Skill-Biased Technical Change: Theoretical Concepts, Empirical Problems and a Survey of the Evidence*

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Abstract

The structure of wages and employment has shifted against the low-skilled in many OECD countries over the last decade. Many authors have attributed this shift to the impact of new technologies, and or technical change in general. This paper investigates and structures the growing body of literature on skill-biased technical change (SBTC) by first presenting a model in which SBTC is formalised and decomposed into factor and sector biases of technical change. We show that as we go down to the job level the scope for pure within unit-skill bias decreases and between-unit effects explain the within-unit effects detected at higher aggregation levels. Second, we address some potential sources of skill bias, which are learning, R&D, human capital formation, organisational change and the introduction of new general purpose technologies. Finally we present some conceptual and practical problems we encounter when studying SBTC empirically. We conclude with a survey of selected empirical literature on the subject and discuss the results in light of the empirical and theoretical problems pointed out above.

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1. Introduction

In analysing the labour market trends in most OECD countries over the last decades of the twentieth century one finding stands out prominently. The perspectives for low-skilled workers have deteriorated dramatically in most countries. Katz and Murphy (1992) for example find for the US that between 1979 and 1987 the average weekly wages of college graduates with one to five years of experience have increased by some 30 percent relative to the average weekly earnings of comparable high-school graduates. At the same time employment ratios of high-school graduates fell significantly. Evidence from other countries, brought together by Machin and van Reenen (1998), suggest that relative wage decreases were more moderate in other OECD countries but relative unemployment rates rose. Table 1 gives an overview of the evidence on wage divergence in the OECD over the last three decades.

[INSERT TABLE 1 OVER HERE]

Throughout the 1980s relative wages for low-skilled workers declined strongly in the UK and US and Australia, Austria, Belgium, Canada, Japan, Portugal and Spain also experienced decreases in relative wages. The pattern for the Netherlands, Denmark, France, Germany, Italy and Sweden are less pronounced but the exclusion of the unemployed in most countries even strengthens the general conclusion that labour market perspectives have worsened dramatically. For the 1990s the little evidence that is available seems to suggest a levelling off of this trend. Meanwhile the relative supply of low-skilled workers has dropped significantly in most OECD countries, implying that demand shifts may somehow be detrimental.

In search of possible explanations for this general demand shift, economists have come up with four related hypotheses. All are based on the hypothesis that the structure of the economy has changed in favour of the high-skilled.

The first hypothesis simply states that somehow final goods demand has shifted towards skill-intensive sectors causing aggregate demand for labour to shift towards high-skilled workers (e.g. Schimmelpfennig, 1998). The second, and closely related, hypothesis attributes this structural change to changing international patterns of specialisation due to trade liberalisation (e.g. Leamer, 1996 and 1997, Agenor and Aizenman, 1998 and Wood, 1998). This hypothesis claims that OECD countries, in accordance with the Heckscher-Ohlin model, have a comparative advantage in the production of skill-intensive goods and hence opening up trade with less-developed countries puts pressure on the wage rate of low-skilled workers due to factor price equalisation and shifts aggregate labour demand in favour of high-skilled workers. Analytically these hypotheses affirm the shift to changing output-market conditions given stable input-output relationships.

An alternative to these final-goods demand oriented hypotheses is the suggestion that the structure of the economy has changed due to changes in the production structure itself. Again two different but closely related hypotheses exist. First, a demand shift may be due to biased technical change at the production-unit level, the so-called factor bias (e.g. Krugman, 1995 and Acemoglu, 1998). This hypothesis states that production simply changed throughout the economy towards more skill-intensive methods. Second, the bias can be the result of diverging rates of unbiased technical change between production units (e.g. Haskel and Slaughter, 1998). In this case skill-intensive industries are assumed to have higher rates of technical change causing them to expand relative to other industries; hence, causing the bias in aggregate demand. In short, these two hypotheses attribute the shift to changes in input-output relationships under stable output market conditions.

Obviously these hypotheses are complements and the debate should focus on the relative importance of these explanations in formulating strategies to ameliorate the harsh conditions low-skilled workers face. The polarisation in the literature does not prohibit this because (empirical) support for one hypothesis does not make the alternative hypotheses necessarily less relevant but can be interpreted as an indication of its relative relevance in explaining the entire shift in aggregate labour demand.

In this paper we set out to survey and evaluate the empirical evidence offered in the literature on this issue. For this purpose we first present in Section 2 the concept of bias in a more formal way. This section presents some basic concepts and supports our analysis of the four alternative hypotheses in the literature. To identify important conceptual shortcomings in the empirical literature to date, we proceed in Section 3 with a preliminary analysis of the potential sources of bias in technical change. This allows us to critically evaluate the proxies used in empirical work to test for the technical change hypotheses. We deal with the general structure of most empirical models on this issue and the specific econometric problems in empirically testing for skill biases in Section 4. In Section 5 we present a survey of the empirical literature. We draw some conclusions and end the paper with some directions for further research in Section 6.

2. Skill Biases in Aggregate Labour Demand

The concept of bias between production factors was originally developed by Hicks (1932) who asserted that relative factor prices between capital and labour would give firms an incentive to innovate towards saving the relatively expensive production factor; in his time labour. He proposed this as a possible explanation for the fact that capital-labour ratios seemed to be rising permanently, which was more than a simple substitution mechanism could explain. For the purpose of his analysis, he devised the concept of biased technical change in a one sector economy. In a multi-sector economy, skill biases at the aggregate level arise from biases at the sectoral level but also from shifts in demand or differences in unbiased technical change between sectors.

Since such biases are prominently discussed in the current debate on wage and employment differentials, this section formally comes to grips with this phenomenon and argues that the interpretation of the results obtained in the literature so far requires some caution. First we present Hick's concept of neutrality in a single sector case and apply it to skills. The following paragraphs introduce the sectoral, firm and individual levels of aggregation as well as the international dimension of skill bias.

The one sector economy

To illustrate the concepts we use a model with two factors of production: high (L_H) and low-skilled (L_L) labour. Suppose, production takes place according to the following constant elasticity of substitution (CES) production function:[1]

$$Y = \left[(\theta_L L_L)^{\rho} + (\theta_H L_H)^{\rho}\right]^{1/\rho}, \qquad \textbf{(1)}$$

[1] Using Cobb-Douglas or Leontief production technologies would not yield identifiable biases because the elasticity of substitution is in these cases either unity or zero.

where $0 < \rho < 1$ and $1/(\rho-1)$ is the elasticity of substitution between $\theta_L L_L$ and $\theta_H L_H$. In (1) Y equals output and θ_H and θ_L are the parameters that capture factor saving technical progress. Profit maximisation, taking wages and prices as given, yields the result that relative wages ω in equilibrium are given by

$$\omega = \frac{w_H}{w_L} = \left[\frac{\theta_H}{\theta_L}\right]^{\rho}\left[\frac{L_H}{L_L}\right]^{\rho-1}. \qquad \textbf{(2)}$$

In this simple case, Hicks-neutral technical change can be defined as an increase in productivity which leaves relative factor prices (wages) stable for a given factor employment ratio; or equivalently leaves the factor employment ratio stable for a given wage ratio. From (2) it follows that technical change is Hicks neutral as long as θ_H and θ_L change proportionately. Technical change is biased against low-skilled labour if growth in θ_H exceeds growth in θ_L. In Figure 1 the factor biased technical change is illustrated graphically. Technical progress shifts the isoquant towards the origin, from I_0 to I_1. The bias is evident since at the original wage rate factor intensities would have changed because the points of tangency are not on the original ray. Alternatively it can be shown that relative wages move in favour of the high-skilled when the factor ratio is held constant. Hence skill biases show up empirically either as relative wage changes when controlling for supply shifts or as employment-ratio changes when controlling for relative wage shifts.

[INSERT FIGURE 1 OVER HERE]

The multi-sector economy

In a one sector economy technologically induced changes in relative wages, given relative employment, always indicate factor biases in technical change, as shown above. This is no longer valid once we allow for more than one sector. If we assume the economy to consist of two or more sectors, biases in demand at the aggregate level can result not only from non-proportionate changes in the θparameters but also from sector biases, which cause changes in ω given aggregate L_H/L_L, the definition we offered for aggregate biases in technical change. Assume production takes place in k sectors, each producing according to a CES function as in (1):

$$Y_j = A_j\left[(\theta_{Lj}L_{Lj})^{\rho} + (\theta_{Hj}L_{Hj})^{\rho}\right]^{1/\rho}, \quad j=0,1,...,k \tag{3}$$

where the subscript j is a sector index and the A_j captures factor neutral sector specific technical change. Again taking prices and wages as given, each sector j optimizes by choosing employment. This yields the following 2k first order conditions:

$$\begin{aligned} P_1A_1\left[(\theta_{L1}L_{L1})^{\rho} + (\theta_{H1}L_{H1})^{\rho}\right]^{1/\rho-1}\theta_{L1}^{\rho}L_{L1}^{\rho-1} &= w_L \\ P_1A_1\left[(\theta_{L1}L_{L1})^{\rho} + (\theta_{H1}L_{H1})^{\rho}\right]^{1/\rho-1}\theta_{H1}^{\rho}L_{H1}^{\rho-1} &= w_H \\ P_2A_2\left[(\theta_{L2}L_{L2})^{\rho} + (\theta_{H2}L_{H2})^{\rho}\right]^{1/\rho-1}\theta_{L2}^{\rho}L_{L2}^{\rho-1} &= w_L \\ &. \\ P_kA_k\left[(\theta_{Lk}L_{Lk})^{\rho} + (\theta_{Hk}L_{Hk})^{\rho}\right]^{1/\rho-1}\theta_{Lk}^{\rho}L_{Lk}^{\rho-1} &= w_H \end{aligned} \tag{4}$$

If labour is perfectly mobile across sectors[2] we know wages are equal for equal workers across sectors and hence relative wages can be expressed similar to (2):

$$\omega = \frac{w_H}{w_L} = \left[\frac{\theta_{Hj}}{\theta_{Lj}}\right]^{\rho}\left[\frac{L_{Hj}}{L_{Lj}}\right]^{\rho-1}. \quad j=0,1,...,k \tag{5}$$

As in the one sector model factor biases can occur at the sector level. Factor neutral technical change in sector j is defined as a change in the technology parameters which leaves L_{Hj}/L_{Lj} unchanged, given stable relative wages. Biases in aggregate demand, however, can also be attributed to neutral technical changes

[2] Empirically we would replace this assumption by controlling for fixed sector effects.

that differ between sectors. This can be shown by setting the odd and even first order conditions equal across sectors, i.e. setting 1=3=...=2k-1 and 2=4=...=2k. Substituting output back in then yields:

$$L_{Hi} = \left[\frac{P_i}{P_j}\right]^{\frac{1}{1-\rho}} \left[\frac{Y_i}{Y_j}\right] \left[\frac{\theta_{Hi}}{\theta_{Hj}}\right]^{\frac{\rho}{1-\rho}} L_{Hj} \qquad for\ \ i \neq j\ \in k$$

$$L_{Li} = \left[\frac{P_i}{P_j}\right]^{\frac{1}{1-\rho}} \left[\frac{Y_i}{Y_j}\right] \left[\frac{\theta_{Li}}{\theta_{Lj}}\right]^{\frac{\rho}{1-\rho}} L_{Lj} \qquad for\ \ i \neq j\ \in k \tag{6}$$

Now we sum both sides over all i and set the resulting aggregate demand equal to the exogenous labour supplies L_H^* and L_L^* where we assume labour markets clear. Then dividing the first expression by the second and substituting for L_{hj}/L_{Lj}, using (5), we obtain the following expression for relative wages in the aggregate economy:[3]

$$\omega = \frac{w_H}{w_L} = \left[\frac{L_H^*}{L_L^*}\right]^{\rho-1} \left[\frac{\sum_{i=0}^{n} P_i^{\frac{1}{1-\rho}}\ Y_i\ A_i^{\frac{\rho}{1-\rho}} \theta_{Hi}^{\frac{\rho}{1-\rho}}}{\sum_{i=0}^{n} P_i^{\frac{1}{1-\rho}}\ Y_i\ A_i^{\frac{\rho}{1-\rho}} \theta_{Li}^{\frac{\rho}{1-\rho}}}\right]^{1-\rho} . \tag{7}$$

From this equation it can be observed that relative wages only remain stable – given stable relative aggregate employment – if technical change is not factor or sector biased.[4] The last term on the right-hand side does not necessarily rise *ceteris paribus* when there is factor bias in sector i. High-skilled biased technical change in

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[3] We put output back in to allow demand factors such as increased international trade and shifting consumer preferences. Output and prices are, however, endogenous and determined simultaneously. It makes the equation more elegant.

