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1 Introduction

Technological change is taken for granted for almost all production functions. Yet in most discussions of human capital including the current debate over widening skill differentials, it plays no role. It is rarely even discussed.[1] In this paper we consider a country's education system and on-the-job training environment as a set of production functions that produce human capital. The important innovation is that technological change in the production functions associated with any level of education or on-the-job training is permitted and the rate of change may be different at different levels. This, along with selection into particular levels of schooling or post-schooling investment, has important implications for growth and wages. These implications include a substantial role for technological improvement in human capital production in the United States for the period 1975-2001 that results in an underestimation of the true labor input and consequently of the role that human capital has played in growth over that period. In addition, it yields a price series for the labor input that is substantially different from previously estimated aggregate wage series and results in a new explanation for the path of the college premium in the United States.

Allowing technological change in human capital production functions makes explicit a fundamental identification problem for measuring human capital and its price. In the literature on the college wage premium, for example, the *absence* of technological change is implicitly assumed to provide identification of the relative price of "college" and "non-college" human capital. In this paper we assume, to the contrary, that technological change has taken place in the human capital production functions like all other production functions, and seek to provide initial

[1]This literature is exhaustively surveyed in the recent Handbook of Labor Economics chapter by Katz and Autor (1999). The broad survey covers a great variety of influences on the wage structure over time but makes no mention of possible technological change in human capital production.

estimates of the possible magnitude of this change and hence its contribution to growth. At the same time we provide estimates of the stocks of human capital and the price paid by firms for it that can be used in aggregate models to explain growth, wages and technological change in human capital production functions.

The approach taken here is in the same spirit as recent work on estimating a true price series for computers based on an underlying constant standard of computations per second. An important part of the work is the choice of this standard for human capital. Given the usefulness of an aggregate measure of human capital, an ideal framework is the efficiency units approach since this produces a single price and quantity, avoiding any aggregation issues. This approach has a long history in human capital studies, going back to at least Ben Porath (1967), and formed the basis of much of the structural estimation of human capital production functions. It became less popular in the 1990's when it was apparently inconsistent with the rising "skill premium" during that period.[2] However, as shown below, this inconsistency disappears when the implicit assumption of zero technological change in human capital production functions is relaxed. Moreover, an efficiency units model, that incorporates technical change and selection in a simple and intuitive cohort based form, is consistent with the post-war path of the skill premium including both the well known increase in the 1990s, and the less well known decomposition pattern of the change in the skill premium by age.

We argue that the efficiency units approach, simply amended to take account of technical change and selection, is much less restrictive than it at first appears. We subject this amended framework to empirical tests based on methods previously used to estimate heterogeneous human capital prices. The results of these tests provide evidence to support the single price assumption as a valid characterization of the US data for 1975-2001, even in the period when the gap in average wages of skilled and unskilled workers widened considerably.

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[2]As late as 1996, Card and Lemieux (1996) still considered the approach useful arguing that "a one dimensional skill model provides a reasonably accurate, although oversimplified, description of changes in the structure of wages for white men and women between 1979 and 1989." (p. 319)

The theoretical framework is a simple model of optimal human capital investment in an environment of heterogeneous initial endowments of human capital and human capital production functions at different levels of the education system and on-the-job training that are subject to technological change. The estimates of the labor input price and quantity in this paper are derived in such a way that it is not necessary to parameterize and explicitly estimate the full structural model. This approach allows us to answer a number of important questions concerning wage and human capital patterns and to provide initial estimates of the potential magnitude of technological change in human capital production functions in the United States for 1975-2001.[3]

Section 2 outlines the theoretical framework and identification issues. The primary identification strategy is the use of a "standard" group of workers that have only their "initial endowment" of human capital and are thus unaffected by technological change in human capital production functions. An alternative approach employed in Heckman, Lochner and Taber (1998), that essentially assumes a known "flat spot" in the life-cycle path of an individual's human capital supply, can produce a similar series. Heckman, Lochner and Taber (1998) adopt a heterogeneous human capital model and permit two prices to be identified by the flat spot approach applied separately to the college and non-college group. Our application of the flat spot approach provides evidence to support the homogeneous human capital model since it shows little evidence of any change in "relative prices" for the human capital of college graduates compared to high school drop-outs. Given the maintained assumption of a single price, the problem of human capital measurement is greatly simplified conceptually and measures of human capital stocks for any group of workers are readily computable from wage observations.

