disparate endowments and technology. We find evidence supporting the predictions. In addition: (1) The factor content predictions perform best for country pairs with larger endowment differences, and (2) for trade between capital-abundant countries, Ricardian international technology differences matter more than Heckscher–Ohlin factor endowment differences.

Keywords: Heckscher–Ohlin model; Factor content of bilateral trade; Ricardian technology differences

JEL classification: F1

Empirical research on the Heckscher–Ohlin model, the centerpiece of traditional trade theories, has largely focused on its generalization, the Heckscher–Ohlin–Vanek (HOV) theorem. The HOV theorem compares the factor content of *net* trade with factor abundance and predicts that a capital-abundant country should export capital services. Empirically, the HOV theorem that maintains strict assumptions of identical technology, factor price equalization and identical homothetic preferences has been rejected repeatedly (e.g., Maskus, 1985; Brecher and Choudhri,

☆ We are indebted to James Harrigan, Pravin Krishna, Dan Trefler, and two anonymous referees for very helpful comments and suggestions. We also benefit from seminar presentations at the workshop on "Recent Advances in International Economics" at the City University of Hong Kong, University of Windsor, and University of Kiel.
* Corresponding author. Tel.: +1 517 355 9647; fax: +1 517 432 1068.
E-mail address: zhuc@msu.edu (S.C. Zhu).

0022-1996/$ - see front matter
doi:10.1016/j.jinteco.2006.07.002

1988; Staiger, 1988). In recent major contributions, Trefler (1993, 1995) and Davis and Weinstein (2001) amend the traditional model by relaxing those restrictive assumptions and provide evidence supporting the modified HOV theorem.[1]

The objective of this paper is to test the Heckscher–Ohlin model. Deviating from the traditional approach, we do not examine the HOV prediction. Instead, we follow the empirical approach taken by Choi and Krishna (2004) and test the theoretical predictions that relate the factor content of *bilateral* trade to bilateral differences in technology and endowments. Our theory is built on the work by Brecher and Choudhri (1982), Helpman (1984) and Staiger (1986). Following these authors, we consider a trade equilibrium in which factor prices are allowed to differ across countries. In the absence of factor price equalization one can predict the factor content of trade from post-trade data without imposing any restrictions on preferences, and this can be done not only for every country's net trade vector but also for bilateral trade patterns. Choi and Krishna (2004) are the first to note the implications of those relaxed assumptions for Heckscher–Ohlin testing. Using a sample of 8 OECD countries and assuming identical technology across countries, they test the theoretical predictions in Helpman (1984) and find strong evidence supporting the theory.

In this paper we extend Choi and Krishna (2004) in two important directions. First, we expand the sample substantially to include 41 developed and developing countries with sufficiently disparate factor abundance and productivity. The large sample variation in factor abundance is essential for testing the theory that emphasizes endowment differences. Second, because countries in our sample are at very different technology levels, we incorporate international technology differences into our empirical analysis. In particular, we allow technology differences to be country- and industry-specific, i.e., Ricardian technology differences. As shown by Harrigan (1997), Ricardian technology differences are an important determinant of specialization. However, in the literature on HOV testing, the effective factor content of trade is not well defined when there are non-uniform technology differences across sectors. In contrast, we will show that it is straightforward to incorporate Ricardian technology differences into our framework.[2]

We focus on the following empirical hypotheses. First, on average, a country imports the content of those factors that are cheaper in its trading partner and exports the content of those factors that are more expensive for its trading partner. It implies that in the trade equilibrium the exporter's *actual* unit cost of production (i.e., using the actual exporter's factor prices and factor usage) cannot be greater than the importer's *hypothetical* unit cost of production (i.e., using the importer's factor prices and exporter's factor usage). In the presence of international technology differences, both factor prices and factor usage should be expressed in productivity-equivalent units. Inspired by Debaere (2003), we derive our second hypothesis which relates the factor content of bilateral trade to relative factor abundance. It says that exports by capital-abundant countries embody a higher capital–labor ratio than the exports by labor-abundant countries. However, differing from Debaere (2003) who examines the relationship between relative factor abundance and trade in factor services from the HOV perspective, we focus on the factor content of *bilateral* trade rather than the factor content of *net* trade. Also note that the second hypothesis has

[1] Trefler (1995) reports that the traditional HOV model is rejected in favor of a modification that allows for international technology differences and Armington home bias in consumption. Davis and Weinstein (2001) show that the HOV model, when modified to allow Hicks-neutral technology differences, factor price differences, the existence of nontraded goods and trade costs, is consistent with data from ten OECD countries.

[2] Extending Helpman (1984), Choi and Krishna (2004) derived theoretical restrictions when there exist Ricardian technology differences. However, their empirical analysis assumes identical technology across countries. This assumption is reasonable in their context because their sample includes countries with fairly similar technology.

not been examined by Choi and Krishna (2004). Finally, it is worth pointing out that the two hypotheses represent complimentary views about the relationship between the factor content of bilateral trade and bilateral differences in technology and factor abundance. The first hypothesis looks at the relationship in absolute terms, while the second one is in relative terms.

We find that the empirical hypotheses are confirmed by the vast majority of country pairs in our sample. This result is robust to various alternative specifications. Compared to Choi and Krishna (2004), we find even stronger evidence supporting the model, which confirms their expectation: "While it is unwise to speculate out of sample, this raises the expectation that the theory would hold with even greater "success" outside of the OECD countries we are working with, where factor price differences may be expected to be even larger" (page 905). We also find that the model performs better for country pairs with substantially different endowments. This result accords well with the finding by Debaere (2003) that the HOV model works remarkably well for country pairs with very different capital–labor ratios. Furthermore, we find that Ricardian technology differences appear to play a bigger role than endowment differences in determining trade between capital-abundant countries.

The paper is organized as follows. Section 1 lays out the theoretical framework. Section 2 derives the empirical hypotheses. Section 3 details how productivity differences are measured. Empirical results are presented in Sections 4–5. Section 6 draws the conclusions.

1. Theory

In this section we derive theoretical restrictions on the factor content of bilateral trade, factor prices, and Ricardian technology differences in the trade equilibrium. The basic setup follows Staiger (1986). Final goods are produced using primary factors (e.g., labor, capital) and intermediate inputs. Production exhibits constant returns to scale. All product markets are perfectly competitive. There are no barriers to trade. As will become clear, the theory can be extended easily to include nontraded intermediate inputs. And the assumption whether intermediate inputs are freely traded or non-traded does not make any difference empirically.

Extending Staiger (1986), we allow technology to differ across countries and industries. For simplicity, we assume that technology differences are factor-augmenting and Hicks-neutral.[3] We also assume that the requirement for intermediate inputs is identical across countries. As argued by Davis et al. (1997), a car may be produced with varying degrees of substitution between capital and labor across countries. Yet the same car may require a certain amount of steel, rubber and other intermediate inputs. However, the assumption of identical requirement for intermediates is not needed when intermediate goods are nontraded.

Let g index goods, and c index countries. Let ϕ_{gc} be the production function for good g in country c. Let d_{gc} be the vector of factors needed *directly* to produce one unit of good g in country c. By definition, $\phi_{gc}(d_{gc})=1$. To simplify notation, in ϕ_{gc} we suppress the requirement for intermediate inputs because it is identical across countries. Let λ_{gc} denote productivity of industry g in country c. With factor-augmenting and Hicks-neutral technology differences, $\phi_{gc}(d_{gc})=\phi_g(\lambda_{gc}d_{gc})$ for some internationally common production functions ϕ_g (see Trefler, 1995). Because $\phi_{gc}(d_{gc})=1$, $\phi_g(\lambda_{gc}d_{gc})=1$. Thus, a larger λ_{gc} indicates fewer inputs per unit of output or greater productivity.

[3] It is straightforward to extend the theory to allow for factor-bias technology differences. However, the lack of measures of factor-bias technology differences prevents us from pursuing any empirical test for this interesting case.

Let $T_{gc'c}$ be the volume of gross exports of good g from country c to country c'. When intermediates are freely traded, all countries face the same price of intermediate inputs and have identical requirements for intermediate inputs, implying that the cost of intermediate inputs must be equal across countries. Let p_g^I be the cost of intermediates used to produce one unit of good g. Let w_c be the vector of factor prices in country c. With constant returns-to-scale technology, the per-unit cost of producing g in country c is given by $w_c d_{gc} + p_g^I$. Perfect competition implies zero profits on exports of g from country c to country c'. Hence,

$$p_g = w_c d_{gc} + p_g^I \tag{1}$$

where p_g is the world price of good g.