[4] Or both factors would change in an exactly offsetting way that would require a miraculous coincidence which we need not consider any further here.

low-skilled intensive industries and low-skilled biased technical change in high-skill intensive industries have ambiguous effects. A higher rate of neutral technical change and exogenous increases in prices or output will increase the relative demand for the factor used intensively in those sectors. Assuming factor-neutral technical change, we can define the sector bias of technical change in the following way: a bias in aggregate labour demand due to sector bias against low-skilled workers arises if their relative wages drop in face of stable relative factor supplies and factor-neutral technical change in all sectors, i.e. if the last term on the right-hand side increases but all θ_{Hi}/θ_{Li} ratios remain stable, implying that at given wages sectors would not change their factor ratios. We label such a sector bias structural change if the rise is caused by changes in the relative size of sectors in the economy in terms of value added as a result of output demand shifts or trade-induced price changes - i.e. due to changes in the P_i or Y_i terms. Technical change is sector-biased against low-skilled labour if the final term increases in absence of these structural shifts, which is the case when for example a skill-intensive sector experiences a *ceteris paribus* large factor-neutral productivity increase, an increase in A_i. Figure 2 shows such a sector bias graphically for a two sector model. Figure 2 shows the movement of the isoquants towards the origin. In both sectors technical progress is factor neutral since at the original wage rate we move along the original ray from the origin. However, in Figure 2 aggregate relative wages still go up because the shift is larger in the initially skill-intensive sector.

[INSERT FIGURE 2 OVER HERE]

This figure shows that factor neutrality is not a guarantee for absence of biases in aggregate labour demand. Alternatively the sector bias can also offset the impact of biased technical change. If for example the skill-extensive sector experiences skill-biased technical progress the impact on relative wages is indeterminate due to offsetting effects.

A multi-stage multi-sector model

We now show that factor biases at the sectoral level can be split up in between sub-sector and within sub-sector unit biases in a similar vein as in the above analysis. If we assume every sector in the multi-sector model to consist of *m* sub-sector units or firms we can derive a similar result as displayed in (7) for sector *i*'s specific relative wage as follows:

$$\omega_i = \frac{w_H}{w_L}^i = \left[\frac{L_{Hi}}{L_{Li}}\right]^{\rho-1}\left[\frac{\sum_{p=0}^{m} P_p^{\frac{1}{1-\rho}} Y_p A_p^{\frac{\rho}{1-\rho}}\theta^{i\,\frac{\rho}{1-\rho}}_{Hp}}{\sum_{p=0}^{m} P_p^{\frac{1}{1-\rho}} Y_p A_p^{\frac{\rho}{1-\rho}}\theta^{i\,\frac{\rho}{1-\rho}}_{Lp}}\right]^{1-\rho} . \qquad \textbf{(8)}$$

Here factor biases within sector *i* can be separated into *within* firm factor biases (due to changes in $\theta^i_{Hp}/\theta^i_{Lp}$) and *between* firm biases (due to all other changes) in labour demand. (8) shows that – given stable relative wages – sector *i* will alter its factor ratio in response to both within and between firm shifts in productivity, which is in line with our definition of factor bias within a sector. Identifying the sources of bias in the aggregate would require two rounds of aggregation, one over all firms *p* within all sectors *i* and another over all *i* sectors.

Haskel and Slaughter (1998) show that a higher elasticity of substitution in demand, a lower elasticity of substitution between factors and a higher mobility of labour between units (allowing the unit's share in total employment to adjust) will increase the importance of between-unit biases for the aggregate biases. Having shown this in a multi-stage multi-sector model, we also derive that the level of aggregation is crucial for the results. Dunne, Foster, Haltiwanger and Troske (2000) exploit establishment-level data and find evidence for the sector biases between establishments. Particularly, they find that the between plant component of SBTC is a growing part of total wage dispersion.

The multi-stage multi-sector approach outlined above can be represented by a tree shown in Figure 3, where every knot represents a further subdivision from a one sector model all the way down to the job level. At the lower levels the elasticity of substitution in output demand is obviously very high due to the similarity of products.

[INSERT FIGURE 3 OVER HERE]

In addition, the substitution between factors is low at the job level since increasing the factor ratio would imply replacing or retraining the current worker and also low at the aggregate level due to sector and firm specific knowledge. We offer as evidence for the latter by arguing that migration across jobs is higher within firms than between firms and within sectors than between sectors (Doms, Dunne and Troske, 1997 and Bresnahan, 1999). Hence, in our search for sector versus factor biases at a less-aggregated level, the importance of within unit-factor biased technical change should decline relative to between-unit differences of technical change in explaining the aggregate bias in technical change. As we go down to the job level the scope for pure within unit-skill bias decreases and between-unit effects explain the within-unit effects detected at higher aggregation levels. If however between effects remain of little importance even at low aggregation levels we should conclude that technical change itself is biased.

The open multi-sector economy

Going one step up from the multi-stage multi-sector economy above, we arrive at an international level. If we assume two or more countries opening up trade in goods for all sectors – and each country is assumed to employ identical production technologies, has the same tastes but is different in factor endowments – relative wages are given by (5), but relative prices are now linked to the world market. Given these settings, relative wages respond in a similar fashion to shocks in productivity. Due to factor price equalization relative wages tend to be equal in the trading countries and differences in endowments are compensated for in terms of relative output.

This extension of the model complicates the interrelation between wages and technology but a multi-country extension does not change our analysis above. The only new element to our multi-stage multi-sector model is labour immobility, which is compensated for by relative output levels. The country level is also a useful additional level of aggregation if we allow for divergent technology developments between countries. In such a model relative wages in all trading countries would also respond to country biased or localised technical change (e.g. Davis and Reeve, 1997 and Davis, 1998).

Figure 4 illustrates how these biases may occur in aggregate labour demand. Changing relative prices or quantity adjustments can be reflected by shifting iso-profit curves (that obviously also respond to productivity changes but for now we assume these to be absent). Shifts in the iso-profit curves of two sectors can cause shifts in relative wages at given factor ratios and/or shifts in factor ratios at the original relative wage. This would show up as bias at the aggregate level but is not necessarily a bias that stems from a change in the productivity parameters.

[INSERT FIGURE 4 OVER HERE]

Summary

To summarize what we have derived above we present in Table 2 again the joint impact which sector and factor biases of technical change have at each level of aggregation on relative wages over all units and relative employment within the units considered. Columns represent factor biases at the unit-level, skill-using, factor-neutral and skill-saving technical change respectively. Rows show the between-unit bias of that technical change as either concentrated in a skill-intensive, not concentrated (or exactly offsetting) and concentrated in a skill-extensive unit.

[INSERT TABLE 2 OVER HERE]

This table could be extended with a sector bias in final demand dimension. As was argued above structural change, either stemming from opening up trade, shifting final goods demand or otherwise, will affect the relative profitability of sectors and hence since different sectors have different skill intensities may cause shifts in the composition of aggregate labour demand.

The framework outlines in this section allows us to study the alternative hypotheses, factor price equalisation vs. factor biased technical change, and shows that empirical identification of the separate effects is tricky. The possibility of sectoral biases in technical change complicates the picture even more and stresses the importance of disaggregated analyses.

Finally this section suggests a basic structure for the empirical literature survey in section 5. We have shown that biases in labour demand show up either through relative wage changes holding employment ratios constant or vice versa. Both approaches have been developed in the literature and a logical first step in organising the literature is to separate studies that focus on relative wages from those that focus on relative employment ratios. Furthermore the possibility of sector biases in technical change and final goods demand create the need to carefully consider the aggregation level of the studies.

3. Potential Sources of Bias in Technical Change

The previous section has shown that biases in technical change are a potential explanation for the dramatic worsening of labour market perspectives for the relatively low-skilled in the OECD over the past decades. Even though empirical evidence seems to support this hypothesis and factor bias performs better in explaining labour market developments the question remains what causes this bias. If technical change is indeed biased against low-skilled workers, is this an exogenous fact of life or do economists have anything more to say on this issue? This brings us to the issue of sources of bias in technical change and we turn to the economics of technical change for some inspiration.

Ever since the seminal work by Solow (1956) in the late 1950s a vast number of formal models has been proposed to capture the interrelation of economic growth and technological change. Solow (1956) showed that in a neoclassical world with diminishing returns to capital there could be no long run growth in per capita income unless technical change continuously increased factor productivity. The importance of the technology factor was overwhelming and economists turned their attention to technical change.

Arrow's (1962) early attempts to escape the diminishing returns led him to develop the concept of learning by doing, which links factor augmentation to the accumulation of knowledge that occurs as an external effect to production. His model could sustain long-run growth. It did so, however, without allocating resources to the generation of new technologies. Many models attempted to overcome the neoclassical diminishing returns but only in the mid-1980s Romer presented the first truly endogenous growth model in which a trade-off was introduced between long-run stable growth and current consumption. This trade off, the decision to invest in R&D, was made subject to economic decision making and thus growth became an endogenous process. The absence of diminishing returns to knowledge again served as a way to escape the diminishing returns to capital accumulation. Lucas (1988), Grossman and Helpman (1991), Romer (1990) and Aghion and Howitt (1992) all present slightly different models that generate this endogenous growth. Jones (1995a and 1995b) provides an excellent overview and presents the Jones' critique which states that these models all generate growth rates that depend on the size of the population implying explosive growth when populations grow fast (e.g. as we now observe in India). His paper also presents a second generation of endogenous growth models that does not exhibit this flaw, however, the sources of economic growth and technical change, which are of particular interest to us, are similar. From endogenous growth theory we can identify learning, the accumulation of human capital and R&D as sources of economic growth. Having identified these sources of growth and linking them to the *rate* of technological change makes an extension to the *direction* or *bias* of technical change a logical next step.

In addition biases in technical change can also be linked to the organisation of innovative activities and production at the firm level. Various authors have argued that the introduction of new management practices favour skilled labour in particular by requiring higher communications and management skills. Ashton, Felstead and Green (1999) argue that using modern work organisation practices (such as team working and quality circles), including human resource practices (such as appraisal and consultation procedures), leads firms to recruit workers with the new skills they require.

Finally the introduction of so called general purpose technologies like the computer is a possible source of skill bias in aggregate labour demand we want to consider. In the following sections all above mentioned sources of bias in technical change will be considered in detail.

Learning

Arrow (1962) conceptualised learning as an unintended byproduct of production. As new types of capital are produced this accumulated knowledge is embodied in the capital stock and learning builds on this embodied knowledge stock. Hence the cumulated production of capital goods not the current levels of investment are the source of growth. Later on other authors extended this concept to for example investment and R&D (see e.g. Segerstrom, 1998 and Dinopoulos and Thompson, 1999 for an overview).

According to Arrow learning makes the production process more transparent and allows for a better division of labour. In this sense it is reminiscent of Adam Smith's conceptualisation of technical progress. Specialisation would allow workers to build up product specific skills and increase their value. Product cycle theory (Hirsch, 1965) suggests the possibility that learning by doing in fact is low-skilled biased. As products mature and the capital stock designed to produce the product develops, low-skilled labour tends to become more important as a factor of production.

On the other hand one could argue that by being embodied in capital goods learning captures the increased efficiency following from introducing new capital goods and therefore is most likely to exhibit a capital bias which would through capital-skill complementarity (Goldin and Katz, 1998) imply a bias towards skilled labour.

Or, alternatively, that learning possibilities change over the product cycle. In early phases high-skilled workers can learn how to design capital goods and production practices and in a later stage low-skilled workers can come in to learn how to operate and refine such machines.

Whatever the exact direction of the bias one would conjecture, there is little attention to the possibility that learning may cause biases in technical change in the empirical literature. In part this can be explained because learning is hard to capture empirically. It is clear that experience is an important element in any wage equation, however, the separation of seniority, tenure and productivity effects is a difficult issue. We know of no studies that tried to link learning to factor biases.

Human Capital Formation

In models that link economic growth to human capital accumulation, the skill level of a worker is endogenous. Typically technology is assumed constant and there are no diminishing returns to the accumulation of knowledge. This knowledge is usually assumed to be embodied in the worker and thus human capital accumulation cannot cause a factor bias at the production unit level. In these models wage divergence due to biases in technical change will ultimately cause the level of investment in human capital to go up or down and the relative supply of skills would adjust. This may be an adequate representation of the economy in the long run, however, it does not help us in our search for the sources of factor and sector biases in production technology changes. The responsiveness of relative labour supply to price signals is an empirical question frequently addressed in the literature and of importance for the policies to be designed. If skills supply is relatively price elastic or can be made more elastic, this may present a more efficient way to improve the low-skilled labour market position then trying to change biases in technical change.

R&D and Innovations

Among the several sources of technical change that have been proposed in the growth literature, R&D is by far the most popular. Most recent models introduce R&D as a source of technical change. In these models monopoly rents or the expectation of such rents is the incentive to allocate scarce resources to R&D. This idea was first formulated by Schumpeter (1942) whose contributions to growth theory are by now readily acknowledged (e.g. Aghion and Howitt, 1992). This R&D-effort is assumed to yield a (stochastic) flow of innovations.

In the new growth literature innovations take the form of quality improvements to products and processes as well as the introduction of new final products and intermediate goods. The first class of models is known as the *quality ladder models* whereas we may label the latter *expanding varieties models*.

Product cycle theory allows us to make inferences about the bias in labour demand these types of innovations are likely to imply. Since product cycle theory is aimed at the product it is only useful to look at factor biases at the unit level when considering R&D-driven technical change. The aggregate economy can be considered to consist of many such production units producing products in various stages of their cycle.