In Section 3 the estimating framework is specified. The framework can nest alternative methods of identifying human capital prices and quantities, including composition adjusted

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[3]Future work will estimate a more fully specified structural model that can be used to generate the estimated path of human capital investment and observed wages and to separately identify technological change parameters in the human capital production functions and selection effects.

aggregate wage and hours measures. The identification assumptions are explicitly given and the interpretation of what is identified is discussed. Section 4 presents the estimates of the efficiency units price for the United States for 1975-2001 obtained from the March Current Population Surveys for 1976-2002. The series shows a very strong decline from 1975 to 1993, followed by a partial recovery. Over the full period the decline in the efficiency units price is almost 70% larger than that of the aggregate wage measure. Accounting for technological change in human capital production and endogenous choice of human capital investment therefore produces a major difference in the time path of the price of the labor input over the 1975-2001 period.

In Section 5 estimates of the total input of efficiency units are presented and compared with a sophisticated measure of the aggregate labor input. Both measures increase greatly over the period due to population increase and increasing average educational attainment, but the efficiency units measure that allows for technological change results in a total labor input in 2001 that is larger than the aggregate labor input measure by 16-18%. This has important implications for the sources of growth over this period.

Estimates of the cohort patterns of efficiency units per worker by education group are consistent with substantial technological improvement in human capital production functions, and provide a new explanation for the college premium. The overall pattern is consistent with a model that posits technological improvement in human capital production, including the college level, and implies negative selection in periods where the college graduate fraction increases in successive cohorts due to the drawing into this group from increasingly lower points in the initial endowment distribution. In the period of the pre-war birth cohorts, successive cohorts had increasingly larger fractions of the cohort in the college graduate group, continuously lowering the average initial endowment of this group. This reduction in initial endowment masked the technological improvement at the college level in the 1970s and 1980s. By 1990, however, the negative selection effect was largely eliminated by the stabilization of the post-war cohort fractions going to college and the dominance of the newly stabilized cohorts in the total labour force so that the technological improvement became apparent. Measures of these cohort patterns are presented in Section 6. Some preliminary conclusions and discussion of future work is presented in Section 7.

2 Technical Change in Human Capital Production Functions and Optimal Investment in Human Capital

Wages and the Price of Human Capital

In standard human capital models with competitive firms the hourly wage is the product of a price and a quantity:

$$w_{it} = \lambda_t E_{it} \quad (1)$$

where E_{it} is the amount of human capital supplied to the firm (number of efficiency units) by worker i in time period t, and λ_t is the rental price paid for renting a single unit of human capital (the price of an efficiency unit). [4] The hourly wage is observed, but its two components are not. This is the fundamental under-identification property of human capital models.

In a homogeneous human capital model there is a single price, λ, and wages differ across workers in any given time period because of differences in the amount of (homogeneous) human capital they are supplying. Over time a worker's wage could change either because of a change in the quantity of efficiency units he/she supplied, or because of a change in the efficiency units price. Over time, *relative* wages between any two observable "types" of workers reflect only relative changes in quantity supplied by each type since there is a single price. This is the main consequence of the efficiency units approach in a homogeneous human capital model. If selection and technical change in human capital production are assumed to be zero, relative wages between "types" could never change. However, with technical change and selection relative wages can change and will reflect the combination of technological change and selection

[4]The number of efficiency units supplied to the firm does not have to equal the human capital stock of the worker since the worker may be investing some human capital to augment his/her stock.

effects.

In heterogeneous human capital models, an efficiency units approach is retained within some exogenously defined worker "type" (e.g. college degree) but is abandoned across types. With two worker types (e.g. college and non-college) there are two factors and two prices with wages given as follows (suppressing the subscripts for convenience):

$$w^a = \lambda^a E^a \qquad \text{and} \qquad w^b = \lambda^b E^b$$

where λ^a and λ^b are the prices of efficiency units of type *a* and *b*, respectively, and E^a and E^b are the number of efficiency units of type *a* supplied by a type *a* worker, and the number of efficiency units of type *b* supplied by a type *b* worker, respectively. Within type, the wage implications are the same as the homogeneous human capital model. For relative wages across types the implications are potentially different. Since there are now two prices, changes in relative wages between two types will reflect changes in relative quantities E^a/E^b and changes in relative prices λ^a/λ^b . However, heterogeneous models in the skill premium literature implicitly assume that E^a and E^b are constant.

Any change in relative wages, w^a/w^b, is consistent with either model. In the homogeneous model the model assumptions imply that the change in relative quantities can be inferred from the change in relative wages. In the heterogeneous model, with the implicit assumption of no change in quantities, the change in relative prices can be inferred from the change in relative wages. Since any pattern of relative wages is consistent with both models, other criteria are needed to judge between them.[5] Since technological change is taken for granted in almost all other production processes, it would seem extreme to rule it out for human capital. In addition,

[5]In practice neither approach is expected to be an exact reflection of reality. In heterogeneous human capital models, for example, skill definitions are quite arbitrary and are usually based on a simple count of the number of years of schooling. Above and below some cutoff, efficiency units prevail.

the essence of human capital theory is that human capital investment is chosen optimally, with individual heterogeneity having long been recognized as important in this context. The model we propose is a homogeneous human capital model with both these features and the evidence we present later in the paper shows that such a model, which also retains the major advantage of simple aggregation, can explain important wage patterns as well or better than alternative approaches.