For importing country c', unit profits on good g must be nonpositive:

$$p_g \leq w_{c'} d_{gc'} + p_g^I. \tag{2}$$

With constants returns-to-scale technology and no firm heterogeneity within industries, Eq. (2) holds for all firms in industry g in country c'. Zero profits obtain only when country c' produces good g. Combining Eqs. (1) and (2) we obtain

$$w_c d_{gc} \leq w_{c'} d_{gc'}. \tag{3}$$

p_g^I cancels because, being costlessly tradable, intermediates are not a source of comparative advantage.[4]

However, direct factor requirements may differ across countries, i.e., $d_{gc} \neq d_{gc'}$. The gap in factor usage arises from international differences in both technology and factor prices. With Hicks-neutral differences in factor efficiency, if country c and country c' had the same factor prices, country c' would need $(\lambda_{gc}/\lambda_{gc'})d_{gc}$ directly to produce one unit of good g. (Recall that a higher λ_{gc} indicates greater productivity.) For example, for industry g, if workers in country c' are twice as productive as workers in country c (i.e., $\lambda_{gc'}/\lambda_{gc}=2$), country c' would need just half of the workers that are required by country c to produce the same amount of output. However, if country c' and country c face different factor prices, although $(\lambda_{gc}/\lambda_{gc'})d_{gc}$ is a feasible way for country c' to produce one unit of g, it may not be optimal. Country c' can reduce production cost via factor substitution. The optimal bundle of factors is given by $d_{gc'}$. Therefore, cost minimization implies

$$w_{c'} d_{gc'} \leq w_{c'} (\lambda_{gc}/\lambda_{gc'}) d_{gc}. \tag{4}$$

Combining inequalities (3)–(4) yields $w_c d_{gc} \leq w_{c'}(\lambda_{gc}/\lambda_{gc'})d_{gc}$ or

$$\frac{w_c}{\lambda_{gc}} d_{gc} \leq \frac{w_{c'}}{\lambda_{gc'}} d_{gc}. \tag{5}$$

Inequality (5) describes the restriction on factor prices, direct factor requirements and Ricardian technology differences for industry g in the trade equilibrium. Because all the variables are observable in the post-trade equilibrium, inequality (5) is empirically testable. It is worth pointing

[4] If intermediate inputs are traded with costs, country c and country c' may purchase intermediates at different prices. Let p_{gc}^I and $p_{gc'}^I$ be the per-unit cost of intermediates paid by country c and country c', respectively. Then p_g^I in Eq. (1) is replaced with p_{gc}^I while p_g^I in inequality (2) is replaced with $p_{gc'}^I$. If p_{gc}^I is sufficiently smaller than $p_{gc'}^I$, it is possible that $w_c d_{gc} \geq w_{c'} d_{gc'}$ is compatible with Eq. (1) and inequality (2). In this case, the restriction in inequality (5) may be violated. Therefore, admitting both trade barriers and intermediate inputs poses theoretical difficulties. This point has been noted by Deardorff (1979), Brecher and Choudhri (1982) and Staiger (1986). We remind the reader that there is also no substitution possibility between intermediate inputs and primary factors.

out that the derivation does not require the productivity-adjusted factor prices to be equalized internationally i.e., $w_{c'}/\lambda_{gc'}=w_c/\lambda_{gc}$.

To derive the national-level restrictions, we aggregate inequality (5) over g using $T_{gc'c}$ as the weight. By giving a larger weight to industries with a higher trade volume, we can capture the effects of international specialization. Defining $T^V_{gc'c}\equiv d_{gc}T_{gc'c}$ (i.e., the vector of factors required *directly* to produce $T_{gc'c}$), industry aggregation yields

$$\Sigma_g\left(\frac{w_c}{\lambda_{gc}}-\frac{w_{c'}}{\lambda_{gc'}}\right)(\lambda_{gc}T^V_{gc'c})\leq 0. \tag{6}$$

By symmetry,

$$\Sigma_g\left(\frac{w_{c'}}{\lambda_{gc'}}-\frac{w_c}{\lambda_{gc}}\right)(\lambda_{gc'}T^V_{gcc'})\leq 0. \tag{7}$$

As Brecher and Choudri (1982, footnote 10) point out, when bilateral trade is not balanced between country c and country c', it is not appropriate to compare the factor content of total exports. Thus, in the following analysis we will examine the factor content of one million dollars' worth of exports from each country: We divide $T^V_{gc'c}$ by the value (in millions of dollars) of gross exports from country c to country c', and $T^V_{gcc'}$ by the value (in millions of dollars) of gross exports from country c' to country c.

Several points are worth mentioning about inequalities (6) and (7). First, the derivations allow for differences in factor prices. Factor price equalization is likely to break down when countries differ in technology or have sufficiently different factor endowments.[5] On the other hand, the derivations do not require that factor prices must be different between country pairs. As is clear from the weak inequalities, the theoretical restrictions still hold when there exist factor price equalization and identical technology. However, we expect that inequalities (6)–(7) would perform better the larger are the within country-pair differences in endowments.

Second, with factor-augmenting technology differences, both factor prices and the factor content of bilateral trade should be transformed into productivity-equivalent units. Specifically, for industry g, the productivity-adjusted factor costs in country c are w_c/λ_{gc} and the productivity-adjusted factor content of per-unit exports from country c to c' is $\lambda_{gc}T^V_{gc'c}$. This type of productivity transformation has been used by Trefler (1993, 1995).

Third, the restrictions are imposed on the relationship between the post-trade bilateral factor-price differentials and the *direct* factor content of bilateral trade. As stressed by Staiger (1986), with free trade in intermediate goods, inequalities (6) and (7) should not be applied to the *indirect* factor content of bilateral trade.

1.1. Nontraded intermediates

Now we briefly discuss the case where intermediate goods are not traded. In this case, intermediate inputs must come from domestic sources. Let I_{gc} be the vector of factor content of

[5] With sufficiently disparate endowments, countries specialize in the particular subset of goods most suited to their mix of endowments. Using industry-level data, Schott (2003) finds strong empirical evidence supporting this multiple-cone equilibrium against the overly restrictive "one size fits all" equilibrium of the Heckscher–Ohlin model. Debaere and Demiroglu (2003) provide further evidence for the existence of multiple-cone equilibrium in which developed OECD countries and less developed ones belong to different diversification cones.

intermediate inputs used to produce one unit of good g. Hence, Eq. (1) becomes $p_g = w_c(d_{gc} + I_{gc})$ and inequality (2) becomes $p_g \leq w_{c'}(d_{gc'} + I_{gc'})$. They imply that $w_c(d_{gc} + I_{gc}) \leq w_{c'}(d_{gc'} + I_{gc'})$, which is analogous to inequality (3). The national-level restrictions in the presence of nontraded intermediates are analogous to inequalities (6) and (7), except that both direct and indirect factor requirements should be included to calculate the factor content of bilateral trade. Note that when intermediates are nontraded, the assumption of identical requirement for intermediates is not needed.

2. Empirical hypotheses

The empirical hypotheses are derived based on inequalities (6)–(7). Combining the two inequalities yields

$$\Sigma_g \left(\frac{w_{c'}}{\lambda_{gc'}} - \frac{w_c}{\lambda_{gc}} \right) (\lambda_{gc} T^V_{gc'c} - \lambda_{gc'} T^V_{gcc'}) \geq 0. \tag{8}$$

Inequality (8) is the productivity-adjusted version of equation (16) in Helpman (1984). Both factor prices and the factor content of bilateral trade are expressed in productivity-equivalent units to take into account Ricardian technology differences. It says that on average country c' is a net importer from country c of the content of those factors that are cheaper in c than in c' and vice versa.

To test the theory, we rewrite inequality (8) as

$$\theta^{\text{Ricardian}}_{c'c} \equiv \frac{\Sigma_g (w_{c'}/\lambda_{gc'}) \lambda_{gc} T^V_{gc'c} + \Sigma_g (w_c/\lambda_{gc}) \lambda_{gc'} T^V_{gcc'}}{w_{c'} T^V_{cc'} + w_c T^V_{c'c}} \geq 1 \tag{9}$$

where $T^V_{c'c} \equiv \sum_g T^V_{gc'c}$ and $T^V_{cc'} \equiv \sum_g T^V_{gcc'}$. $\theta^{\text{Ricardian}}_{c'c}$ represents a ratio of the importer's *hypothetical* unit cost of production (i.e., using the importer's factor prices and exporter's factor usage) to the exporter's *actual* unit cost of production (i.e., using the actual exporter's factor prices and factor usage). Because in the trade equilibrium the unit cost of production in the importing country cannot be lower than that in the exporting country, the cost ratio represented by $\theta^{\text{Ricardian}}_{c'c}$ should not be less than 1. In addition, the magnitude of $\theta^{\text{Ricardian}}_{c'c}$ can reveal the extent to which the theory is confirmed or violated in the sense that $\theta^{\text{Ricardian}}_{c'c} - 1$ is a measure of excess costs that would be incurred by not specializing.

If international technology differences are uniform across sectors (i.e., $\lambda_{gc'} = \lambda_{c'}$ and $\lambda_{gc} = \lambda_c$ for all g), using $T^V_{c'c} \equiv \sum_g T^V_{gc'c}$ and $T^V_{cc'} \equiv \sum_g T^V_{gcc'}$, inequality (9) reduces to

$$\theta^{\text{Uniform}}_{c'c} \equiv \frac{(w_{c'}/\lambda_{c'}) \lambda_c T^V_{c'c} + (w_c/\lambda_c) \lambda_{c'} T^V_{cc'}}{w_{c'} T^V_{cc'} + w_c T^V_{c'c}} \geq 1. \tag{10}$$

If technology is identical across countries (i.e., $\lambda_{c'} = \lambda_c$ for all c and c'), inequality (9) can be further simplified as[6]

$$\theta^{\text{Identical}}_{c'c} \equiv \frac{w_{c'} T^V_{c'c} + w_c T^V_{cc'}}{w_{c'} T^V_{cc'} + w_c T^V_{c'c}} \geq 1. \tag{11}$$

[6] If $w_{c'} = w_c$, $\theta^{\text{Identical}}_{c'c} = 1$. Thus, the hypothesis in inequality (11) allows factor prices to be equal between country pairs.