Product cycle analysis has shown that the introduction of new products typically involves setting up small-batch high-skill intensive production units initially, hence innovation in final product variety expansion models as in Krugman (1979) and Van Zon, Sanders en Muysken (1998) can be said to have a bias towards high-skilled labour (Hirsch, 1965). One could conclude that in such models innovation is exogenously skill-biased (high-skill using) by *nature*.

As far as innovation through expansion of intermediates is concerned (e.g. Romer, 1990, Segerstrom, 1998, Young, 1998 and Howitt, 1999), it is ambiguous what this implies for the factor bias in final goods production. Fast changing production practices seem to benefit high-skilled workers, whereas a more efficient division of labour usually benefits the low-skilled (Bartel and Lichtenberg, 1987). The design of new intermediate goods seems to be crucial and a factor bias in final goods production is the result of intermediates designed to save on either factor. When Hicks (1934) formulated his theory of induced innovation, he explicitly stated that factor biases in technical change are endogenously determined by relative factor prices. Innovations of this type are thus endogenously skill-biased (in either direction or neutral) by *design*.

The same also holds for quality ladder type innovations to intermediates or fixed capital goods, i.e. improvements to existing production processes. One could even argue that these innovations are more sensitive to cost and price considerations since returns are fully internalised by the innovator. Therefore, such innovations are likely to be designed with an endogenous bias.

Finally, innovations that take the form of quality ladder improvements to final goods, especially if they follow each other relatively fast, tend to require flexibility and general skills from the labour employed in producing them. The causality also runs the other way, as a high-skilled labour force is more likely to identify and implement adjustments to the product. As in the expanding final goods varieties models, these types of innovations seem to be endogenously skill-biased by nature, not by design.

The total impact R&D-efforts have on the composition of labour demand in a sector is thus dependent on the composition of R&D-output over the categories distinguished above. This output is usually assumed to be positively related to the inputs in the R&D-process. These inputs determine (or at least have a positive impact on) the probability and size of the innovations. The inputs are clearly subject to economic decision making. Several studies have empirically linked the bias in factor demand to measures of R&D-inputs or outputs such as R&D-expenditures, R&D-personnel and patents. We would expect to find stronger factor bias towards high-skilled labour in R&D-intensive sectors especially if R&D is aimed at product innovation.

Organisational Biases

Another possible source of bias is proposed in an organisation and management oriented strand of literature. It claims that the move towards flatter organisational structures with more individual responsibility and autonomy and less hierarchical control is inherently biased towards skilled labour. The IT revolution is credited/blamed for making these organisational changes feasible and desirable. IT is said to have lowered the costs of communication between parts of the organisation and thus reduced the need for elaborate control mechanisms by improving, structuring and increasing the information flows within the firm. This implies that the introduction and use of computers can be linked to the (changes in) the composition of labour demand. Arguments like these underlie the frequent use of computerisation measures as a proxy for this source of skill bias at the unit level.

As we will argue later on, however, the causality in this relationship is not undisputed.

Aghion, Caroli and García Peñalosa (1999) discuss in this regard the impact of technical change on organizational change and find that recent developments in the structure of organizations have been characterized by four trends: (i) a move towards flatter organizations, with decreasing layers of hierarchy and increasing responsibilities for ones own or team actions; (ii) increasingly team work is becoming popular; (iii) vertical communication lines are replaced by horizontal lines as a result of the difficulty in defining a labour-demand unit as a job; and (iv) higher levels of homogeneity of a firm's skill/employment structure. Kremer and Maskin (1996) and Caselli (1999) consider, with respect to (ii) and (iv), a model of assignment where workers of different skill levels form teams. The former argue that if the distribution of skills is sufficiently disperse, a further increase in the variance of skills may induce high-skilled workers to produce only with other high-skilled workers and increase wage inequality. In addition, they find evidence that economic activity has shifted from "... firms such as General Motors, which use both high- and low-skilled workers, to firms such as McDonald's and Microsoft, whose workforces are much more homogenous" (p. 18). Dunne, Foster, Haltiwanger and Troske (2000) provide empirical evidence supporting such changes in the structure of employment and organisation. We may thus conclude that technical change can also affect the organisation of the working environment and in doing so affect the competition for jobs.

General Purpose Technologies

Economists in the Schumpeterian tradition have, for some time now, emphasized the conceptually important distinction between incremental and radical technical change. This led Breshanan and Trajtenberg (1995) to coin the term 'general purpose' technologies of which the introduction is by definition 'pervasive' and radical technical change results. Older examples include electricity, steam power and railways. A modern candidate would be information technology. The notion of General Purpose Technologies (GPTs) has become increasingly popular in analyses of economic growth. Helpman (1998) presents new insights in the importance of GPTs by approaching the problem from both a theoretical and empirical point of view.

Murphy, Riddell, and Romer (1998) – in a comparative study of the United States and Canada – conclude that new GPTs are relative complements with more educated labour, which is closely related to the hypothesis that new machinery and new technologies put low-skilled workers at a disatvantage in the labour market.

Bresnahan and Gambardella (1998) examine in this regard the division of inventive labour and the extent of the market. They endogenize the arrival of GPTs and find a self-enforcing loop of inventions induced by increasing specialization of knowledge and diverse markets in which new GPTs continue to contribute to growth, and most importantly this growth continues to permit their invention. This may lead to a growing importance of knowledge-intensive sectors in which high-skilled labour has a comparative advantage. The diffusion of a new GPT is partly endogenous to the economic system and this thus links skill bias to economic decision making but a GPT is usually assumed to be skill biased in either direction by nature, not by design.

Summary

In search of sources of bias in technical change we find that various conceptualisations of technical progress lead to different hypotheses with respect to the direction and endogeneity of skill bias. Table 3 presents the results obtained from this preliminary survey.

[INSERT TABLE 3 OVER HERE]

This section suggests further refinements to the structure for our empirical survey in section five. As was argued above the bias can be attributed to technical change but different types of technical change should be considered. Linking observed biases in technical change to proxies of technical change is likely to show stronger results when the type of technological change considered is more or less exogenously biased else responses in relative wages are expected to partly offset the biases that cause them.

4. Econometric Models and Measurement Problems

Apart from the theoretical considerations presented above, the empirical testing of the SBTC hypothesis has some specific problems. To put the survey of empirical literature in the next section into perspective this section first presents some general modelling features and problems these studies have in common.

Equations (2) (5) and (7) imply we can test for skill biases in technical change by analysing relative wages, wage bill shares, employment shares or both. In the empirical literature researchers have typically estimated cost or employment share equations and controlled for various variables such as capital intensity and fixed individual, firm or industry effects and attributed the residuals of these regressions to skill bias. These residuals implied a bias against low-skilled workers in most studies we have surveyed. Attributing residuals to technical change however, is no more than measuring ignorance. The next step is to find technology proxies that can explain the variance in these residuals as described in the previous section. This would establish the link between technology as we measure it and thus allows testing of the SBTC hypothesis proper.

Most of the literature uses transcendental logarithmic (translog) production frontier equations as suggested by Christensen, Jorgenson and Lau (1973). This very flexible and general representation of production technology allows for non-constant returns to scale, non-linear expansion paths and SBTC.

The translog cost function, which can be derived from the production frontiers, expresses the natural logarithm of total cost as a function of the logarithm of factor prices, real output, technology and or time (which proxies technical change when technology data are not available). Following for example Berman, Bound and Griliches (1993), Betts (1997), Adams (1999) and Riley and Young (1999) we distinguish between high-skilled (H) and low-skilled (L) labour as factors of production and start our analysis from a general translog cost function for a single firm:

$$\ln C = \alpha_0 + \sum_{h} \sum_{i=H,L,M} \alpha_{hi} D_h \ln w_i + \sum_{i=H,L,M} \sum_{j=H,L,M} \beta_{ij} \ln w_i \ln w_j + \beta_Q \ln Q$$
$$+ \sum_{i=H,L,M} \beta_{iQ} \ln w_i \ln Q + \beta_{RD} \ln RD + \sum_{i=H,L,M} \beta_{iRD} \ln w_i \ln RD + \beta_{SP} \ln SP$$
$$+ \sum_{i=H,L,M} \beta_{iSP} \ln w_i \ln SP + \beta_K \ln K + \sum_{i=H,L,M} \beta_{iK} \ln w_i \ln K \qquad \textbf{(9)}$$
$$+ \sum_{i=H,L,M} \beta_{i\phi} \ln w_i \phi_i + \phi_C$$

where C is total cost and ln w_i is the log of the price of the ith variable input. The parameters α_0 and α_{hi} reflect own price effects which differ by industry dummy D_h (D_h equals 1 if the industry is in the hth industry group and 0 otherwise). M, Q, RD, SP and K are materials, plant output, R&D-expenditures, R&D-spillovers and physical capital, respectively. RD and SP together are regarded as a proxy for the technology applied in the production process. The terms ϕ_i and ϕ_C are random error terms. The β parameters measure the effect on total cost of the other factor prices (w), the log of plant output (Q), R&D-expenditures (RD), R&D-spillovers (SP) and the capital stock (K). To estimate SBTC for different groups of individuals often a system of factor share equations derived from the above translog cost function is estimated.

Applying Sheppard's lemma and imposing linear homogeneity in prices as in Adams (1999)[5] then yields a system of cost share equations for both high-skilled and low-skilled workers:

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[5] These restrictions are that since total cost is linear homogenous in prices, the following holds:

$$\sum_{i=H,L,M} \alpha_{hi} = \sum_{h} \sum_{i=H,L,M} \alpha_{hi} D_h = 1, \quad \sum_{i=H,L,M} \beta_{ij} = \sum_{j=H,L,M} \beta_{ij} = \sum_{i=H,L,M} \sum_{j=H,L,M} \beta_{ij} = 0,$$
$$\sum_{i=H,L,M} \beta_{iRD} = 0, \quad \sum_{i=H,L,M} \beta_{iSP} = 0, \quad \sum_{i=H,L,M} \beta_{iK} = 0, \quad \sum_{i=H,L,M} \beta_{i\phi} \ln \phi_i = 0.$$

These restrictions allow for using materials as a numeraire in equation (10). Now differentiating equation (9), given the restrictions, with respect to the relative prices of high-skillled and low-skilled labour yields equation (10).

$$s_{Ll} = \alpha_{Ll} + \sum_{i=H,L} \ln\left[\frac{w_i}{w_M}\right] + \beta_{Lq}\ln q + \beta_{LRD}\ln RD + \beta_{LSP}\ln SP + \beta_{LK}\ln K + \phi_L$$

$$. \qquad \textbf{(10)}$$

$$s_{Hl} = \alpha_{Hl} + \sum_{i=H,L} \ln\left[\frac{w_i}{w_M}\right] + \beta_{Hq}\ln q + \beta_{HRD}\ln RD + \beta_{HSP}\ln SP + \beta_{HK}\ln K + \phi_H,$$

where l is the lth industry and ϕ_H and ϕ_L are i.i.d. and normally distributed error terms . Materials are used as a numeraire and since cost shares sum to unity they are dropped from equation (10). If we now impose homotheticity on cost share functions (10), i.e. $-\beta_{HL,q} = \beta_{HL,RD} + \beta_{HL,SP} + \beta_{HL,K}$ the cost shares take the form which are used for regression analysis by for example Berman, Bound and Griliches (1994), Betts (1997), Machin and Van Reenen (1998), Adams (1999), Hollanders and Ter Weel (2000) and Nadiri and Nandi (1999):

$$s_{Ll} = \alpha_{Ll} + \sum_{i=H,L} \ln\left[\frac{w_i}{w_M}\right] + \beta_{LRD}\ln\left[\frac{RD}{q}\right] + \beta_{LSP}\ln\left[\frac{SP}{q}\right] + \beta_{LK}\ln\left[\frac{K}{q}\right] + \phi_L$$

$$. \qquad \textbf{(11)}$$

$$s_{Hl} = \alpha_{Hl} + \sum_{i=H,L} \ln\left[\frac{w_i}{w_M}\right] + \beta_{HRD}\ln\left[\frac{RD}{q}\right] + \beta_{HSP}\ln\left[\frac{SP}{q}\right] + \beta_{HK}\ln\left[\frac{K}{q}\right] + \phi_H.$$

The system of equations (11) is often tested in a seemingly unrelated regression because it assumes the right-hand side of the equations to be independent of the error terms ϕ_L and ϕ_H.

In such a specification technical change is skill-biased whenever the technology variables *RD* and *SP* have opposite signs, i.e. $\beta_{HRD} > 0$, $\beta_{HSP} > 0$ and $\beta_{LRD} < 0$, $\beta_{LSP} < 0$. In addition, the hypothesis that high-skilled labour is complementary to physical capital, whereas low-skilled labour and capital are substitutes holds if $\beta_{LK} < 0$ and $\beta_{HK} > 0$ (e.g. Griliches, 1969 and Goldin and Katz, 1998).

Specifying and testing for SBTC in this way has the benefits of being rather accurate and simple. However, as Chennells and Van Reenen (1998) note, there might also be some problems with this kind of specification. They stress three econometric problems that may arise: (i) fixed effects for which it is hard to account for (often by a dummy variable or by first differencing), (ii) endogeneity of the technology variable and (iii) measurement problems of an adequate technology variable.