The Price and Quantity of the Human Capital Input

The benefits of a homogeneous human capital model, amended to include selection and technological change in human capital production, are many. The simplicity and ease of aggregation are a major advantage for the purposes of comparing human capital stocks across time or countries or assessing the contribution of human capital to growth. Of particular interest for this paper, the model provides a simple framework in which approaches to identifying technological change in human capital production can be explored.

The single price feature is a major advantage in providing an elegant solution to the problem of defining an aggregate wage.[6] The single type feature provides a similarly elegant solution to the problem of defining an aggregate quantity. If human capital is heterogeneous and the types are observationally identifiable by, say, education level, there is in fact little to be gained by arbitrarily aggregating the different types. Indeed, since the types are different factors of production, from a production function point of view the types can no more be sensibly added than adding kilowatts of electricity and hours of "unskilled" labor. There is no common unit for the addition. If human capital is homogeneous, however, these problems are avoided and the simplicity of a single labor input for aggregate models is gained.

We show below that an efficiency units model that incorporates technical change and

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[6]In fact, one way of viewing the efficiency units price estimated in this framework is as the end point of successive refinements in constructing an aggregate wage. See Section 4 below.

selection in a simple and intuitive cohort based form, is consistent with the post-war path of the skill premium including both the well known increase in the 1990s, and the decomposition pattern of the change in the skill premium by age. This removes perhaps the most serious problem with using a homogeneous human capital model. However, there are two other arguments that may have caused some previous researchers to forsake the homogeneous model despite its major advantages of simplicity and natural aggregation. One argument is that it appears too restrictive to think of production functions as treating human capital as homogeneous. However, for the purposes of pricing human capital it is less restrictive than it appears. Here, the required assumption is not that in all production processes human capital is homogeneous, only that there is a sufficient number of firms using these processes to make them the marginal firms - i.e. to set the relative prices.[7]

The second argument is that, given the change in the college premium over time, it would be too much of a coincidence for this to be explained by a homogeneous model with changing "relative quality" of college workers, as the relative quality change would have to be "by coincidence" exactly equal to the relative wage change. By analogy, suppose we observed a commodity - tomatoes - being sold in a foreign market in two different container sizes, large and small. Suppose that unknown to us this market used an imperial system of weights and that what we identify as "large" and "small" are in fact- 1lb and 1oz containers. Suppose further that consumers regard the commodity as homogeneous and buy the commodity by weight. They have no preference for the containers and thus the market price ratio is 16:1. Over time the country moves to a decimal system and the containers become 500 grams and 25 grams. We still see large and small containers but now the price ratio is 20:1. The new price ratio *by construction* must be exactly equal to the new quantity ratio. The observer would be in error if he/she

[7]That is, if there are two types or workers whose human capital is homogeneous for the production function for these firms, but heterogeneous for the production function for other firms, the pricing of the inputs will be set by the first set of firms at the ratio of the efficiency units in their process such that they are indifferent across types of workers. The remaining firms will then hire the two types such that the ratio of their marginal products in the "heterogeneous" production function is equated to the ratio of the prices.

concluded that there were two heterogeneous commodities and that relative prices must have changed. This outcome is a consequence of the change in the relative container sizes and the fact that the relative quantity change exactly mirrors the relative price change is not a *coincidence*, likely or unlikely, but a certain *consequence* of the fact that the commodity is homogeneous. The real issue is whether the implied quantity changes have a structure that appears reasonable. In the case of the college premium we argue below that it does.

The major innovation we propose is to characterize a country's education and on-the-job training environment as a set of human capital production functions that are subject to technological change over time in the same way as other production functions. This has important implications for human capital prices and quantities. However, for the estimation of these prices and quantities using the methods employed in this paper, no restrictions need be placed on the production functions since the parameters that are estimated are not the underlying structural parameters of the production functions, though they are related to them. While the production functions are different and may change over time, there is a single output: efficiency units of human capital.[8]

The worker's problem is standard and relatively straightforward.[9] All workers of a given

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[8]This is key for an examination of technological change in human capital production functions. Many previous authors have defined "aggregator functions" to map heterogeneous inputs into an aggregate labor input, but discussions of these functions make it clear that there are multiple heterogeneous labor inputs and the parameters of the aggregator function should be viewed as parameters of the output production function. Card and Lemieux (1996) is a recent example, where they discuss technological changes affecting the "relative productivity" differences across education groups. The example they give is that "advances in computer technology may lead to larger productivity gains for relatively highly-skilled workers." (p. 322)