Choi and Krishna (2004) tested inequality (11) using data from 8 OECD countries and find strong evidence supporting the theory.[7] They also derived theoretical restrictions similar to inequalities (9)–(10). But they did not test these restrictions empirically. In contrast, inequality (9) is the focal point of our empirical analysis.

It is worth noting that inequalities (9)–(11) can be applied to many factors. However, due to data constraints, in the empirical analysis we include capital K and aggregate labor L as primary factors. As will be shown in Section 4.4, for the 8 OECD countries examined by Choi and Krishna (2004), our results on $\theta_{c'c}^{\text{Identical}} \geq 1$ are very similar to their estimates which include capital, skilled and unskilled labor as primary factors. Hence, we do not expect that our results would be sensitive to factor aggregation.

Inspired by Debaere (2003), we also derive a relationship between the factor content of bilateral trade and relative factor abundance. It is straightforward to derive

$$\gamma_{c'c} \equiv \left(\frac{w_{c'}^L}{w_{c'}^K} - \frac{w_c^L}{w_c^K}\right)\left(\frac{T_{cc'}^K}{T_{cc'}^L} - \frac{T_{c'c}^K}{T_{c'c}^L}\right) \geq 0 \tag{12}$$

where $w_c^f (f = K, L)$ is the price of factor f in country c and $T_{c'c}^f$ is the amount of factor f required directly to produce gross exports from country c to c'.[8] Inequality (12) implies that if $w_{c'}^L / w_{c'}^K > w_c^L / w_c^K$, then $T_{cc'}^K / T_{cc'}^L \geq T_{c'c}^K / T_{c'c}^L$. That is, if country c' has a higher wage–rental ratio than country c, the capital–labor ratio embodied in country c''s exports to c cannot be lower than the capital–labor ratio embodied in country c's exports to c'.

As noted by Debaere (2003), when considering relative factor abundance, Hicks-neutral and factor augmenting productivity differences do not matter. Hence, the hypothesis $\gamma_{c'c} \geq 0$ is robust to Hicks-neutral technology differences. This property allows us to compute $\gamma_{c'c}$ without first imputing technology parameters. Thus, we can avoid the potential problem of measurement error in the estimated technology parameters.

3. Measuring productivity λ_{gc}

To test the hypothesis $\theta_{c'c}^{\text{Ricardian}} \geq 1$, we first compute the industry-level total factor productivity (TFP) to measure Ricardian technology differences λ_{gc}. Following Caves et al. (1982), Harrigan (1997), Keller (2002) and Griffith et al. (2004), we calculate the multi-lateral TFP index in order to make the measure internationally comparable. TFP calculations require

[7] To be precise, inequality (11) slightly differs from Choi and Krishna's hypothesis. Inequality (10) in Choi and Krishna (2004) does not normalize the factor content of trade by the value of gross exports.

[8] For the case with two factors, K and L, inequality (5) can be rewritten as $w_c^L d_{gc}^L + w_c^K d_{gc}^K \leq (w_{c'}^L / \lambda_{gc'}) \lambda_{gc} d_{gc}^L + (w_{c'}^K / \lambda_{gc'}) \lambda_{gc} d_{gc}^K$, where $d_{gc}^f (f = K, L)$ is the amount of factor f required directly to produce one unit of good g in country c. Multiplying both sides by $T_{gc'c}$ and using $T_{gc'c}^f \equiv d_{gc}^f T_{gc'c}$ we obtain

$$w_c^L T_{gc'c}^L + w_c^K T_{gc'c}^K \leq (w_{c'}^L / \lambda_{gc'}) \lambda_{gc} T_{gc'c}^L + (w_{c'}^K / \lambda_{gc'}) \lambda_{gc} T_{gc'c}^K. \tag{13}$$

By symmetry,

$$w_{c'}^L T_{gcc'}^L + w_{c'}^K T_{gcc'}^K \leq (w_c^L / \lambda_{gc}) \lambda_{gc'} T_{gcc'}^L + (w_c^K / \lambda_{gc}) \lambda_{gc'} T_{gcc'}^K. \tag{14}$$

Because both sides of inequalities (13) and (14) are positive, we multiply both sides of them. Then summing the result over g, we obtain $w_c^L T_{c'c}^L w_{c'}^K T_{cc'}^K + w_c^K T_{c'c}^K w_{c'}^L T_{cc'}^L \leq w_{c'}^L T_{c'c}^L w_c^K T_{cc'}^K + w_{c'}^K T_{c'c}^K w_c^L T_{cc'}^L$. Dividing both sides by $w_{c'}^K T_{cc'}^K w_c^K T_{c'c}^K$ gives $(w_{c'}^L / w_{c'}^K - w_c^L / w_c^K)(T_{c'c}^L / T_{c'c}^K - T_{cc'}^L / T_{cc'}^K) \geq 0$. Since $(T_{c'c}^L / T_{c'c}^K - T_{cc'}^L / T_{cc'}^K)$ and $(T_{cc'}^K / T_{cc'}^L - T_{c'c}^K / T_{c'c}^L)$ have the same sign, inequality (12) follows.

real, internationally comparable data on outputs, inputs of primary factors, and intermediate inputs. At the industry level, data exist only for capital and aggregate labor, not for intermediate inputs. So we calculate the value-added TFP indexes. Therefore, the TFP estimates used in this paper should be viewed as approximations to the true TFP measures.

Because our empirical analysis is cross sectional (for the year 1997), to simplify notation, we will suppress year t as an argument unless it is necessary. Let Z_{gc} denote value added in industry g in country c, L_{gc} labor inputs, K_{gc} capital inputs, α_{gc} labor cost share, and N the number of countries in the sample. Define $\overline{\ln Z_{gc}} \equiv (\Sigma_c \ln Z_{gc})/N$, $\overline{\ln L_g} \equiv (\Sigma_c \ln L_{gc})/N$, $\overline{\ln K_g} \equiv (\Sigma_c \ln K_{gc})/N$ and $\tilde{\alpha}_{gc} \equiv [\alpha_{gc} + (\Sigma_c \alpha_{gc})/N]/2$. Then the multi-lateral TFP index for industry g in country c can be calculated as

$$\ln TFP_{gc} \equiv (\ln Z_{gc} - \overline{\ln Z_g}) - \tilde{\alpha}_{gc}(\ln L_{gc} - \overline{\ln L_g}) - (1 - \tilde{\alpha}_{gc})(\ln K_{gc} - \overline{\ln K_g}). \tag{15}$$

This TFP index is superlative, meaning that it is exact for the flexible translog function. It is also transitive: $TFP_{gc}/TFP_{gc'} = (TFP_{gc}/TFP_{g,\mathrm{US}})/(TFP_{gc'}/TFP_{g,\mathrm{US}})$ where $TFP_{g,\mathrm{US}}$ and $TFP_{gc'}$ denote the industry-level TFP for the United States and country c', respectively. Hence, the choice of the base country is inconsequential. Without loss of generality, the United States is chosen as the base country and thus the estimates of TFP_{gc} are expressed relative to $TFP_{g,\mathrm{US}}$.

Following Keller (2002) and Griffith et al. (2004), we take into account cross-country differences in labor and capital utilization. To adjust labor inputs, we multiply labor employment by average annual hours worked per person in employment. To adjust capital inputs, we multiply capital stock series by an estimate of capacity utilization. Capacity utilization is estimated as follows. The actual usage of capital inputs may fluctuate over economic cycles: during down turns capital may not be fully used while during booms it may be over used. We thus measure capacity utilization for year t as $Q_{gct}/\hat{Q}_{gct}$; where Q_{gct} is the actual output level in industry g in country c in year t, and $\hat{Q}_{gct}$ is predicted from the regression $Q_{gct} = \eta_{gc} + t_c + \mu_{gct}$ where η_{gc} denote the industry–country dummy variables, t_c is the country-specific time trend, and μ_{gct} is the error term. The regression is done for the period 1985–2000 when all the key variables are available (see the Appendix for more details). It is worth pointing out that adjusting capital utilization does not make any difference empirically.

To test the hypothesis $\theta_{c'c}^{\mathrm{Uniform}} \geq 1$, we first calculate the national-level TFP to measure the country-specific productivity differences λ_{c}. To obtain the national-level TFP, we aggregate the industry-level TFP using the industry's share of value added as the weight.

Because international technology differences play an essential role in our analysis, it is important to know whether our results are robust to alternative productivity measures. We construct an alternative measure based on direct factor requirements. Let $d_{gc}^f (f = K, L)$ be the amount of factor f needed directly to produce one unit of good g in country c. Modifying the estimating equation ($\hat{P}$4) in Davis and Weinstein (2001) we run the regression In $d_{gc}^f = \delta_{gc} + \delta_{fg} + \beta_f \ln(K_c/L_c) + \varepsilon_{fgc}$, where δ_{gc} captures the country- and industry-specific productivity differences, δ_{fg} provides average estimates of the factor requirements across countries, K_c/L_c is the capital–labor ratio in country c, and ε_{fgc} is the error term. The inclusion of $\ln(K_c/L_c)$ is motivated by the fact that if factor prices are not equal and countries are in different diversification cones, input coefficients may vary according to country capital abundance. The predicted factor requirements in each country differ from the average factor requirements δ_{fg} depending on the Ricardian technology differences δ_{gc}, and depending on the effect of factor abundance $\beta_f \ln(K_c/L_c)$. Based on the estimated δ_{gc}, λ_{gc} can be imputed as $\exp(-\hat{\delta}_{gc})$. Without loss of generality, the United States is chosen as the numeraire, i.e., $\delta_{g,\mathrm{US}} \equiv 0$. Hence, the productivity estimates for other countries are expressed relative to the U.S. level.