The fixed effects in the system (11) which should be accounted for are captured in the α-parameters. The problem with these fixed effects is that they are in theory uncorrelated with and randomly assigned to the other terms on the right-hand side but in practice this is often not the case. This is because certain types of industries are more or less likely to experience skill biases due to the specifics of the production process.

To control for this the system (11) is often estimated in first differences. In this way we sweep out the correlation but at the same time require panel data. Panel data are, however, rarely available at the level of the firm and hence most studies are only able to apply industry-level data which implies that between and within firm effects are indistinguishable.

An example of an often used dataset in such regressions is the United Nations Industrial Statistics Database (UNISD) which includes, up to 1991 in some countries, data on wage costs and the number of production and non-production workers by industry.[6] The key data are reported in terms of "employees" and "operatives". "Operatives" are taken to be the production workers. However, this distinction is made mainly to divide the per industry workforce into white-collar (employees) and blue-collar (operatives) workers rather than to divide them in terms of high-skilled and low-skilled workers. The distinction between production and non-production workers is far from accurate as

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[6] E.g. Berman, Bound and Machin (1998) and Machin and Van Reenen (1998) have used these data.

a measure to distinguish high-skilled and low-skilled labour.[7]

More recently, the OECD started collecting data on the basis of a high-skilled and low-skilled criterion – cf. Colecchia and Papaconstantinou (1996), OECD (1998) and Hollanders and Ter Weel (2000). The availability of better data will probably ameliorate the fixed effects problem and allows for better controls on the problem.

The second problem is the potential endogeneity of the technology variable. This means that the technology-skills correlation may come from reverse causality between technology proxies and the skill composition of the labour force. The problem of endogeneity does not play a significant role when R&D-intensity is used as a measure of technology, because it only slowly responds to skill shocks. Appropriate lags will eliminate the problem for this technology proxy. Product and to a lesser extent process improvements could pose an endogeneity problem but are seldom used as proxy. However, many studies use computer usage as the technology variable. This variable is highly endogenous with the skills employed in a particular firm; moreover, it fluctuates heavily. The debate between Krueger (1993) and DiNardo and Pischke (1997) – in a critical assessment of Krueger's findings regarding the wage premium of computer users – provides evidence that not computers and ICTs as such are complementary to skills, but that the complementarity between ICTs and high-skilled workers is to be found at the level of the firm and industry rather than at the level of the individual worker. The underlying common cause being organisational changes that require both more computers and higher skills. Caroli and Van Reenen (1998) and Bresnahan (1999) as well as several case studies found that organisational change drives both computer use and skill upgrading in the workforce. Such problems of endogeneity are often solved by using instrumental variables or common factor analysis.

The third problem is inherent in al empirical work but seems to be very

[7] In addition, recent (post-1991) data are not available as the UN stopped collecting disaggregated data in 1993 and changed UNISD into UNIDO.

severe when it comes to technology. The measurement of technology has been subject to investigation for many years now and no convincing measure has been developed yet. First, R&D-intensities have the problem that they are inputs in the production process which do not guarantee positive innovative outcomes. Patents or citations are a measure of output of the R&D-process are of limited use since R&D-activities are often firm based and secrecy often provides a better guarantee for reaping the full benefits of R&D-outcomes. Third, R&D-spillovers are often an arbitrary measure – cf. Griliches (1994). It is thus very hard if not impossible to measure how a firms knowledge base is changing over time. Probably a mix of input and output measures and some proxies for spill-overs based on knowledge proximity yield the best proxy for technology in a firm but the systematic analysis of input-output relations in R&D and spillovers of knowledge is still in an embryonic stage.

For example Hollanders and Ter Weel (2000) apply Verspagen's (1997) method which uses all three measures in a weighting scheme. The results from this analysis are that spillovers are important to wage inequality in many OECD countries.

The use of crude R&D-intensities will also mix up the impact of product and process innovations and improvements which we have argued are likely to have different impacts on the skill composition of labour demand. Duguet and Greenan (1997) is one of the few studies we are aware of that makes a full distinction in R&D-expenditures. They find that only product innovations significantly lower the demand for 'execution labour' or blue collar workers. Several other studies have shown product and process innovation usually both have a positive impact on wages and employment (e.g, Duguet and Greenan, 1997, Hildreth, 1998 and Martinez-Ros, 1998) but did not study the skill bias in these wage and employment changes. Especially when low-skilled labour costs are dropping, it could be expected that process improvements and innovations try to save on high-skilled labour. Dunne, Haltiwanger and Troske (1996) find a weak negative relationship between the introduction of new production technologies and the share of high-skilled labour in employment.

The above suggests that it matters a great deal what measure of technology we use in our regressions. In the next section we show the most common proxies for technical change are computer use and R&D-intensity. Both have their problems and inadequacies.

Despite the empirical and theoretical considerations given above the survey of empirical results so far yields an interesting picture. Therefore we proceed by giving a survey of the literature in this field. The articles in the survey are all subject to the theoretical and empirical qualifications given above and the results should be interpreted correspondingly. Of course our own research agenda is also reflected in the selection of the articles and highlights and stresses we place on some of the studies.

5. Empirical Results

The value added of any survey article lies in the structure the surveyors impose upon the selection of articles they have made. The few surveys available up to now have suggested several possible categorisations.

Bartel and Sicherman (1999) categorize the research along three major lines. The first line of research concentrates on explaining inter-industry wage differentials and has found a positive correlation between industry wages and technical change, using information on capital-labour ratios and R&D-intensities. The second line of research examines the dramatic increase in relative wages of educated or skilled workers, matching educational and occupational data. The results of these studies point in the direction of technical change being skill-biased. The third approach focusses on individual and plant-level data to study the impact of technical change and new technologies like computers on relative wages. The results of these studies show that workers using new technologies receive a notable wage premium.

Ter Weel (1999) adds three approaches which can be distinguished. They focus alongside the above mentioned three approaches on the impact of new technologies on the wage structure from a historical point of view. In addition, two lines of studies have dealt with the international nature of new technology and changes in wage structures. First, there are studies using OECD and UN data on wages, employment shares and R&D at sector level. The findings of these studies are that technical change which is skill-biased is present in all OECD countries. In addition, it are the same sectors which simultaneously increase the demand for skills in different countries. Second, in an international dimension often increasing levels of international trade, as a result of globalization, are pointed at as a cause of SBTC.[8]

[8] We have argued that trade may indeed cause biases on the aggregate level. This is however not factor-biased technical change.

Finally, Schimmelpfennig (1998) deals with the literature by making a distinction between SBTC and structural change and points out for Germany that structural change rather than SBTC is the driving force of wage dispersion.[9]

Our structure is derived from the theoretical and empirical considerations we have brought forward in the previous sections. As in Chennells and van Reenen (1999) we first distinguish the articles by the dependent variable being explained. The two broad categories are wages and employment. Then all studies can be categorised on the basis of their level of analysis and the skill proxy that is used. We start with the papers that take the individual as the unit of aggregation. As was argued in Section 2 this should allow us to interpret the between and within unit effects these studies find. We then move up the tree in Figure 3.

Finally we distinguish between papers that use explicit or implicit measures of technology. Those that introduce explicit measures of technology fall in four broad categories. The first group of papers uses computer or IT related technology measures and as we have argued in Section 3 they thus test for the organisational change and new GPT related skill bias. The category of R&D based technology proxies is more closely related to the SBTC hypothesis. Within this category we can separate R&D-input and output based proxies and pay extra attention to studies that try to distinguish between types of innovations or R&D-expenditures. A third category relates technical change to capital accumulation or machinery and thus illustrates the relevance of capital skill complementarity, which is closely related to the issues studied here. A final category is used for all other technology proxies that have been proposed.

Of all the papers we have surveyed the bulk refers to the United States

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[9] Katz (1999) presents two approaches often cited as being important for recent rises in US wage inequality. The first approach focuses on relative employment of higher educated workers and "non-production" workers stressing the within industry and establishment component of SBTC. The second approach deals with more direct evidence from case-study research. The findings of these studies are that the relative utilization of higher skilled workers is strongly positively related with capital intensity and the introduction of new technologies.

situation roughly between the early seventies and the middle nineties. We have tried to incorporate as many papers as possible on other countries but due to language barriers we fear a lot of interesting work has escaped our attention. The articles we have surveyed are listed in Appendix 1. The survey will proceed category wise and references are made to specific articles to point out deviant or remarkable results.

Employment Shares

The studies addressing employment shares are listed in Tables A1.1 and A1.2 in the Appendix to this paper. At all levels of aggregation there seems to be strong evidence of within unit upgrading of the skill composition of the workforce. It is remarkable that for example Berman Bound and Griliches (1994) and Bartelsman and Gray (1996) find similar results when decomposing the skill upgrading in between and within unit effects whereas the former analyse 450 4-digit SIC industries and the latter analyse the plant level. Berman Bound and Machin (1998) come to similar conclusions when analysing several OECD countries. Some of our own experiments with the NBER's CPS database supports these findings. This indicates the aggregate shift in employment shares is caused predominantly by within unit skill bias in technical change at extremely detailed levels of aggregation. In itself this provides evidence for the SBTC hypothesis. Haskel and Slaughter (1998) do find support for the between sector bias of technical change. Shifts in demand or international trade are generally rejected as explanations for observed skilled labour share developments.

A notable exception is the case study by Levy and Murnana (1996) who conclude that the demand for college graduates increased in the Tammany Bank. However, this has been driven more by growth of the financial sector than through changing skill requirements within the bank.

The above results also seem to be robust when alternative skill proxies are used. When comparing internationally, the results for the US and UK are strongest.

For mainland Europe the results are less pronounced. Aguirregabriria and Alonso-Borrega (1997), Hollanders and Ter Weel (2000) and Machin and van Reenen (1998) find weaker results for Spain, Germany, Finland and France and Sweden and Denmark respectively.

When we consider the explanatory power of technical change proxies in these regressions the results are even more convincing. All technology proxies show up significantly affecting the changes in skill composition of the labour force, supporting the SBTC hypothesis. This points at capital-skill complementarity and R&D-driven skill upgrading. For computer use the results are equally strong but as the previous section and for example Chennells and Van Reenen (1999) point out, there might be a serious endogeneity problem involved in studies that use this proxy for technology.

Relative Wages

The studies addressing relative wage changes are given in Tables A2.1 and A2.2 in the Appendix to this paper. First consider Table A2.1. in this table we investigate studies with no explicit technology variable. Often a time trend of relative wages between e.g. the 90^{th} and 10^{th} percentile of the wage distribution is decomposed in an individual's observable components (e.g. educational level and experience) and unobservable components. Bound and Johnson (1992) and Juhn, Murphy and Pierce (1993) find for the US that the unobservable or residual component increases throughout the period 1963-1988. Katz and Murphy (1992) add to this that the rise in wage inequality over this period was not only due to wage increases for high paid workers. Real wages of high school graduates with 1 to 5 years of experience fell by some 20 percent from 1979 to 1987. The only studies for other countries (Beaudry and Green, 1998 for Canada and Haskel and Slaughter, 1998 for the UK) reveal broadly similar results.

Now we turn to studies which measure technology explicitly in Table A2.2 to check whether these relative wage changes are linked to technology. First consider aggregation levels at the individual worker. These studies often employ relatively large data sets on individuals. Many studies define technology by some measure of computer use or investment in computer equipment. It turns out the workers working with such equipment receive a considerable wage premium. This effect is however not unambiguous because DiNardo and Pischke (1997) have shown that variables like computer use are strongly correlated with white-collar workers who receive a relative wage-premium over blue-collar workers any way.

Another measure employed by Dickens and Katz (1987) and Loh (1992) is R&D-intensity. The findings of these studies are that R&D has a positive impact on wages. Finally, some studies with data on individuals apply other measures to get a grip of technical change. These measures are e.g. organisational change, training intensity, problem solving skills, the introduction of specific technologies and the number of patents. All results point to SBTC.

One aggregation level higher we analyse studies on the level of the establishment. These studies are often case studies. Together with studies at the firm level we observe a similar pattern as the results of studies at the individual level. SBTC is present in all studies, except for one study by Borghans and Van Loo (1999) who find no evidence for a computer wage premium.

Studies at the industry level require often analysed using the empirical specification in the previous section. Again all studies find evidence for SBTC. International studies by Machin and Van Reenen (1998) and Adams (1999) reveal that this phenomenon is most severe in the US and less so in European countries. Finally we are aware of two studies distinguishing the technology variable into process and product innovations. Hildreth (1998) finds for the UK that new process technology leads to higher wages and Martinez-Ros (1998) finds for Spain a significant positive effect on wages when firms do both product and process innovations.

6. Conclusions

As in most survey articles it is impossible to conclude with some unqualified results and conclusions. Results are generally mixed but from the survey in Section 5 we may draw some inferences. The survey shows that biases in labour demand at the aggregate level do exist and can be found at all levels of aggregation. However, as Schimmelpfennig (1998) and Haskel and Slaughter (1998) show sectoral biases or structural shifts are important at the industry level. This makes the firm or worker level the appropriate level of aggregation to test for pure factor biases.

In the quest for sources of these biases many have tested and found significant effects of technical change proxied in various ways. The proxies used, however, are rather crude and usually imply that the authors assume technology to be skill-biased by nature and regress measures that might capture the rate of technical change, not its direction. There may very well be reasons to assume a higher rate of change causing skill bias in itself, but the debate on induced innovations and technology development gives reasons to believe that the direction of technical change is not entirely beyond our control and therefore interesting from a policy perspective as well. Different types of technical change are likely to affect the composition of labour demand in different ways and proxies that differentiate between types of innovation could shed light on the exact causes of skill bias. The little evidence available seems consistent with the hypotheses put forward in Section 3. Product innovations seem to be biased against the low-skilled as is organisational change based on the introduction of IT. The significance of computer use and related proxies can also be interpreted as support for the GPT approach. However, due to endogeneity and measurement problems further research is called for.

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Figure 1
Skill-Biased Technical Change without Wage Effects

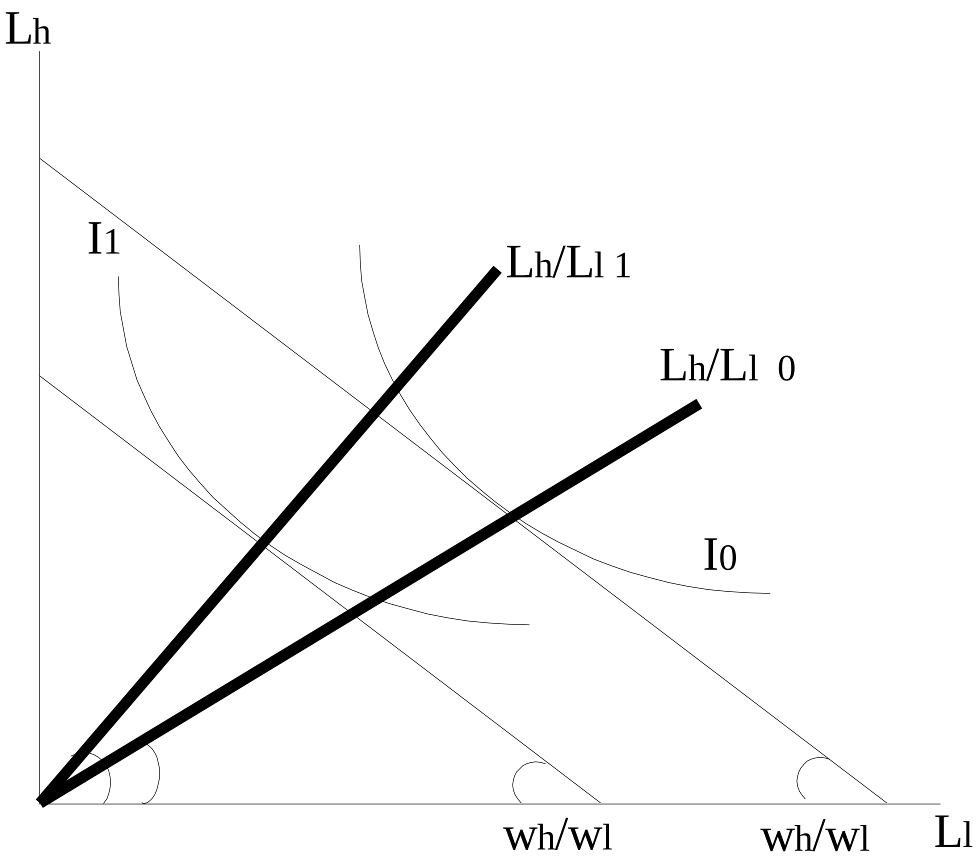

Figure 2
Factor-Neutral Sector Bias

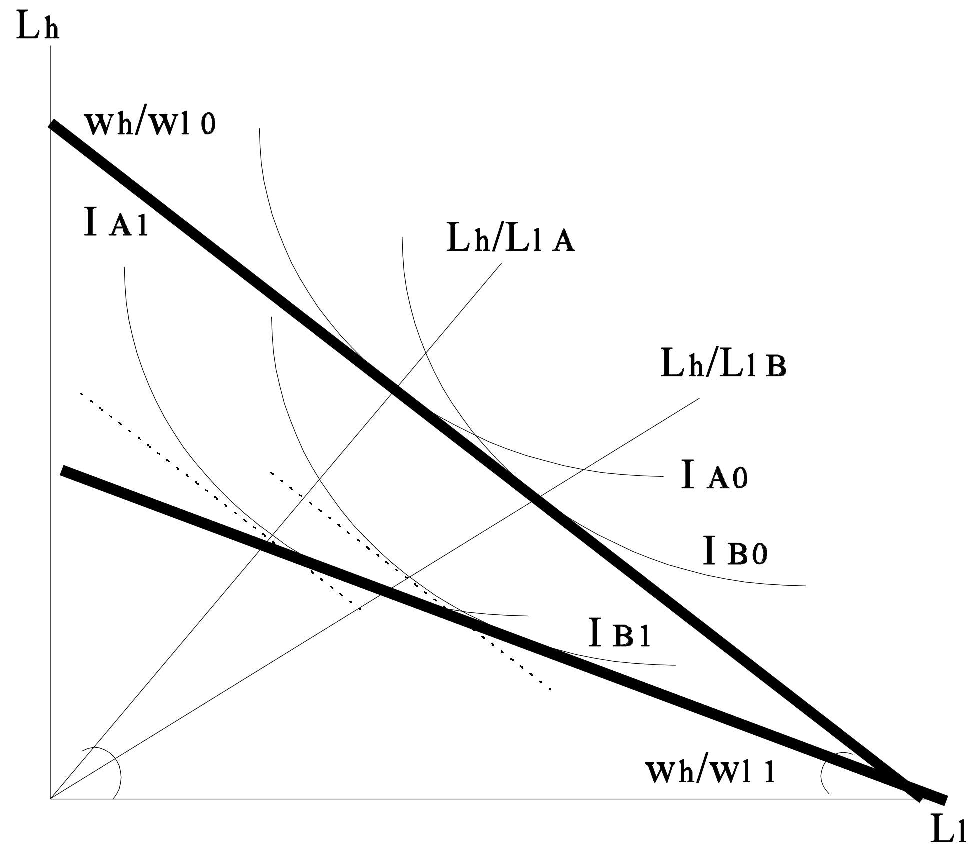

Figure 3
Decomposition of skills

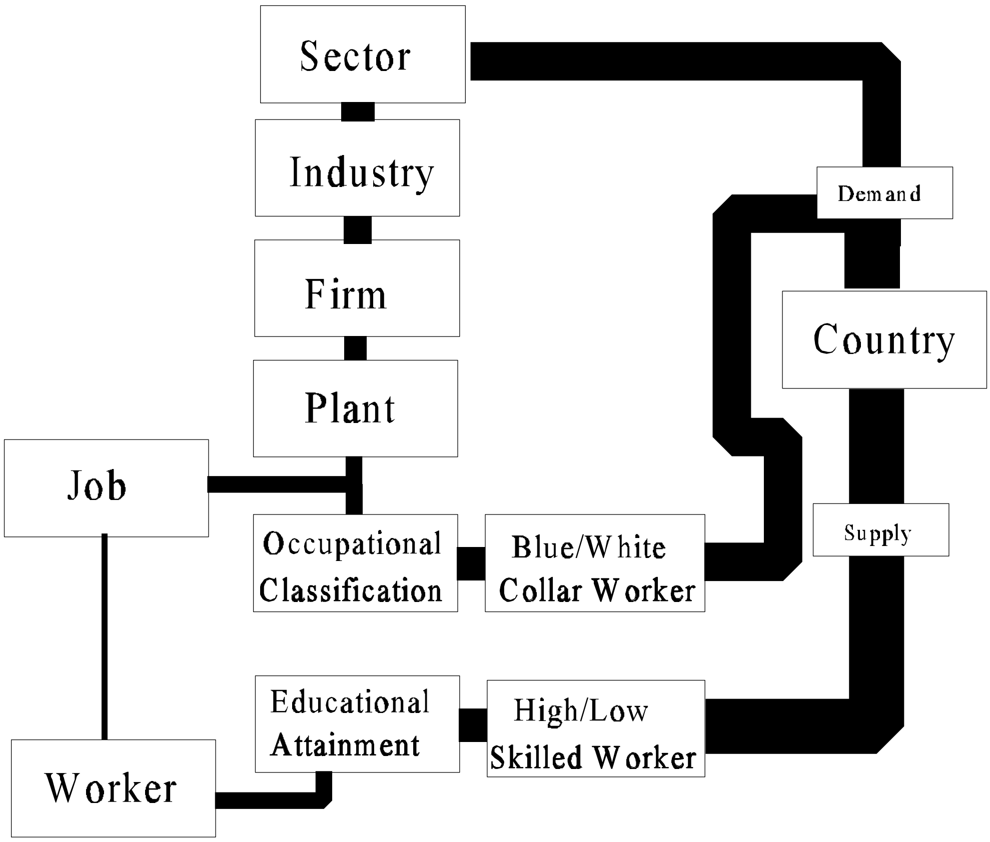

Figure 4
Bias with Sector and Factor-Neutral Technical Change

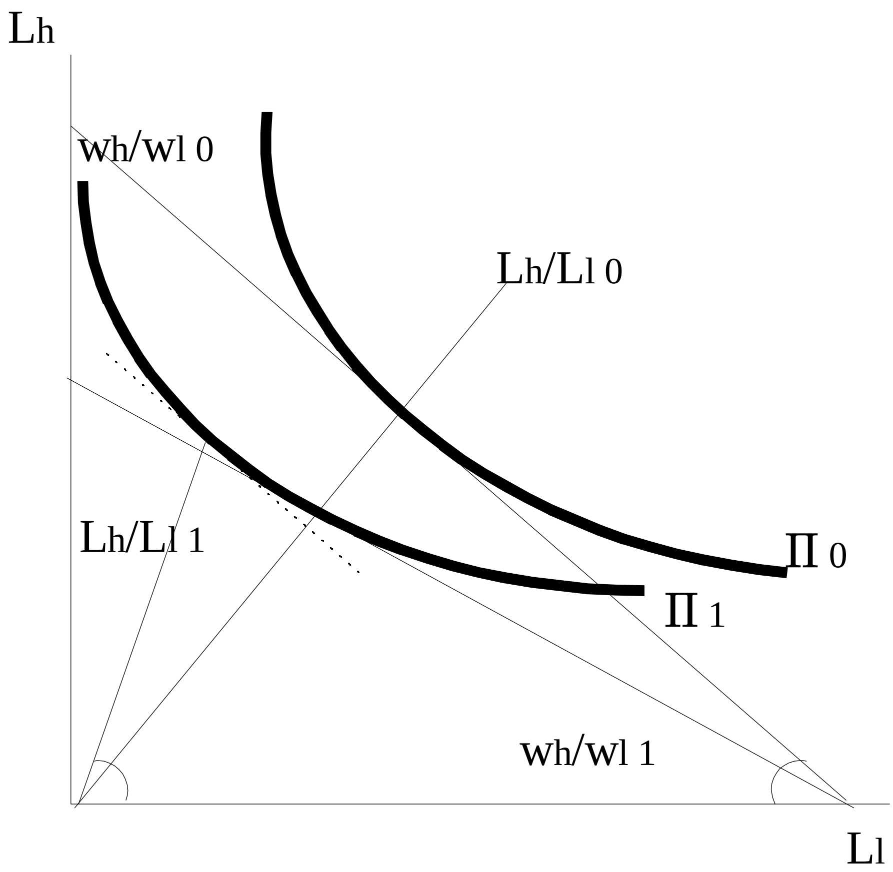

Table 1

Pattern of Changes in the Dispersion of Earnings in the 1970s, 1980s and 1990s

Country	1970s	1980s	1990s	Expectations
Australia[1]	-	+	..	dispersion
Austria[2]	-	+	..	
Belgium[3]	..	+	..	
Canada[4]	0	+	+	compression
Denmark[5]	..	0/+	..	
Finland[6]	-	0	..	
France[7]	-	-/+	+	compression
Germany[8]	0	-/0	+	compression
Italy[9]	-	0	..	
Japan[10]	..	+	..	
Mexico[11]	..	..	..	
Netherlands[12]	0	-/+	0	compression
Norway[13]	..	0	..	
Portugal[14]	..	+	..	
Spain[15]	--/0	+	+	dispersion
Sweden[16]	0	0/+	..	
United Kingdom[17]	-	++	+/-	compression
United States[18]	+	++	+/-	compression

++: strong increase in dispersion, +: increase in dispersion, 0: no clear change, -: decrease in dispersion, --: strong decrease in dispersion, +/-: increase followed by decrease, ..: no information available.