The summary statistics on the industry-level productivity estimates are presented in Appendix Table A.1. Column 1 gives the geometric average of TFP_{gc} with country shares of value added as the weight. As expected, nearly all industries have average TFP estimates below 1 (the U.S. level). Column 2 displays large cross-country variations in productivity for all industries. The table also shows the correlation of the TFP indices with GDP per capita (column 3) and the alternative productivity measure $\exp(-\hat{\delta}_{gc})$ (column 4). Except for a few industries, the TFP indices are strongly correlated with GPD per capita, confirming our expectation that high-income countries should have higher productivity. The TFP estimates are also strongly and positively correlated with $\exp(-\hat{\delta}_{gc})$ for the majority of industries. See the Appendix for more details about data sources and measurement.

4. Exporter's *actual* production cost versus importer's *hypothetical* production cost

In this section we focus on the hypotheses in inequalities (9)–(11). They mean that in the trade equilibrium, the importer's *hypothetical* unit cost of production (i.e., using the importer's factor prices and exporter's factor usage) cannot be lower than the exporter's *actual* unit cost of production (i.e., using the actual exporter's factor prices and factor usage).

4.1. Labor-abundant and capital-abundant country groups

We divide the 41 countries in our sample into two groups based on the similarity of wage–rental ratios (w_c^L/w_c^K) and capital–labor endowment ratios (K_c/L_c).[9] The labor-abundant group has 19 countries and the capital-abundant group has 22 countries. On average, the wage–rental and capital–labor ratios for the capital-abundant group are three times as high as those for the labor-abundant group. The large sample variation in endowments is essential for testing the Heckscher–Ohlin model that emphasizes the role of endowment differences.

4.2. Sign tests

We first examine the hypothesis $\theta_{c'c}^{\text{Ricardian}} \geq 1$ in inequality (9) where Ricardian technology differences, λ_{gc} and $\lambda_{gc'}$, are measured by the industry-level TFP. The results are listed in column 1 of Table 1. Rows 1–3 report the sign statistics which are defined as the percentage of country pairs that satisfy $\theta_{c'c}^{\text{Ricardian}} \geq 1$. For 418 (= 22 × 19) pairs involving one capital-abundant country and one labor-abundant country, $\theta_{c'c}^{\text{Ricardian}} \geq 1$ is satisfied for 96% of the time (see row 1). The *p*-value of the sign test is below 0.01 which means that the probability of having $\theta_{c'c}^{\text{Ricardian}} \geq 1$ for more than 96% of the time is less than 1%. Thus, the hypothesis $\theta_{c'c}^{\text{Ricardian}} \geq 1$ performs remarkably well for pairs of capital-abundant and labor-abundant countries. Rows 2–3 of column 1 show that $\theta_{c'c}^{\text{Ricardian}} \geq 1$ is satisfied for more than 80% of the pairs involving only capital-abundant or labor-abundant countries.[10] Again, the hypothesis $\theta_{c'c}^{\text{Ricardian}} \geq 1$ cannot be rejected at the 1% significance level.

Column 2 of Table 1 gives the results for $\theta_{c'c}^{\text{Uniform}} \geq 1$ where international technology differences are assumed to be uniform across sectors. The technology parameters, λ_c and $\lambda_{c'}$, are

[9] On a more technical level, our country clustering is based on the Euclidean distances computed from K_c/L_c and w_c^L/w_c^K. The cluster centers are based on least-squares estimation and are the means of the observations assigned to each cluster when the algorithm is run to complete convergence. See Anderberg (1973) for more details.

[10] Because $\theta_{c'c}^{\text{Ricardian}} = \theta_{cc'}^{\text{Ricardian}}$, the number of non-duplicate pairs involving only capital-abundant countries is 231 (=22 × 21/2). Similarly, the number of non-duplicate pairs of only labor-abundant countries is 171 (=19 × 18/2).

Table 1
Exporter's *actual* production cost versus importer's *hypothetical* production cost

	$\theta_{c'c}^{\text{Ricardian}} \geq 1$ (1)	$\theta_{c'c}^{\text{Uniform}} \geq 1$ (2)	$\theta_{c'c}^{\text{Identical}} \geq 1$ (3)	Obs
Sign test				
1. Pairs of capital-abundant and labor-abundant countries	0.96	0.96	0.99	418
	(<0.01)	(<0.01)	(<0.01)	
2. Pairs of capital-abundant countries	0.82	0.68	0.73	231
	(<0.01)	(<0.01)	(<0.01)	
3. Pairs of labor-abundant countries	0.85	0.85	0.81	171
	(<0.01)	(<0.01)	(<0.01)	
Probit regressions				
4. $\lvert K_c/L_c - K_{c'}/L_{c'}\rvert$	33.94	32.37	33.28	820
Standard error	4.65	3.71	4.27	
Log-likelihood	−240.27	−298.28	−270.18	
5. $\sum_{f=K,L}(w_c^f - w_{c'}^f)^2(V^f)^2$	0.79	0.71	3.41	820
Standard error	0.17	0.14	0.47	
Log-likelihood	−257.20	−318.70	−237.71	
OLS regressions				
6. $\lvert K_c/L_c - K_{c'}/L_{c'}\rvert$	13.28	13.75	19.19	820
Standard error	0.82	0.81	1.02	
R^2	0.28	0.30	0.37	
7. $\sum_{f=K,L}(w_c^f - w_{c'}^f)^2(V^f)^2$	0.39	0.39	0.80	820
Standard error	0.03	0.03	0.03	
R^2	0.21	0.20	0.57	

Notes: This table examines the hypotheses in inequalities (9)–(11) that compare the importer's *hypothetical* unit production cost with the exporter's *actual* unit production cost. The sample includes 22 capital-abundant countries and 19 labor-abundant countries. In the probit regressions the dependent variable is a dummy variable that equals one if the hypothesis is satisfied and zero otherwise. In the OLS regressions the dependent variable is log $\theta_{c'c}^{\text{Ricardian}}$, log $\theta_{c'c}^{\text{Uniform}}$ and log $\theta_{c'c}^{\text{Identical}}$, respectively, in columns 1–3. In rows 4 and 6, $\lvert K_c/L_c - K_{c'}/L_{c'}\rvert$ is the difference in capital–labor ratios between country c and country c'. In rows 5 and 7, $\sum_{f=K,L}(w_c^f - w_{c'}^f)^2(V^f)^2$ is an alternative measure of country-pair differences in endowments, where w_c^f is the price of factor f in country c, and V^f is the sample average of actor endowment (capital K or labor L) relative to GDP. The standard errors are robust to heteroskedasticity. In parentheses are p-values of the sign test.

measured by the national-level TFP. Column 3 reports the results for $\theta_{c'c}^{\text{Identical}} \geq 1$ under the assumption of identical technology across countries. Columns 2–3 show that for all country pairs, both hypotheses cannot be rejected at the 1% level. For pairs involving capital-abundant and labor abundant countries, both hypotheses are satisfied at a higher rate than for the pairs of only capital-abundant or labor-abundant countries. Therefore, the sign tests show strong support for the theory. The model performs even better for pairs of countries with more disparate endowment differences.

Interestingly, we also find that for the pairs that consist of only capital-abundant countries, the sign statistic for $\theta_{c'c}^{\text{Ricardian}} \geq 1$ is 82% which is higher than the success rate for both $\theta_{c'c}^{\text{Uniform}} \geq 1$ and $\theta_{c'c}^{\text{Identical}} \geq 1$. The result suggests that allowing for Ricardian technology differences may help one explain trade in factor services between capital-abundant countries.

4.3. Model performance and endowment differences

Now we present more direct evidence supporting the view that the Heckscher–Ohlin model performs better for country pairs with larger endowment differences (Evenett and Keller, 2002).

We directly measure endowment differences between country pairs in order to avoid the potential problem of 'arbitrary' country grouping. Endowment differences are measured in two ways. The first measure is $|K_c/L_c - K_{c'}/L_{c'}|$ which is the difference in capital–labor ratios between country c and country c'. It has been used by Debaere (2003). Following Choi and Krishna (2004), we construct the second measure as $\sum_{f=K,L}(w_c^f - w_{c'}^f)^2(V^f)^2$, where V^f is the sample average of factor endowment f (capital K or labor L) relative to GDP. Using V^f as the weight handles the problem of different measurement units of wage (w_c^L) and rental (w_c^K). The correlation between the two measures of endowment differences is 0.59 ($p < 0.01$).

We run probit regressions on endowment differences. The dependent variable is a dummy variable that equals one if the hypothesis is satisfied, and zero otherwise. The regression results are given in rows 4–5 of Table 1.[11] In all cases the coefficients on endowment differences are positive and statistically significant, which indicates that the hypotheses are more likely to be satisfied for country pairs with bigger endowment differences. This result accords well with Debaere (2003) who finds that the HOV model performs well for countries with very different capital–labor ratios.

Because the θ's represent a ratio of the importer's hypothetical unit cost to the exporter's actual unit cost, the magnitude of the θ's is meaningful. We thus regress the logarithm of θ on endowment differences using the ordinary least squares (OLS) estimation. Rows 6–7 show that in all cases the estimated coefficients on endowment differences are significantly positive, suggesting that the cost ratio increases in bilateral endowment differences. It further implies that the probability of $\theta \geq 1$ is likely to be higher for country pairs with more disparate endowments.

Further evidence is given in Figs. 1 and 2. Panel A of Fig. 1 displays the percentage of country pairs that satisfy the hypothesis $\theta_{c'c}^{\text{Ricardian}} \geq 1$ by percentile of endowment differences measured by $|K_c/L_c - K_{c'}/L_{c'}|$. For country pairs with very small endowment differences, e.g., below the 10th percentile of the distribution, $\theta_{c'c}^{\text{Ricardian}} \geq 1$ is satisfied for less than 70% of the time. In contrast, for country pairs with very large endowment differences, e.g., above the 90th percentile, $\theta_{c'c}^{\text{Ricardian}} \geq 1$ is confirmed for 100% of the time. Panel B reveals a similar pattern for the hypothesis $\theta_{c'c}^{\text{Identical}} \geq 1$. Country pairs in the upper end of the distribution satisfy the hypothesis at much higher rates than country pairs in the lower end, indicating that the model performs better for country pairs with larger endowment differences. We obtain similar patterns for $\theta_{c'c}^{\text{Uniform}} \geq 1$. Results are also similar when endowment differences are measured by $\sum_{f=K,L}(w_c^f - w_{c'}^f)^2(V^f)^2$. To save space, we do not show those plots in the paper.

Fig. 2 plots log $\theta_{c'c}^{\text{Ricardian}}$ and log $\theta_{c'c}^{\text{Identical}}$ against $|K_c/L_c - K_{c'}/L_{c'}|$. Evidently, the OLS estimates shown in Table 1 are not driven by outliers. In addition, the plots reveal that for country pairs with larger endowment differences, log $\theta_{c'c}^{\text{Identical}}$ are more likely to be bigger than log $\theta_{c'c}^{\text{Ricardian}}$. It implies that ignoring Ricardian technology differences is likely to overstate the cost ratio and thus model performance for country pairs with more disparate endowments. This is consistent with the sign statistics as shown in row 1 of Table 1: $\theta_{c'c}^{\text{Identical}} \geq 1$ has a higher sign statistic than $\theta_{c'c}^{\text{Ricardian}} \geq 1$ for the pairs involving capital-abundant and labor-abundant countries. In the following robustness analysis we will focus on $\theta_{c'c}^{\text{Ricardian}} \geq 1$.

4.4. Robustness

In the previous analysis we have assumed that intermediate inputs are traded without any costs. Now we allow intermediates to be nontraded. Under this assumption, both direct and indirect

[11] Because $\theta_{c'c} = \theta_{cc'}$, with 41 countries in the sample, the number of non-duplicate country pairs is 820 ($=41 \times 40/2$).

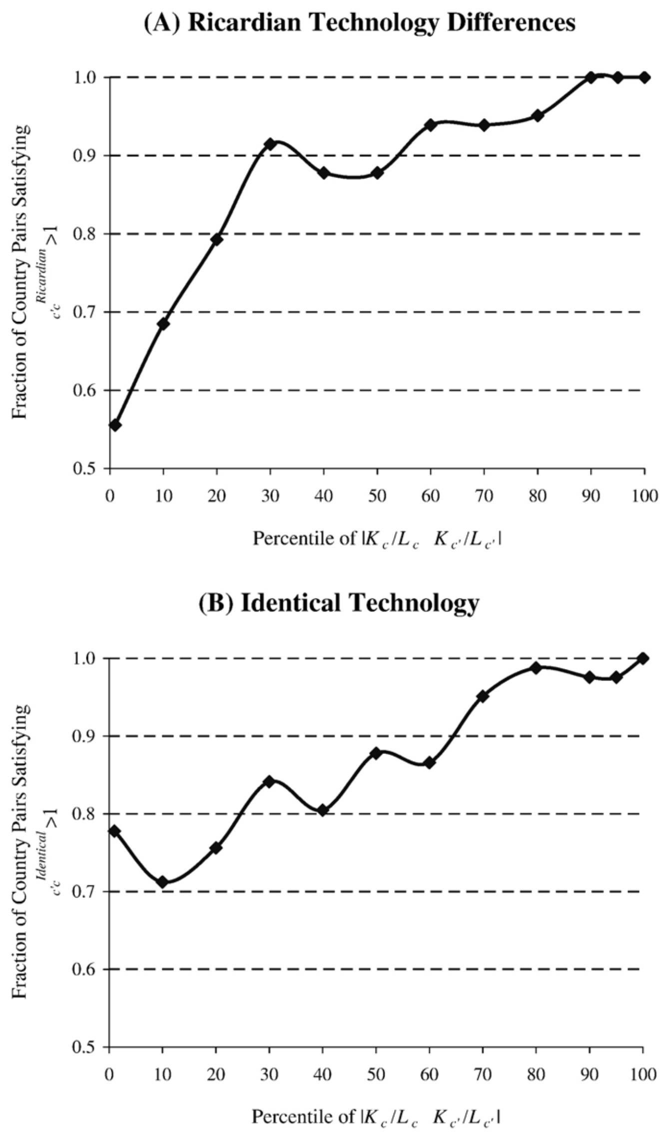

Fig. 1. Performance of $\theta_{c'c}^{\text{Ricardian}} \geq 1$ and $\theta_{c'c}^{\text{Identical}} \geq 1$ by endowment differences.

factor requirements should be used to compute the factor content of bilateral trade (see Section 1). The results for $\theta_{c'c}^{\text{Ricardian}} \geq 1$ with nontraded intermediates are presented in column 2 of Table 2. For comparison, column 1 of Table 2 lists the baseline result carried over from column 1 of Table 1. For pairs of capital-abundant and labor-abundant countries, the sign statistic is 97% which is almost identical to the baseline result. For pairs of only capital-abundant or labor-abundant countries, the sign statistics are slightly higher than the baseline case. Both the probit and OLS regressions yield significantly positive coefficients on endowment differences, suggesting that the model performs better for country pairs with bigger endowment differences. Therefore, our results are not sensitive to the assumption whether intermediates inputs are freely traded or nontraded.

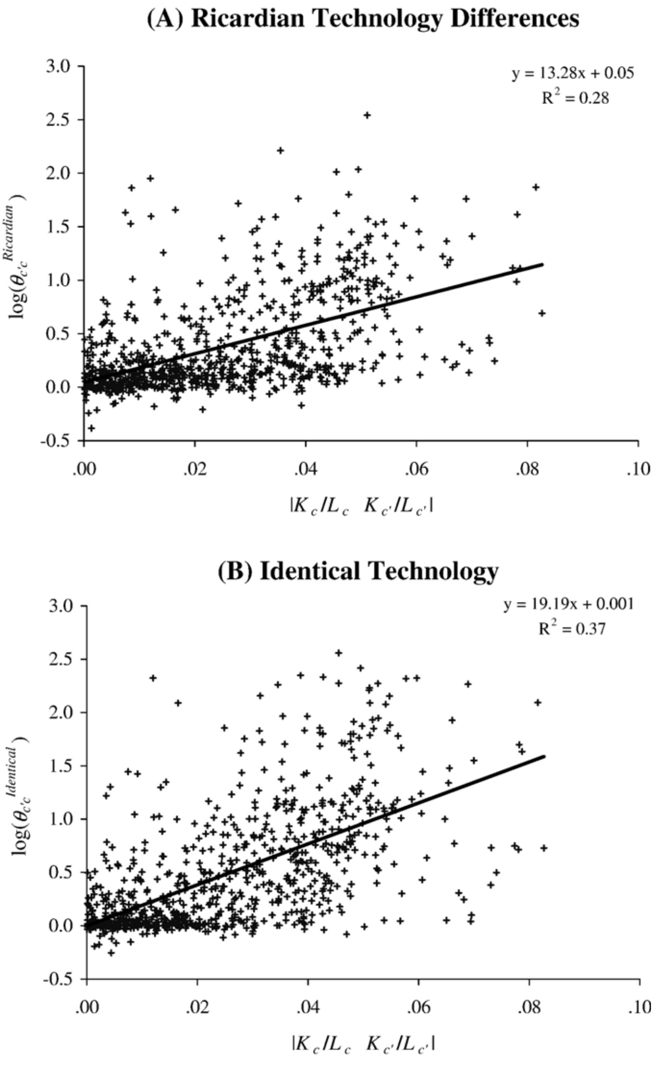

Fig. 2. The magnitude of $\theta_{c'c}^{\mathrm{Ricardian}}$ and $\theta_{c'c}^{\mathrm{Identical}}$ by endowment differences.