1: Gregory and Vella (1995) and OECD (1996); 2: OECD (1996); 3: OECD (1996); 4: Baldwin, Diverty and Johnson (1995), Reilly (1995), Card, Kramarz and Lemieux (1996), Murphy, Riddel and Romer (1998); 5: Machin and Van Reenen (1998); 6: Laaksonen and Vainiomaki (1995); 7: Entorf and Kramarz (1997), Goux and Maurin (1997), Machin and Van Reenen (1998), and Entorf, Gollac and Kramarz (1999); 8: Abraham and Houseman (1995), Machin and Van Reenen (1996); 9: Casavola, Gavosto and Sestito (1996), OECD (1996); 10: Machin and Van Reenen (1998); 11: Tan and Batra (1997); 12: Groot and De Grip (1991), Borghans and Van Loo (1999), Ter Weel (1999); 13: OECD (1996); 14: OECD (1996); 15: OECD (1996) and Martinez-Ros (1998); 16: Hansen (1995) and OECD (1996); 17: Chennells and Van Reenen (1995) and (1997), Bell (1998), Haskel and Slaughter (1998), Machin and Van Reenen (1998), Green (1999), Riley and Young (1999); 18: Katz and Murphy (1992), Juhn, Murphy and Pierce (1993), Krueger (1993), Murphy and Welch (1993) and (1999), Autor, Katz and Krueger (1998), Bartel and Sicherman (1999), Bresnahan (1999) and Katz (1999).

Table 2
Summary of Results

Sign of change due to:		Factor Bias		
		Skill Saving	Neutral	Skill Using
Sector Bias	Skill Intensive	w_H/w_L (?) L_{Hi}/L_{Li} (-)	w_H/w_L (+) L_{Hi}/L_{Li} (0)	w_H/w_L (+) L_{Hi}/L_{Li} (+)
	Not Concentrated	w_H/w_L (0) L_{Hi}/L_{Li} (-)	w_H/w_L (0) L_{Hi}/L_{Li} (0)	w_H/w_L (0) L_{Hi}/L_{Li} (+)
	Skill Extensive	w_H/w_L (-) L_{Hi}/L_{Li} (-)	w_H/w_L (-) L_{Hi}/L_{Li} (0)	w_H/w_L (?) L_{Hi}/L_{Li} (+)

Table 3
Summary of Results

Source of Technical Progress		Direction of Bias in Technical Change
Learning		Ambiguous
Knowledge Accumulation		None
R&D	Product Improvements	Skill Using
	Process Improvements	Endogenous
	Product Expansion	Skill Using
	Intermediates Expansion	Endogenous
Organisational Change		Skill Using
GPT		Skill Using

Table A1: EMPLOYMENT SHARE STUDIES

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Skill Proxy[2]
CAN	Betts (1997)	Time trend which is industry specific	18 industries spanning Canadian manufacturing, 1961-1986 from Statistics Canada	In 16 of 18 industries, non-neutral technical change has been the rule. The most prevalent types of SB T were biases away from blue-collar workers and toward energy	4	22
GBR	Nickell and Kong (1987)	Residual	55 manufacturing industries (3 digit) 1974-1985 panel	In 7 of 9 sectors there is a positive effect of labour augmenting technical change	5	0
GBR, USA	Haskel and Slaughter (1998)	Technical change that is defined either being skill-biased or not by definition	Some aggregate data on non-production/ production wage premium	The evidence suggests that the sectoral bias of skill-biased technical change rather than its pervasiveness or acceleration can help explain changing skill premiums	4	22
GER	Falk and Koebel (1997)	Residual	All industries 1977-1994	SBTC drives labour demand	4	12
GER	Steiner and Mohr (1998)	Sector specific time trend 1975-1990	IABS from the German Statistical Office 1975-1990	The skills ratio has declined by about 3 percent per year for men and 6 percent for women. There is a modest effect from technical change on the employment share of unskilled labour in the manufacturing sector, whereas trade with low-wage countries is rejected as an explanation for the trend decline.	5	12

Table A1 (Cont'd): EMPLOYMENT SHARE STUDIES

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Skill Proxy[2]
GER (W)	Steiner and Wagner (1997)	Residuals	IABS 1975-1990	Both trade and SBTC explain little of the shifts in employment shares	5	12
IRL	Kearney (1998)	Residuals	Manufacturing panel by sector 1979-1990	SBTC drives labour demand in high growth industries. Trade in low growth industries. Demand is stable in the intermediate range.	3	22
Several OECD countries	Berman, Bound and Machin (1998)	Change in skilled employment share focussed on from both a "Heckser-Ohlin" and a "Stolper-Samuelson" point of view	Data mainly on industry or country level	Pervasive skill-biased technical change is the main cause for the decreased demand for less skilled workers; not trade.	4,6	22
Several OECD countries	Nickell and Bell (1996)	Unemployment levels among low-skilled workers	Mainly OECD data on employment and unemployment by skill level	Rising levels of unemployment among low-skilled workers might be due to both technical change and trade	6	12
USA	Bernard and Jensen (1997)	Residual productivity growth	Annual survey of manufactures 1976-1987	Within industry shifts explain changes in skill composition. When analysing at plant level trade also explains shifts in employment shares.	3	22
USA	Garcia Cervero (1997)	Residual	Annual Survey of Manufacturing 1958-1984	Industries with higher rate of TFP growth have higher skilled labour share	4	12

Table A1 (Cont'd): EMPLOYMENT SHARE STUDIES

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Skill Proxy[2]
USA, UK, JP and FRA	Katz, Loveman and Blanchflower (1995)	Changes in sectoral employment shares	CPS (US), New Earnings Survey, General Household Survey LFS (UK), Basic Survey on Wage Structure Employment Status Survey (JP), Declarations Annuelles de Salaires (FRA)	Educational and Occupational wage differentials narrowed in 70s in all 4 countries. Reverse with increases in skill differentials in US, UK, and JP in early 80s. Similar pattern in FRA as of 1985. Reduction in growth rates of high-skilled labour supply in face of persistent increases in relative demand.	5,6	12
USA	Kahn and Lim (1997)	Total Factor Productivity	Manufacturing Industries Panel 1970-1980	Growth not related to investment but mainly to skill intensities over the 70s	4	12
USA and OECD total	Wood (1998)	Growth of college graduates relative wages	Aggregate data from the OECD	Technical change has raised the relative demand for skilled workers. However, there is no conclusive evidence found whether or not the pace of skill-biased technical change has increased over the past two decades	6	12

[1] Aggregation level
1: job or worker level
2: establishment level
3: firm level
4: industry level
5: sector level
6: national level

[2] Skill Proxy
11: educational attainment in years
12: educational attainment aggregated into low-high skill
21: occupational classification
22: occupational classification into blue collar-white collar

Table A2: EMPLOYMENT SHARE STUDIES WITH TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Technology Proxy[3]	Skill Proxy[2]
DNK, FRA, GER, GBR, JPN, SWE, USA	Machin and Van Reenen (1998)	R&D-intensity at industry level and in some cases computer use	STAN, ANBERD, UNISD and other OECD data aggregated on industry level which allow for making a distinction between manual and non-manual workers	For all seven countries skill-upgrading is found to be strongly correlated with R&D intensity.	4	1,2,3	22
ESP	Aguirregabiria and Alonso-Borrega (1997)	R&D expenditure on technological capital.	Balanced panel of 1080 spanish manufacturing firms 1986-1991	Factor demand equations for 5 types of labour and 3 types of capital are estimated. No effect is found of R&D, the stock of technological capital has an unskilled bias. The dummy variable for the introduction of technological capital has a negative effect on blue collar employment.	2	2,3	22
FRA	Greenan, Mairesse and Topiol-Bensaid (1998)	IT capital and the number of IT workers	French firm data 1986-1990 and 1996	Strong correlations between sectors but only a negative effect of the technology variables on the lowest skill group over time.	3	1	21
FRA, GBR	Caroli and van Reenen (1998)	Computer use	402 british establishments 1984-1990 divide in 6 occupational groups and 992 french establishments 1992-1996 divided in 5 occupational groups	OLS egressions of the change in the employment share of skilled workers is significantly affected by computer use.	2	1	21

Table A2 (Cont'd): EMPLOYMENT SHARE STUDIES WITH TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Technology Proxy[3]	Skill Proxy[2]
GBR	Haskel and Heden (1999)	Change in computer use from 1973-1992 on a yearly basis and the ratio of computer equipment investment to total investment	Data of roughly 15.000 establishments distinguishing between manual and non-manual workers and data on computer use	Skill-upgrading is mostly driven by within-establishment changes in skill-composition. In addition, computerisation reduced the demand for manual workers, even after controlling for several possible endogeneity problems	2	1	22
GBR	Haskel (1996)	Computer usage	New earnings survey panel data set, Census of production and Customs and excise data 1980-1989	Within industry changes account for skill-composition of demand. Computer use is correlated with skill-upgrading. Trade has no significant effect	4	1	22
GER	Licht et al. (1997)	Innovations	ZEW Services Sector Panel 1995	Innovation correlated with skill intensity of firm.	3	4	12
GER	Blechinger and Pfeiffer (1997 and 1998)	Innovative activities	Mannheim Innovation Panel 1993-1996	Innovation and skill intensity are correlated	3	4	22
GER, FIN, FRA, GBR, JPN, USA	Hollanders and Ter Weel (1999)	R&D-intensity at industry level and knowledge spillovers between countries and industrial sectors	STAN, ANBERD, UNISD and unique OECD data on skill level aggregated on industry level	For all countries evidence is found that technical change is skill-biased towards white-collar high-skilled workers. In addition, the results are extended by stressing the importance of knowledge spillovers on changes in employment shares between high- andlow-skilled workers	4	2	22

Table A2 (Cont'd): EMPLOYMENT SHARE STUDIES WITH TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Technology Proxy[3]	Skill Proxy[2]
SWE	Hansen (1995)	R&D intensity and number of S&Es	16 swedish manufacturing industries 1970-1990	Change in proportion of educated workers in employment and wage bill regressions are regressed on both technology variables. Both technology measures have a positive impact.	4	2	12
USA	Levy and Murnana (1996)	Computer skills	Data on the Tammany Bank in the United States	Computerization has increased Tammany Bank's demand for college graduates. However, this has been driven more by the impact in increasing the size of the financial sector than on changing skill requirements with the bank	2	1	11
USA	Autor, Katz and Krueger (1998)	Whether computer use leads to a demand shift in favour of college graduates relative to high-school graduates	Current population survey, National income and Product accounts, and two databases on computer use to document the growing utilization of computers among higher skilled in the workplace	An analysis of aggregate changes in the relative supply, wage and wage-bill share of college graduates over the period 1940-1996 suggests strong relative demand growth favouring highly educated workers. Within-industry skill-upgrading accelerated in industries with high levels of computer utilisation	2	1	12
USA	Breshnahan, Brynjolfsson and Hitt (1998)	IT capital stock a measure of computing capacity and the number of PCs	IT information for fortune 1000 1987-1994 and a survey of workplace organisation on 380 firms in 1995 and 1996. Computing capacity data from compustat.	IT combined with organisational chnage increases the relative demand for skilled workers more than IT by itself. Output increases are larger when firms put increased effort in IT and have highly skilled workers and or decentralised organisations	2	1	12

Table A2 (Cont'd): EMPLOYMENT SHARE STUDIES WITH TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Technology Proxy[3]	Skill Proxy[2]
USA	Dunne, Haltiwanger and Troske (1996)	Change in R&D stock, IT applications and implementation of 17 types of new technologies	1820 manufacturing plants 1972-1988	The relation between the change in non-production workers wage bill and employment share and R&D is significant and positive.	2	1,2	22
USA	Adams (1999)	The flow of firm R&D is used as a proxy for the firm's knowledge. In addition, industry R&D spillovers are applied	Data from the Annual Survey of Manufactures of firms owned by chemical conglomerates 1974-1988	(i) R&D and capital increase the factor intensity of labour relative to materials; (ii) firm R&D in the same product as the plant carries the strongest and most consistent skill bias; and (iii) equipment capital is skill-biased while structures are biased against skill.	2	2	22
USA	Berndt, Morrison and Rosenblum (1992)	High-technology office and information technology equipment as a proportion of total industry capital stock	Manufacturing data from Bureau of Economic Analysis 1952-1986	Evidence for skill-upgrading and shift to white-collar work due to capital improvements	3	1	22

Table A2 (Cont'd): EMPLOYMENT SHARE STUDIES WITH TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Technology Proxy[3]	Skill Proxy[2]
USA	Berman, Bound and Griliches (1994)	Impact of R&D investments and computers dependent on the annual change in non-production worker's share in the wage bill	Annual survey of manufactures, the census of manufactures and the NBER trade data which allow to make a distinction between manual and non-manual workers	The shift away from unskilled toward skilled labour is based on two facts. First, it is due to increased use of skilled workers. Second, increased use of non-production workers is strongly correlated with investment in computers and in R&D.	3	1,2	22
USA	Siegel (1995)	Introduction of various kinds of manufacturing technologies and R&D intensities.	79 long island manufacturing firms 1987-1990. Data are divided in 6 skill groups	Positive effect of technology on skill composition of employment and wage bill shares.	3	2,4	11
USA	Bresnahan (1999)	Use and application of computers and ICT	Several detailed studies on use and application of computers and ICT	Technical change has been skill-biased. Four subsequent results have been occurred: (1) computer decision making has substituted for human decision making in modest cognitive tasks; (2) computers in organizations have been complementary to cognitive skill; (3) organisational computing has been complementary to people skills; and (4) changes have come at the time and in industries where organisational computing has had its largest impact	4	1	22