Our second robustness check is on the rental rate of capital. The inclusion of many developing countries in our sample prevents us from constructing the return to capital in the same way as done by Choi and Krishna (2004). As described in the Appendix, our data include information on $w_c^K / w_{\mathrm{US}}^K$ rather than w_c^K. To overcome this obstacle, in the previous analysis we have set $w_{\mathrm{US}}^K = 16.5\%$ based on the Capital II measure of U.S. rental rate in Choi and Krishna (2004). Then w_c^K is imputed as $(w_c^K / w_{\mathrm{US}}^K) \times 16.5\%$. In order to examine whether our results are sensitive to this imputation, we now choose $w_{\mathrm{US}}^K = 8\%$ based on Choi and Krishna's Capital I measure of U.S. rental rate and impute w_c^K as $(w_c^K / w_{\mathrm{US}}^K) \times 8\%$. The results are given in column 3 of Table 2. It is clear that our results are little changed.

Since international technology differences play an essential role in our analysis, it is important to see whether our results are robust to alternative measures of productivity differences. In

Table 2
Robustness of $\theta_{c'c}^{\text{Ricardian}} \geq 1$

	Baseline	Nontraded intermediates	$w_{\text{US}}^{K}=8\%$	$\lambda_{gc}=\exp(-\delta_{gc})$	λ_{gc}=lagged TFP	$\theta_{gc'c}^{\text{Ricardian}} \geq 1$
	(1)	(2)	(3)	(4)	(5)	(6)
Sign test						
1. Pairs of capital-abundant and labor-abundant countries	0.96	0.97	0.95	0.87	0.95	0.88
	(<0.01)	(<0.01)	(<0.01)	(<0.01)	(<0.01)	(<0.01)
2. Pairs of capital-abundant countries	0.82	0.84	0.83	0.71	0.81	0.70
	(<0.01)	(<0.01)	(<0.01)	(<0.01)	(<0.01)	(<0.01)
3. Pairs of labor-abundant countries	0.85	0.90	0.82	0.71	0.85	0.80
	(<0.01)	(<0.01)	(<0.01)	(<0.01)	(<0.01)	(<0.01)
Probit regressions						
4. $\lvert K_c/L_c - K_{c'}/L_{c'}\rvert$	33.94	25.10	34.00	22.74	32.38	17.13
Standard error	4.65	4.71	4.56	3.04	4.63	0.85
Log-likelihood	−240.27	−209.57	−254.65	−395.00	−247.75	−9152.30
5. $\sum_{f=K,L}(w_c^f - w_{c'}^f)^2 (V^f)^2$	0.79	1.32	0.70	0.61	0.79	0.41
Standard error	0.17	0.29	0.15	0.11	0.16	0.03
Log-likelihood	−257.20	−203.17	−275.84	−405.64	−263.28	−9345.49
OLS regressions						
6. $\lvert K_c/L_c - K_{c'}/L_{c'}\rvert$	13.28	12.15	15.39	6.14	13.24	12.42
Standard error	0.82	0.82	0.93	0.37	0.82	0.31
R^2	0.28	0.25	0.30	0.26	0.29	0.20
7. $\sum_{f=K,L}(w_c^f - w_{c'}^f)^2 (V^f)^2$	0.39	0.36	0.45	0.19	0.42	0.35
Standard error	0.03	0.03	0.03	0.01	0.03	0.01
R^2	0.21	0.18	0.22	0.19	0.26	0.13

Notes: The sample includes 22 capital-abundant countries and 19 labor-abundant countries. Column 1 reports the baseline results for $\theta_{c'c}^{\text{Ricardian}} > 1$ carried over from column 1 of Table 1, in which $\theta_{c'c}^{\text{Ricardian}}$ is computed using the 1997 industry-level TFP and under the assumption of freely traded intermediates and $w_{US}^{K}=16.5\%$. In columns 4–5, Ricardian technology differences λ_{gc} are measured by $\exp(-\delta_{gc})$ and the 1996 industry-level TFP, respectively. Column 6 examines the industry-level hypothesis $\theta_{gc'c}^{\text{Ricardian}} > 1$ in inequality (16) for 24 ISIC industries. In the probit regressions the dependent variable is a dummy variable that equals one if the hypothesis is satisfied and zero otherwise. In the OLS regressions the dependent variable is log $\theta_{c'c}^{\text{Ricardian}}$ in columns 1–5, and log $\theta_{gc'c}^{\text{Ricardian}}$ in column 6. See the notes to Table 1 for a description of other variables. The standard errors are robust to heteroskedasticity. In parentheses are p-values of the sign test.

column 4 of Table 2 we replace the industry-level TFP measure with $\exp(-\hat{\delta}_{gc})$, which is estimated based on direct factor requirements (see Section 3). A comparison of columns 1 and 4 reveals that our results are somewhat sensitive to how productivity is measured. However, the sign tests in rows 1–3 show that the hypothesis $\theta_{c'c}^{\text{Ricardian}} \geq 1$ cannot be rejected for all country pairs at the 1% level. The regression results in rows 4–7 show that for all specifications coefficients on endowment differences are significantly positive. Thus, our main conclusions hold.

For a further robustness check, we use lagged industry-level TFP estimates rather than contemporaneous ones (for the year 1997) used in the previous analysis. We find almost no change in our results. For example, column 5 of Table 2 displays the results when the 1996 industry-level TFP estimates are used. We also experimented with the industry-level TFP estimates that do not make any adjustments to labor and capital inputs. Our results are little changed. To save space, we do not report them in the table.

So far we have focused on the aggregate-level results. An alternative way to test the theory is to examine the industry-level restriction on factor requirements, factor prices and productivity differences. Based on inequality (5), it is straightforward to derive the industry-level counterpart of inequality (9) as

$$\theta_{gc'c}^{\text{Ricardian}} \equiv \frac{(w_{c'}/\lambda_{gc'})\lambda_{gc}d_{gc} + (w_c/\lambda_{gc})\lambda_{gc'}d_{gc'}}{w_{c'}d_{gc'} + w_c d_{gc}} \geq 1. \tag{16}$$

Differing from inequality (9), however, inequality (16) is not directly related to international specialization. The industry-level results are shown in column 6 of Table 2. Because larger industries tend to be measured more accurately than smaller industries, both the sign tests and regressions are weighted by the industry shares of output in order to give a bigger weight to larger industries. It is evident that the industry-level results are consistent with the aggregate-level estimates.

Finally, we examine model performance for a sample of 8 OECD countries examined by Choi and Krishna (2004).[12] Compared to our sample, the variation among the 8 countries in endowments, factor prices and productivity levels is relatively small. On the other hand, because we expand the sample substantially to include many developing countries, our data include capital and aggregate labor. In contrast, the analysis of Choi and Krishna (2004) deals with capital and disaggregated labor (skilled and unskilled). We interpret the labor cost in our empirical analysis as an average cost of skilled and unskilled labor. Choi and Krishna (2004) tested the hypothesis $\theta_{c'c}^{\text{Identical}} \geq 1$. Although our data sources and measurements differ from theirs, our estimates of $\theta_{c'c}^{\text{Identical}}$ are fairly similar to those reported in Choi and Krishna (2004). In particular, for the majority of country pairs that exclude Korea, the estimated $\theta_{c'c}^{\text{Identical}}$ are slightly above 1. In contrast, for country pairs involving Korea, the estimated $\theta_{c'c}^{\text{Identical}}$ are well above 1. The hypothesis $\theta_{c'c}^{\text{Identical}} \geq 1$ holds for 86% of 28 country pairs, which is comparable to the 79%–86% in Choi and Krishna (2004, Tables 4–5).[13] When we allow for Ricardian technology differences, we find that $\theta_{c'c}^{\text{Ricardian}} \geq 1$ holds for 82% of the time ($p<0.01$).

To summarize, we find that the hypothesis $\theta_{c'c}^{\text{Ricardian}} \geq 1$ cannot be rejected for all country pairs. This result is robust to alternative assumptions of the model and alternative measures of productivity differences. We also find that the model gains the strongest support from country pairs that differ substantially in endowments. Thus, our results confirm the expectation of Choi and Krishna (2004) that the theory would hold with even greater "success" outside of the OECD countries where factor price differences are even larger.

5. Relative factor abundance and the factor content of bilateral trade

Now we turn to the hypothesis $\gamma_{c'c} \geq 0$ in inequality (12). It relates the factor content of bilateral trade to bilateral differences in relative factor abundance. The hypothesis implies that if country c' has a higher wage–rental ratio than country c, country c''s exports to c embody a higher capital–labor ratio than country c's exports to c'. Thus, $\theta_{c'c}^{\text{Ricardian}} \geq 1$, $\gamma_{c'c} \geq 0$ is not affected by Ricardian technology differences which assume that productivity differs across industries but not between factors within each industry.

Column 1 of Table 3 lists the results for $\gamma_{c'c} \geq 0$. The sign statistics are summarized in rows 1–3. Notably, for pairs of only capital-abundant countries, $\gamma_{c'c} \geq 0$ is confirmed for just 54% of the time, a success rate that is not much better than a coin toss (Trefler, 1995). The p-value is 0.15. So $\gamma_{c'c} \geq 0$ can be rejected for pairs involving only capital-abundant countries at the 5% level. Because the hypothesis

[12] The 8 countries are Canada, Denmark, France, Germany, Korea, the Netherlands, the United Kingdom and the United States.