Table A2 (Cont'd): EMPLOYMENT SHARE STUDIES WITH TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Technology Proxy[3]	Skill Proxy[2]
USA	Bartel and Lichtenberg (1987)	Proxies for age of capital stock	61 manufacturing industries in 1960, 1970 and 1980	Positive relation between younger capital and higher utilization of skills	4	3	22
USA	Berndt, Morrison and Rosenblum (1994)	High-Tech Capital Share	2-digit US Manufacturing 1968-1986	Skill upgrading of blue collar is linked to OF/K. So is white collar share in total employment. Labour productivity falls as result of increased white collar work.	4	3	22
USA	Mishel and Bernstein (1997)	Computer and capital equipment and share of S&Es	34 industries CPS 1973-1994	Change in employment share of 5 educational groups.Correlation with technology proxies is positive but no change over time in coefficients.	4	1,2,3	11
USA	Wolff (1996)	Skill Proxy, TFP, R&D and Computer Use	43 US manufacturing industries 1970-1990	Three skill groups are identified: Substantive complexity skills, interactive skills and complexity skills, rated for 12.000 jobs. Positive relation of R&D and computers to growth of first two skill groups is found	4	1,2,4	0

Table A2 (Cont'd): EMPLOYMENT SHARE STUDIES WITH TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Technology Proxy[3]	Skill Proxy[2]
	WITH R&D SPECIFICATION						
FRA	Duguet and Greenan (1997)	five types of innovation: product improvement, new products, product imitation, process breakthrough and process improvement	panel of 4954 french manufacturing firms in 1986 and 1991	Skill bias in favour of white collar workers. Blue collar workers are substitutes for capital. Reduction in the demand for blue collar workers is mainly due to new product innovation.	3	2	22
NLD	Brouwer, Kleinknecht and Reijnen (1993)	R&D intensity	859 Dutch manufacturing firms 1983 and 1988	No effect of R&D intensity level. Growth of R&D intensity has a negative effect, which is mitigated by product R&D and R&D towards IT	3	2	0

[1] Aggregation level — 1: job or worker level; 2: establishment level; 3: firm level; 4: industry level; 5: sector level; 6: national level

[2] Skill Proxy — 11: educational attainment in years; 12: educational attainment aggregated into low-high skill; 21: occupational classification; 22: occupational classification into blue collar-white collar

[3] Technology Proxy — 1: computerisation; 2: R&D; 3: capital goods; 4: other

Table A3 : WAGE SHARE STUDIES WITHOUT TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Skill Proxy[2]
CAN	Beaudry and Green (1998)	Within cohort wage dispersion	Survey of Consumer Finances 1971-1993	Age-earnings profiles have deteriorated for younger cohorts at all educational levels. There is no evidence of increased within cohort dispesion	1	11
GBR, USA	Haskel and Slaughter (1998)	Technical change that is defined either being skill-biased or not by definition	Some aggregate data on non-production/ production wage premium	The evidence suggests that the sectoral bias of skill-biased technical change rather than its pervasiveness or acceleration can help explain changing skill premiums	4	22
USA	Goldin and Katz (1999)	Returns to schooling throughout the first half of the twentieth century	1915 Iowa state census and several other studies on wages and education	The wage structure narrowed at several moments in the first half of the twentieth century. Inequality and the returns to education across the entire century first declined before their more recent and steep ascent	1	11
USA	Hellerstein, Neumark and Troske (1999)	Differences is marginal productivity among several age, skill and demographic groups	New data set combining data on individual workers and their employers to estimate differentials in marginal productivity	The findings are twofold: (1) prime-aged workers (aged 35-54) receive a higher wage relative to older workers because of higher marginal products; (2) Women receive lower wages not based on lower marginal productivity	1	11
USA	Juhn, Murphy and Pierce (1993)	Changes in relative wages among skilled and unskilled workers	Data on wages and employment are taken from the March current population survey from 1960-1990 on an individual level	Wage inequality is attributed to increases in premiums on both unobserved and observed (education) dimensions of skills. The increased demand for skilled labour is the main cause for wage inequality and divergence	1	11

Table A3 (Cont'd): WAGE SHARE STUDIES WITHOUT TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Skill Proxy[2]
USA	Heckman, Lochner and Taber (1998)	Differences in skill prices and aggregate production technology between different sectors	White male earnings for the period 1979-1993 and data from the Current population survey	A model of skill-biased technical change is consistent with the feature of rising wage inequality. In addition, immigration of low-skilled workers contributes little to rising wage inequality	1	12
USA	Katz and Murphy (1992)	College premiums and other wage premiums	Data on gender, wages and employment are taken from the March current population survey from 1963-1987 on an individual level	The changing wage structure can be explained by the growth in the demand for more skilled workers	1	12
USA	Bound and Johnson (1992)	Annualized proportionate change in the relative wage of a particular demographic group of workers adjusted for the change in total average industry wage effects is defined as the per year change in industry-specific technical change	The analysis is based on imputed wage rates from questions on usual weekly earnings and hours from the Current population survey form 1973, 1979 and 1988	Four explanations are examined: (1) increasing trade deficit during the 1980s; (2) loss of wage premiums paid to blue-collar workers as a result of increased union power; (3) increased computer utilization; and (4) slowdown of the growth rate of college graduates increases the demand for these workers. The conclusion is that technical chnage in favour of high-skilled workers is the major cause of wage divergence	1	22

Table A3 (Cont'd): WAGE SHARE STUDIES WITHOUT TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Skill Proxy[2]
USA	Nadiri and Nandi (1999)	Growth rate of total factor productivity	data on telecommunications industry 1935-1987	Conventionally measured TFP growth does not accurately measure the rate of technical change for a multiproduct firm when the pricing policy of the firm departs from marginal cost pricing an when economies of scale are present. A significant proportion canbe attributed to the mark up effect generated by non marginal cost pricing, which has no impact on efficiency in production.	3	0
USA	Lawrence an Slaughter (1993)	Residuals	Annual Survey of Manufacturing 1970-1990	SBTC is driving force in creating wage differentials between blue and white collar workers.	3	22
USA	Krueger (1997)	Residuals	150 manufacturing industries 1989-1995	Wage growth is closely linked to price developments passed on in proportional to factor shares. Product prices grew less in exporting sectors, reducing wage growth.	4	22
GER	Abraham and Houseman (1995)	Residuals after controlling for supply shifts (wage bill shares)	Survey of Compensation in Industry and Trade	Inequality fallen in Industry and Trade since mid 70s. Due to wage setting institutions. Demand for more educated workers increased but supply has increased as well leaving wages stable. German educational system does better job in providing workers with demanded skills	5	22

Table A3 (Cont'd):		WAGE SHARE STUDIES WITHOUT TECHNOLOGY PROXY				
Countries	**Authors**	**(Skill-biased) technology measure**	**Data**	**Results**	**Aggregation Level[1]**	**Skill Proxy[2]**
USA	Francois and Nelson (1998)	Skilled-labour share of sectoral employment, factor intensities in a "Stolper-Samuelson" framework	Data on a sectoral level from the United States' department of labour	International trade is a good explanation to examine the returns to labour market participation of particular skills	5	12
SWE	Edin and Holmlund (1995)	Residuals after controlling for relative supply shifts	Level of Living Survey and Houshold Market and Non-Market Activities Survey	From late 60s up to early 80s decreases in wage differentials accross gender, experience and educational categories. From mid 80s widening of differentials.	6	11
USA, AUS	Gregory and Vella (1995)	None	LFS (AUS), CPS (USA)	Employment earnings distribution is widening at same rate in both countries from 76-90 but Aus has a more compressed distrubution throughout. Different explanations apply. US the returns to education increased. In AUS not. There is no evidence of factor price equalisation. No explanation for the wideling wage distribution in Australia is offered.	6	11
GBR	Schmitt (1995)	Residuals after controlling for relative supply shifts	General Household Survey 1974-88	Skill differentials fell slightly in late 70s and rose sharply in 80s. Simple relative demand and supply framework can explain. Increasing supply narrowed differentials in 70s, during the 80s a strong rise in relative demand led to widening.	6	11,21

Table A3 (Cont'd): WAGE SHARE STUDIES WITHOUT TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Skill Proxy[2]
USA	Krusell et al. (1997)	New Capital Equipment	CPS	Capital Skill complementarity can explain the bulk of the SBTC responsible for wage divergence despite supply increases.	6	12
USA	Murphy and Welch (1999)	Residuals after controlling for supply shifts	CPS	Growth in College premium slowed down in 90s. Partly due to supply but not all of slowdown can be explainen. SBTC must have slowed down	6	11

[1] Aggregation level

1:	job or worker level	4:	industry level
2:	establishment level	5:	sector level
3:	firm level	6:	national level

[2] Skill Proxy

11:	educational attainment in years	21:	occupational classification
12:	educational attainment aggregated into low-high skill	22:	occupational classification into blue collar-white collar

Table A4 : WAGE SHARE STUDIES WITH TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Technology Proxy[3]	Skill Proxy[2]
CAN	Reilly (1995)	Computer use	607 employees in 60 firms	Positive effect of technology on wages. Wages account for the employer size wage effect	1	1	11
CAN	Baldwin, Diverty and Johnson (1995)	Use of specific types of advanced manufacturing technologies	Mean income per worker in specific plant	Technology wage premium between 10 and 30% depending on technology category	2	3	11
CAN	Gera, Gu and Lin (1998)	R&D Stock, Patent Stock and age of Capital Stock and TFP	29 industries 1981-1994	All technology variables are significant except TFP in explaining within group wage and employment differentials between higher occupational groups and knowledge workers.	4	2,3,4	22
CAN, FRA, USA	Card, Kramarz and Lemieux (1996)	Whether or not workers use a computer at work	Data for all three countries at worker level	In all three countries the same forces have led to falling wages for less-skilled workers. Relative wages of less-skilled workers fell most in the United States. Little evidence is found that wage inflexibilities generate divergent patterns of relative employment growth	1	1	12

Table A4 (Cont'd): WAGE SHARE STUDIES WITH TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Technology Proxy[3]	Skill Proxy[2]
CAN, USA	Murphy, Riddel and Romer (1998)	Differences in wages between skilled and unskilled workers	For the United States, data on gender, wages and employment are taken from the March current population survey from 1963-1987 on an individual level. For Canada comparable data from the Survey of consumer finances are utilized	The introduction of new technologies clearly affects the wage distribution. In addition, labour market data suggest that new technologies may arrive at different rates and different levels. This kind of variation arises at the level of the firm and industry and leads to biases between firms and industries. Differences in the demand for workers do not account for the discrepancies in income. in Canada the government has adopted a variety of post-secondary educational policies that boosted the number of workers at that level of educations. this resulted in a lower wage differential between skilled and unskilled workers compared to te US. hence it is the supply differences that explain the national differences. Skill-biased technical change does drive labour demand similarly in both countries though.	1	4	11
COL, MEX, TAI	Tan and Batra (1997)	Investment in R&D and know-how and exports and or formal workplace training	500 Colombian firms 1992, 5070 Mexican firms 1992 and 8408 Taiwanese firms 1986	Size-wage differentials for investing and non-investing firms are estimated. Large positive effects of R&D and training are found for skilled workers	3	2	12
DNK FRA, GER, GBR, JPN, SWE, USA	Machin and Van Reenen (1998)	R&D-intensity at industry level and in some cases computer use	STAN, ANBERD, UNISD and other OECD data aggregated on industry level which allow for making a distinction between manual and non-manual workers	For all seven countries skill-upgrading is found to be strongly correlated with R&D intensity.	4	1,2,3	22

Table A4 (Cont'd): WAGE SHARE STUDIES WITH TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Technology Proxy[3]	Skill Proxy[2]
FIN	Vainiomaki (1998)	R&D intensity, the introduction of new technologies and computer investment in 1990	Finnish manufacturing establishment data 1985-1994 linked with employee data and R&D surveys	Wage bill and employment share regressions of non-production workers and educational groups show that a change in R&D intensity has positive effects on the wage bill share. Other measures have unstable effects.	2	1,2	1122
FIN	Laaksonen and Vainiomaki (1995)	Industry level technology	Manual and non-manual workers	The lowest technology industries consistently paid the lowest wages, but the highest technology industries did not pay the highest	4	4	22
FRA	Entorf and Kramarz (1997)	Whether workers use specific technologies or not	Detailed worker data on characteristics like education, age etc.	Up to 4%, initially, and 1% per year of experience	1	4	11
FRA	Entorf, Gollac and Kramarz (1999)	Whether the introduction of new technologies, particularly computers, has led to wage inequality	Panel data from the longitudinal dimension of the Labour force survey on individuals and firms	Computer users are better paid than non-users. The nominal wage premium for users ranges from 15 to 20%. However, computer users already received a premium of about 11 to 16% before using computers. Hence, the real premium has a maximum of about 5%	3	1,4	11
FRA	Goux and Maurin (1997)	Computer use and industrial technologies	35 french industrial sectors 1982-1993	Wage bill share of higher and lower grade professionals, administrators and officials are regressed on industry fixed effects and the technology variables. It turns out that fixed effects are positively correlated with computer use and negatively with other technologies.	4	1,4	21
FRA, GER, GBR, ITA	Machin and Van Reenen (1996)	Lagged R&D per worker	Global vintage firms 1982-1990	Positive effects of R&D on average wages even after controlling for fixed effects. Largest effects in UK and Germany	3	2	0

Table A4 (Cont'd):		WAGE SHARE STUDIES WITH TECHNOLOGY PROXY					
Countries	**Authors**	**(Skill-biased) technology measure**	**Data**	**Results**	**Aggregation Level[1]**	**Technology Proxy[3]**	**Skill Proxy[2]**
GBR	Bell (1998)	Computer use 1991	British national child survey of 1000 individuals	Computer effect is positive and robust to controls for ability	1	1	11
GBR	Green (1999)	Computer use	Survey data from a unique UK experiment carried out in 1992 and 1997	The premium for computer skills at moderate levels of complexity is approximately 13 percent. In addition, professional communication and problem solving skills are highly valued (6 percent wage premium). Finally, verbal skills and job involving tasks do not seem to receive a premium. Finally complex jobs receive a significantly higher pay.	1	1	11
GBR	Green, Felstead and Gallie (1999)	Computer use at work	Survey data from a unique UK experiment carried out in 1986, 1992 and 1997	Job skills have increased between 1986 and 1997. The spread of computer usage is very strongly associated with the process of up skilling, while trade has only a weak effect.	1	1	11
GBR	Arabsheibani, Enami and Marin (1996)	Computer use	British social attitudes survey	positive effect of technology on wages but no differences between skilled and unskilled workers	1	1	12
GBR	Ashton, Felstead and Green (1999)	Educational time trend, organisational change and training intensities and particular problem solving skills	Survey data from a unique UK experiment carried out in 1992 and 1997	Problem solving, team working, professional communication, social and computer skills pay off a wage premium ranging from almost zero to 22 percent.	1	4	12

Table A4 (Cont'd): WAGE SHARE STUDIES WITH TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Technology Proxy[3]	Skill Proxy[2]
GBR	Chennels and Van Reenen (1997)	Whether during the past three years there had been the introduction of new plant machinery or equipment that includes new microelectronics technology	Three worker categories	In a wage regression for 1990, the wage premium ranged from 1 to 6%.	1	4	12
GBR	Haskel and Heden (1999)	Change in computer use from 1973-1992 on a yearly basis and the ratio of computer equipment investment to total investment	Data of roughly 15.000 establishments distinguishing between manual and non-manual workers and data on computer use	Skill-upgrading is mostly driven by within-establishment changes in skill-composition. In addition, computerisation reduced the demand for manual workers, even after controlling for several possible endogeneity problems	2	1	22
GBR	Chennels and van Reenen (1995)	Introduction of new technology	1984-1990 WIRS plant based	New technologies are correlated with high wage premia but causality may be reverse. Controls reduce significance.	2	4	22
GBR	Riley and Young (1999)	Computer use and capital-skill ratios	Several UK data sources 1970-1990	Increasing rewards to education. There are changes over time in the extent of the skill bias. There has been a deceleration in the bias in favour of the highest skill group and an acceleration in the bias against the unskilled in comparison to those with some qualifications. Cross sectional evidence suggests that greater skill bias in the early 80s was related to industry computer intensity.	3	1	12

Table A4 (Cont'd): WAGE SHARE STUDIES WITH TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Technology Proxy[3]	Skill Proxy[2]
GBR	Machin, Menezes-Filho and Van Reenen (1998)	Lagged R&D per worker	UK datastream companies (660) from 1983-1994	R&D earnings elasticity is significant for workers and directors. Directors wage elasticity is twice as large as that of workers	3	2	22
GBR	Haskel (1999)	Computer Use	80 industries in UK Manufacturing 1980-1989	50% of the rise in wh/wl due to computerisation, 20% due to contracting out and 15% deunionisation	4	1	22
GBR	Machin (1996)	R&D-intensity at industry level and computer use	Data on industry level on several occupational groups	Evidence is found that within-sector shifts in terms of technical change have attributed to the rising wage inequality in the United Kingdom. In addition, labour market transformations have favoured particularly white-collar high-skilled labour	4	2	21
GER	DiNardo and Pischke (1997)	Whether or not workers use computers, but also whether or not workers are white-collar or not	West German qualification and career survey consisting of about 30.000 individual observations	This paper is a reaction to Krueger (1993). The authors find that there is no clear link between the influence of technology on wages and the computer treatment effects on workers, even if the latter effect can be estimated in a consistent manner	1	1	22
GER	Bellman and Boeri (1995)	Status of technology relative to competitors qualitative response between a rating of 1 and 5	Proportion of qualified workers at the plant	Technology wage premium up to 16.6%	2	4	12

Table A4 (Cont'd): WAGE SHARE STUDIES WITH TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Technology Proxy[3]	Skill Proxy[2]
GER	Kaiser (1998)	Investment in new physical assets and investment in information technologies	Service Sector Business Survey in Germany which is an unbalanced panel of on average 1,000 firms carried out in 1995, 1996 and 1997	SB T is present in the German business-related services. Labour costs do not play a significant role. Foreign competition does have an effect on the demand of university graduates	3	1,3	11
ITA	Casavola, Gavosto and Sestito (1996)	Share of intangible capital in total capital relative to industry average	private sector Italian firms 1986-1990	About 2-6% increase in wages for each group associated with technology measure	3	2	22
NLD	Groot and De Grip (1991)	Various variables on automation, like computer equipment use, share of automation workers etc.	A detailed data set on 100 plants of one of the eight big payments bank in the Netherlands from 1980-1987	The diffusion of office automation has significant positive effects on both the skill level and the share of vocationally skilled workers. Automated banks also use recruitment policies more intensively than less automated banks in adjusting the skill structure	2	1	11
NLD	Borghans and Van Loo (1999)	Computer use	Data from a survey of a large firm in the financial services sector in the Netherlands	No clear wage premium for computer use	3	1	12
SWE	Hansen (1995)	R&D intensity and number of S&Es	16 swedish manufacturing industries 1970-1990	Change in proportion of educated workers in employment and wage bill regressions are regressed on both technology variables. Both technology measures have a positive impact	4	2	12

Table A4 (Cont'd): WAGE SHARE STUDIES WITH TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Technology Proxy[3]	Skill Proxy[2]
USA, Europe, Asia	Adams (1997)	Patents and R&D	World Intellectual Property Organisation, United Nations Statistical Yearbook. OECD MSTI. 24 manufacturing industries	Trade and technology affect relative wages in the same direction. A positive relation between innovation and wage differentials is found.	5	2	12
USA	Troske (1997)	Manufacturing technologies and computer investment in the plant	118320 individuals from the WECD (LRD and 1990 census) and the 1988 SMT	No effects of plant computer presence conditional on plant characteristics	1	1	11
USA	Autor, Katz and Krueger (1998)	Whether computer use leads to a demand shift in favour of college graduates relative to high-school graduates	Current population survey, National income and Product accounts, and two databases on computer use to document the growing utilization of computers among higher skilled in the workplace	An analysis of aggregate changes in the relative supply, wage and wage-bill share of college graduates over the period 1940-1996 suggests strong relative demand growth favouring highly educated workers. Within-industry skill-upgrading accelerated in industries with high levels of computer utilisation	1	1	12
USA	Krueger (1993)	Whether or not workers use a computer at work	Detailed worker data on characteristics like education, age etc.	Up to a 15% wage premium	1	1	12
USA	Dickens and Katz (1987)	R&D intensity	1983 CPS and industry level measures of technology	Positive impact of R&D on wages, especially for non-union workers	1	2	11

Table A4 (Cont'd): WAGE SHARE STUDIES WITH TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Technology Proxy[3]	Skill Proxy[2]
USA	Loh (1992)	Industry level R&D and equipment age	CPS 1983 matched to some industry level data	Positive effect of innovaiton on hourly wage, particularly in union sample	1	2	
USA	Bartel and Sicherman (1999)	Five measures of technology are utilized: (1) total factor productivity; (2) ratio of investment in computers to total investment; (3) ratio of R&D funds to net sales; (4) number of patents used; (5) scientists and engineers in total employment by industry	Micro-level data from the National longitudinal Survey of Youth, a sample of 12.686 individuals	Wage premium with regard to technical change is primarily due to the employment of skilled workers. An educational premium associated with technical change is the result of a greater demand for the innate ability or unobserved characteristics of more educated workers	1	4	1222
USA	Dunne, Haltiwanger and Troske (1996)	Change in R&D stock, IT applications and implementation of 17 types of new technologies	1820 manufacturing plants 1972-1988	The relation between the change in non-production workers wage bill and employment share and R&D is significant and positive.	2	1,2	22
USA	Dunne and Schmitz (1995)	Use of advanced computer based machinery, nature of manufacturing at plant and average product price	6909 plants 1988 from survey of manufacturing	Plants using advanced technologies pay highest wages and emply largest proportion of skilled workers. Technology use reduces size wage premiums up to 60%.	2	3	12

Table A4 (Cont'd): WAGE SHARE STUDIES WITH TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Technology Proxy[3]	Skill Proxy[2]
USA	Doms, Dunne and Troske (1997)	Indicators for the adoption use of 17 advanced manufacturing technologies in more than 10.000 plants	Detailed worker data on characteristics like education, age etc.	Technology wage premium ranging from 6 to 15% depending on sub-sample and set of control variables; technology wage premium substantially muted when detailed worker and plant controls are included.	2	4	22
USA	Holthausen, Larcker and Sloan (1995)	1987-1990 industry patents	1982-1984 confidential survey of the divisional CEO compensation in the US	Weak postive effect of patents on the proportion of long-term to total compensation	3	2	22
USA	Siegel (1995)	Introduction of various kinds of manufacturing technologies and R&D intensities.	79 long island manufacturing firms 1987-1990. Data are divided in 6 skill groups	Positive effect of technology on skill composition of employment and wage bill shares.	3	2,4	11
USA	Bresnahan (1999)	Use and application of computers and ICT	Several detailed studies on use and application of computers and ICT	Technical change has been skill-biased. Four subsequent results have been occurred: (1) computer decision making has substituted for human decision making in modest cognitive tasks; (2) computers in organizations have been complementary to cognitive skill; (3) organisational computing has been complementary to people skills; and (4) changes have come at the time and in industries where organisational computing has had its largest impact.	4	1	22

Table A4 (Cont'd): WAGE SHARE STUDIES WITH TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Technology Proxy[3]	Skill Proxy[2]
USA	Harrigan and Balaban (1999)	Capital Intensity	CPS 1964-1992 3-digit industries	The impact of trade on wages is less important than the impact of technical change in explaining returns to skills	4	3	11
USA	Goldin and Katz (1998)	Information on electricity use and the capital stock and employment by broad occupational categories and production and non-production workers	Industry level data from 1909-1940 broken down by high- and low-education and capital and not-capital intensive industries	Technology-skill and capital-skill complementarity was already present from 1909 on. There is also a positive correlation between changes in capital intensity and the non-production worker wage bill	4	3	22
USA	Allen (1996)	R&D intensity, growth in capital labour ratio, age of capital, TFP and S&Es	Individual level data from CPS 1979 and 1989 combined with industry level data on technology (39 industries)	Levels and changes in return to schooling and education are significantly related to R&D, high-tech capital, and K/L acceleration	4	2,3,4	11
Several OECD Countries	Desjonqueres, Machin and van Reenen (1999)	Computer Use	UNISD and OECD data 1970-1990	Little support for basic H-O model. Wage inequality is unrelated to trade.	6	1	22
USA	Krusell et al. (1997)	New Capital Equipment	CPS	Capital Skill complementarity can explain the bulk of the SBTC responsible for wage divergence despite supply increases	6	3	12

Table A4 (Cont'd): WAGE SHARE STUDIES WITH TECHNOLOGY PROXY

Countries	Authors	(Skill-biased) technology measure	Data	Results	Aggregation Level[1]	Technology Proxy[3]	Skill Proxy[2]
WITH R&D SPECIFICATION							
GBR	Hildreth (1998)	Number of product and process innovations	Detailed worker data on characteristics like education, age etc.	In examining product demand and process technology, evidence is found that new process technology leads to higher wages (rent sharing)	1	2	0
ESP	Martinez-Ros (1998)	Process and product innovation	Spanish panel of 1306 manufacturing firms 1990-1994	Significant positive effect on wages when firms do both product and process innovation	3	2	11

[1] Aggregation level
- 1: job or worker level
- 2: establishment level
- 3: firm level
- 4: industry level
- 5: sector level
- 6: national level

[2] Skill Proxy
- 11: educational attainment in years
- 12: educational attainment aggregated into low-high skill
- 21: occupational classification
- 22: occupational classification into blue collar-white collar

[3] Technology Proxy
- 1: computerisation
- 2: R&D
- 3: capital goods
- 4: other