[13] We compare our results with Tables 4 and 5 in Choi and Krishna (2004) because our calculations use their Capital II measure of U.S. rental rate.

$\gamma_{c'c} \geq 0$ relates the factor content of bilateral trade to endowment ratio differences, the result indicates that trade between capital-abundant countries cannot be fully explained by endowment differences. On the other hand, as mentioned above, allowing for Ricardian technology differences improves model performance for the pairs of only capital-abundant countries (see row 2 of Table 1). Thus we conclude that Ricardian technology differences might be a more important factor than endowment differences in determining the trade patterns between capital-abundant countries.

For pairs involving capital-abundant and labor-abundant countries, $\gamma_{c'c} \geq 0$ is satisfied for 89% of the time (see row 1). The p-value of the sign test is below 0.01. Thus, the hypothesis $\gamma_{c'c} \geq 0$ performs remarkably well for country pairs with sufficient disparate endowments. This is consistent with the result for $\theta_{c'c}^{\text{Ricardian}} \geq 1$.

The industry-level counterpart of $\gamma_{c'c} \geq 0$ can be expressed as

$$\gamma_{gc'c} \equiv \left(\frac{w_{c'}^{L}}{w_{c'}^{K}} - \frac{w_{c}^{L}}{w_{c}^{K}}\right)\left(\frac{d_{gc'}^{K}}{d_{gc'}^{L}} - \frac{d_{gc}^{K}}{d_{gc}^{L}}\right) \geq 0. \tag{17}$$

Recall that $d_{gc}^{f}(f=K, L)$ gives the amount of factor f needed directly to produce one unit of good g in country c. Inequality (17) implies that capital-abundant countries use more capital-intensive techniques than labor-abundant countries in each industry g. The results for $\gamma_{c'c} \geq 0$ are given in column 2 of Table 3. The sign tests are weighted by the industry shares of output in order to give a bigger weight to larger industries. It is clear that the industry-level results are fairly similar to those at the aggregate level. In particular, the hypothesis $\gamma_{gc'c} \geq 0$ is satisfied for just half of the pairs involving only capital-abundant countries (see row 2). In contrast, $\gamma_{gc'c} \geq 0$ is confirmed at a much higher rate for pairs of capital-abundant and labor-abundant countries.

Table 3
Relative factor abundance and the factor content of bilateral trade

	$\gamma_{c'c} \geq 0$		$\gamma_{gc'c} \geq 0$	
	(1)	Obs	(2)	Obs
Sign test				
1. Pairs of capital-abundant and labor abundant countries	0.89	418	0.77	10,032
	(<0.01)		(<0.01)	
2. Pairs of capital-abundant countries	0.54	231	0.50	5544
	(0.15)		(0.35)	
3. Pairs of labor-abundant countries	0.63	171	0.56	4104
	(<0.01)		(0.01)	
Probit regressions				
4. $\lvert K_c/L_c - K_{c'}/L_{c'} \rvert$	35.59	820	20.86	19,680
Standard error	3.22		0.75	
Log-likelihood	−410.21		−12,007.62	
5. $\sum_{f=K,L}(w_c^f - w_{c'}^f)^2 (V^f)^2$	0.73	820	0.05	19,680
Standard error	0.12		0.03	
Log-likelihood	−448.38		−12,370.22	

Notes: This table examines the hypotheses in inequalities (12) and (17) that relate the factor content of bilateral trade to bilateral differences in relative factor abundance. The sample includes 22 capital-abundant and 19 labor-abundant countries. Column 1 reports the aggregate-level results for the 41 countries. Column 2 gives the industry-level results which involve 24 ISIC industries. The dependent variable in the probit regressions is a dummy variable that equals one if the hypothesis is satisfied and zero otherwise. See the notes to Table 1 for a description of other variables. The standard errors are robust to heteroskedasticity. In parentheses p-values of the sign test.

In order to illustrate how model performance varies with bilateral endowment differences, rows 4–5 of Table 3 present the results from probit regressions on endowment differences.[14] The dependent variable is a dummy variable that equals one if the hypothesis is satisfied and zero otherwise. Endowment differences are measured by $|K_c/L_c - K_{c'}/L_{c'}|$ in row 4 and by $\sum_{f=K,L}(w_c^f - w_{c'}^f)^2(V^f)^2$ in row 5. For all specifications the coefficients on endowment differences are positive and statistically significant, indicating that the hypotheses are more likely to be satisfied for country pairs with bigger endowment differences. Thus, our results are consistent with the finding by Debaere (2003) that the HOV model performs well for countries with very different capital–labor ratios.

6. Conclusions

In this paper we incorporated Ricardian technology differences into Staiger (1986) and derived testable restrictions that relate the factor content of bilateral trade to bilateral differences in technology and endowments. This departs from the traditional HOV theorem that compares the factor content of net trade with factor abundance. Following Helpman (1984) and Staiger (1986), we considered a trade equilibrium in which factor prices are allowed to differ across countries. In the absence of factor price equalization one can predict the factor content of trade from post-trade data without restricting preferences, and this can be done for bilateral trade patterns. So less restrictive assumptions are required than the traditional HOV model.

We studied the following empirical hypotheses. First, the exporter's actual unit cost of production cannot be greater than the importer's hypothetical unit cost of production. This hypothesis was first examined by Choi and Krishna (2004) under the assumption of identical technology across countries. Our second hypothesis relates the factor content of trade to relative factor abundance. It says that exports by capital-abundant countries embody a higher capital–labor ratio than the exports by labor-abundant countries. The two hypotheses are complementary. The first one looks at the relationship between factor abundance and the factor content of bilateral trade in absolute terms, while the second one is in relative terms.

In contrast to previous studies that have been confined to developed countries, our empirical analysis exploited a unique dataset that covers 41 countries with sufficiently disparate endowments and technology. We find that the empirical hypotheses are confirmed by the majority of country pairs in our sample. This result is robust to various alternative specifications. Thus, our empirical study confirms the finding in Choi and Krishna (2004). In addition, the Heckscher–Ohlin model performs even better for country pairs with substantially different endowments. This is consistent with Debaere (2003) who finds that the HOV model performs remarkably well for countries with very different capital–labor ratios. Finally, we find some evidence suggesting that for trade between capital-abundant countries, Ricardo matters more than Heckscher–Ohlin.

Appendix A. Data sources and measurement

All data pertain to 1997 unless otherwise stated.

A.1. Factor Endowment and Factor Price Data

Capital. — Capital stock is constructed as follows. We use the latest capital stock data from the Penn World Table 5.6 (PWT 5.6) and update the data to 1997 by applying Leamer's (1984) double

[14] Although the sign of $\gamma_{c'c}$ and $\gamma_{gc'c}$ is economically meaningful, the magnitude of them is not. Thus we do not regress their values on endowment differences as done for the θ's.

declining balance method to investment. The real gross domestic investment series come from the Penn World Table 6.1 (PWT 6.1). Let K_{c,t_0} be capital stock in country c in year t_0 (the latest year available) from PWT 5.6 (in 1985 international prices).[15] Let k_{ct} be the investment series for year t from PWT 6.1 (in 1996 international prices).[16] Let $PI_{t_0}^{\text{PWT5.6}}$ and $PI_{t_0}^{\text{PWT6.1}}$ be the price level of investment for year t_0 from PWT 5.6 and PWT 6.1, respectively. Assuming a typical asset life of 15 years, the depreciation rate is $\sigma=13.3\%$. Then country c's capital stock K_c at the beginning of 1997 (in 1996 international prices) is defined as

$$K_c \equiv (1-\sigma)^{1996-t_0} K_{c,t_0} PI_{t_0}^{\text{PWT6.1}} / PI_{t_0}^{\text{PWT5.6}} + \sum_{t=t_0+1}^{1996} (1-\sigma)^{1996-t} k_{ct}.$$

Data on w_c^K are the PWT 6.1 investment index which is expressed relative to U.S. rental rate w_{US}^K. Under the assumption that interest rates and depreciation rates are equalized across countries, w_c^K / w_{US}^K is equal to the ratio of user costs of capital in country c relative to the United States.

Labor. — Data on industry labor employment L_{gc} are from the OECD STAN database for OECD countries, the UNIDO data base for manufacturing in non-OECD countries and from the ILO for non-manufacturing in non-OECD countries. The endowment of labor, $L_c \equiv \sum_g L_{gc}$, is scaled so that it sums to the PWT 6.1 workforce totals in 1997. Data on w_c^L are calculated as total payroll divided by the total labor employment.

A.2. Technology and International Trade Data

Data on input–output tables are from GTAP (version 5). Direct usage of capital by industry is generated by assuming that industry capital stocks are proportional to industry payments to capital. This will be the case in steady state under the assumption of constant depreciation rates. Data on capital payments are from the GTAP input–output accounts. Direct usage of labor by industry is calculated as industry labor employment divided by industry output. Industry output is from GTAP. In order to match the classification of industries in data on factor usage with those in input–output tables, we aggregated industries up to 24 ISIC (rev. 2) industries.

Data on international trade flows are from GTAP (version 5).

A.3. TFP Measures

Calculations of the TFP indices in Eq. (15) require real, internationally comparable data on value added, labor and capital inputs.

OECD Countries. — Data come from the OECD STAN database. Value added are deflated using the value added deflators available from the STAN database. To obtain the labor input measure, the number of employees is adjusted by the average annual hours worked per person in employment from the STAN. Capital stock series are constructed using a 15-year double declining balance method applied to deflated gross fixed capital formation. The country- and industry-specific investment deflators are derived from the STAN database. The capital stock measure is also adjusted for cyclical

[15] $K_{c,t_0} \equiv KAPW_{c,t_0} \times RGDPCH_{c,t_0} \times POP_{c,t_0} / RGDPW_{c,t_0}$ where $KAPW_c$ is country c's capital per worker, $RGDPW_c$ is c's real GDP per worker using the chain index, $RGDPCH_c$ is c's real GDP per capita using the chain index, and POP_c is c's population.

[16] $K_{ct} \equiv RGDPL_{ct} \times KI_{ct} \times POP_{ct}$ where $RGDPL_c$ is country c's real GDP per capita using the Laspeyre index, KI_c is c's share of real gross domestic investment in $RGDPL_c$ and POP_c is c's population.

differences in capacity utilization. Since the STAN data only go back to 1970, with a typical asset life of 15 years, 1985 is the earliest year for which the capital stock measure is available. Thus, capacity utilization is estimated based on industry gross output over the period 1985–2000 for which all the key variables are available. Industry gross output come from the STAN database.

Non-OECD Countries. — Data are taken from the UNIDO database. Value added are deflated using the GDP price index from the PWT 6.1. The average annual hours worked per person are derived by multiplying the ILO average weekly hours worked per person by 52 weeks. Capital stock series are constructed using a 15-year double declining balance method applied to deflated gross fixed capital formation. The investment deflators are taken from the PWT 6.1. Since the UNIDO data only cover the manufacturing industries, we impute the non-manufacturing TFP as the average manufacturing TFP.

A.4. Countries

The 41 countries are divided into two groups according to the capital–labor ratio and wage–rental ratio. The capital-abundant group has 22 countries including Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Hong Kong, Ireland, Italy, Japan, the Netherlands, New Zealand, Singapore, Korea, Spain, Sweden, Switzerland, Taiwan, the United Kingdom, and the United States. The labor-abundant group has 19 countries including Argentina, Brazil, Chile, China, Colombia, Greece, Hungary, Indonesia, Malaysia, Mexico, Peru, the Philippines, Poland, Portugal, Sri Lanka, Thailand, Turkey, Uruguay, and Venezuela.

A.5. Industries

The 24 ISIC industries are: 110–130 (Agriculture, Hunting, Forestry and fishing); 200 (Mining and quarrying); 311 + 312 (Food); 313 + 314 (Beverages, Tobacco); 321 (Textiles); 322 (Apparel); 323 + 324 (Leather products, Footwear); 331 + 332 (Wood products, Furniture); 341 + 342 (Paper products, Printing and publishing); 353 + 354 (Petroleum refineries, Misc. petro and coal products); 351 + 352 + 355 + 356 (Industrial chemicals, Other chemicals, Rubber products, Plastic products); 361 + 362 + 369 (Pottery, Glass, Other non-metallic mineral products); 371 (Iron and steel); 372 (Non-ferrous metals); 381 (Fabricated metal products); 384 (Transport equipment); 382 + 383 + 385 (Non-electrical machinery, Electric machinery, Instruments); 390 (Misc. manufacturing); 400 (Electricity, gas, and water); 500 (Construction); 600 (Wholesale and retail trade and restaurants and hotels); 700 (Transport, storage and communication); 800 (Financing, insurance, real estate and business services); and 900 (Community, social and personal services).

Table A1
Summary Statistics on the Industry-level TFP_{gc}

Industry description	Average	Std dev.	Corr (TFP_{gc}, GDP_c)	Corr(TFP_{gc}, exp $(-\delta_{gc})$)
	(1)	(2)	(3)	(4)
Agriculture, Hunting, Forestry and fishing	0.83	0.27	0.21	0.21
Mining and quarrying	1.01	0.41	0.33**	0.31**
Food	0.78	0.29	0.42*	0.32**
Beverages, Tobacco	0.64	0.28	0.11	0.18
Textiles	0.77	0.30	0.73*	0.66*
Apparel	0.73	0.31	0.76*	0.63*

(*continued on next page*)

Table A1 (*continued*)

Industry description	Average	Std dev.	Corr (TFP_{gc}, GDP_c)	Corr(TFP_{gc}, exp ($-\delta_{gc}$))
	(1)	(2)	(3)	(4)
Leather products, Footwear	0.68	0.31	0.70*	0.44*
Wood products, Furniture	0.77	0.26	0.74*	0.65*
Paper products, Printing and publishing	0.82	0.24	0.57*	0.44*
Industrial chemicals, Other chemicals, Rubber products, Plastic products	0.73	0.22	0.53*	0.43*
Petroleum refineries, Misc. petro and coal products	0.93	0.35	0.32**	0.21
Pottery, Glass, Other non-metallic mineral products	0.74	0.28	0.53*	0.74*
Iron and steel	0.72	0.29	0.41*	0.41*
Non-ferrous metals	0.82	0.38	0.18	0.21
Fabricated metal products	0.74	0.24	0.64*	0.62*
Non-electrical machinery, Electric machinery, Instruments	0.93	0.35	0.65*	0.64*
Transport equipment	0.75	0.23	0.52*	0.56*
Misc. manufacturing	0.72	0.24	0.75*	0.42*
Electricity, gas, and water	0.74	0.22	0.48*	0.43*
Construction	0.72	0.24	0.62*	0.67*
Wholesale and retail trade and restaurants and hotels	0.82	0.21	0.54*	0.55*
Transport, storage and communication	0.74	0.20	0.55*	0.55*
Financing, insurance, real estate and business services	0.61	0.19	0.44*	0.35**
Community, social and personal services	0.87	0.27	0.62*	0.56*

Notes : The TFP_{gc} are relative to the U.S. industry-level TFP. Column 1 reports the geometric average of TFP_{gc} across countries with country shares of value added as the weight. Column 2 gives the standard deviations of TFP_{gc} across countries. Columns 3–4 report the correlation of TFP_{gc} with GDP per capita and exp($-\delta_{gc}$), respectively. * and ** indicate the 1% and 5% significance level, respectively.

References

Anderberg, M.R., 1973. Cluster Analysis for Applications. Academic Press, New York.

Brecher, R.A., Choudhri, E.U., 1982. The factor content of international trade without factor–price equalization. Journal of International Economics 12, 277–283.

Brecher, R.A., Choudhri, E.U., 1988. The factor content of consumption in Canada and the United States: a two-country test of the Heckscher–Ohlin–Vanek model. In: Feenstra, R.C. (Ed.), Empirical Methods for International Trade. MIT Press, Cambridge, MA, pp. 5–17.

Caves, D.W., Christensen, L.R., Diewert, W.E., 1982. Multilateral comparisons of output, input, and productivity using superlative index numbers. Economic Journal 92, 73–86.

Choi, Y., Krishna, P., 2004. The factor content of bilateral trade: an empirical test. Journal of Political Economy 112, 887–914.

Davis, D.R., Weinstein, D.E., 2001. An account of global factor trade. American Economic Review 91, 1423–1453.

Davis, D.R., Weinstein, D.E., Bradford, S.C., Shimpo, K., 1997. Using international and Japanese regional data to determine when the factor abundance theory of trade works. American Economic Review 87, 421–446.

Deardorff, A.V., 1979. Weak links in the chain of comparative advantage. Journal of International Economics 9, 197–209.

Debaere, P., 2003. Relative factor abundance and trade. Journal of Political Economy 111, 589–610.

Debaere, P., Demiroglu, U., 2003. On the similarity of country endowments. Journal of International Economics 59, 101–136.

Evenett, S.J., Keller, W., 2002. On theories explaining the success of the gravity equation. Journal of Political Economy 110, 281–316.

Griffith, R., Redding, S., Van Reenen, J., 2004. Mapping the two faces of R&D: productivity growth in a panel of OECD industries. Review of Economics and Statistics 86, 883–895.

Harrigan, J., 1997. Technology, factor supplies, and international specialization: estimating the neoclassical model. American Economic Review 87, 475–494.

Helpman, E., 1984. The factor content of foreign trade. Economic Journal 94, 84–94.

Keller, W., 2002. Geographic localization of international technology diffusion. American Economic Review 92, 120–142.

Leamer, E.E., 1984. Sources of International Comparative Advantage: Theory and Evidence. MIT Press, Cambridge, MA.
Maskus, K.E., 1985. A test of the Heckscher–Ohlin–Vanek theorem: the Leontief Commonplace. Journal of International Economics 19, 201–212.
Schott, P.K., 2003. One size fits all? Heckscher–Ohlin specification in global production. American Economic Review 93, 686–708.
Staiger, R.W., 1986. Measurement of the factor content of foreign trade with traded intermediate goods. Journal of International Economics 21, 361–368.
Staiger, R.W., 1988. A specification test of the Heckscher–Ohlin theory. Journal of International Economics 25, 129–141.
Trefler, D., 1993. International factor price differences: Leontief was right! Journal of Political Economy 101, 961–987.
Trefler, D., 1995. The case of the missing trade and other mysteries. American Economic Review 85, 1029–1046.