[9]Heckman, Lochner and Taber (1998) were the first to propose and estimate a general equilibrium dynamic structural model in which workers chose optimal human capital investments over the lifecycle, taking into account the time path of rental rates on human capital. Our model is in a similar spirit but is greatly simplified by the homogeneous human capital assumption leading to a single price and the separate identification of the price from a standard unit.

cohort are assumed to draw from an "initial endowment" distribution of human capital.[10] They can add to this endowment by producing human capital via the production functions that characterize the education system and on-the-job training environment that the cohort faces. Since there is only one type of human capital, there is no choice of which type of human capital to invest in. The only choice is the amount of investment each period and the production function according to which it should be produced - schooling or on-the-job training. Since there is only one price, the worker only has to consider a single price in evaluating the returns. The optimizing behaviour implies that human capital investment choices depend on the initial endowment and the time path of the price of an efficiency unit, and this is taken into account in the interpretation of the estimated parameters.

Identifying the Price and Quantity

Standard Unit Method

The basic approach to identification is to find a "standard" unit of human capital that is the same across time. In that case, observing the wage paid for a standard unit at different points in time identifies the price change. This is similar to the notion of finding a time invariant common unit for computers. The solution in the computer case was to assume that the common unit that represents the factor provided by all computers is calculations per second. That is, calculations per second are the efficiency units. The relevant price is the price of a "standard" computer defined as having a given number of calculations per second. Given the assumption of the common unit, the problem in the computer case is made very simple by the fact that computations per second can be observed so it is not necessary to actually observe "standard" computers over time to identify the relevant price. In the human capital case it is necessary to observe a standard unit over time because efficiency units are not directly observed.

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[10]In a more general model, workers may also draw from a distribution of idiosyncratic production function parameters which would allow for "comparative advantage" at different types of production, mimicking some aspects of a Willis and Rosen (1979) model, even though there remains a single type of human capital.

The computer case was motivated by the fact that the typical "box" on an employee's desk five years ago could do much less than the typical box now, even though the box today may cost a lot less. It would not make any sense to try and measure the computer input by reference to the price since that went down when the input in a production function sense obviously went up. This change in the amount of input contained in the typical box on an employee's desk came about through major technological change. The number of efficiency units associated with a given observable container or box changed dramatically. Since efficiency units could be observed, this technical change in the box could be measured. In the human capital case the issue of what is in the box (i.e. the worker defined by observable characteristics) is affected by both technical change and selection. The model structure assumes that human capital comes from two sources: an initial endowment and subsequent production by schooling and on-the-job training. We assume that the initial endowment distribution is relatively slow to change.[11] Given a stable initial endowment distribution and no selection in schooling level, the ideal standard unit would be the type of worker that had no exposure to any human capital production functions, retaining only their initial endowment - no schooling and no experience. Of course, given the specification of the worker's problem there will be endogenous selection of schooling levels. Selection effects *per se* do not present a serious problem, but any change over time in the selection effects for this group would be a problem.[12]

The Flat Spot Method

The flat spot method, proposed in Hechman, Lochner and Taber (1998), is based on the fact that most optimal human capital investment models have the feature that at some point in the

[11]This is an assumption to be explored in the future. The rationale for assuming relatively slow change is the idea that this evolution is primarily genetic and that this is a slow process. However, in practice the operational form of the initial endowment may be influenced by other factors such as nutrition, that at least in some periods may have a faster rate of change.

[12]Examination across cohorts of the fraction in the key identifying group specified in Section 3 suggests that any selection problem would be minor.

working life-cycle, optimal investment must be zero. If there is a period of years in which this occurs and in which depreciation is zero, by assumption the human capital of a given cohort over those years will be constant. That is, there will be a flat spot in the human capital life-cycle profile. Observing the changes in average wages for the cohort over the flat spot will, therefore, identify the human capital price changes. Provided such flat spots exist, this method can be used with any skill group to identify skill prices. The primary drawback of this method is that the flat spots, if they exist, are unknown. In addition, theoretical considerations suggest that any flat spot that does exist is unlikely to be the same for all schooling groups.

3 General Estimation Framework

Consider first the log efficiency units and log wage equations for observations with "zero" schooling (D = 0) for all possible experience groups from a repeated cross section, such as the March Current Population Survey (MCPS). For simplicity consider a three period model. There are three experience groups identified by T0 = 1 if experience is zero, T1=1 if experience is one year (period) and T2=1 if experience is two years. Sample observations for this group occur only at these three levels of experience. Retirement takes place beyond two periods of experience. Assume three years (periods) of observations identified by, Y0=1, Y1=1 and Y2=1. Define:

$E(\ln E_j |\ Tk_j=1, Y0=1, D_j=0) = \theta_{k0}$ $\qquad$ $E(\ln w |\ Tk_j=1, Y0=1, D_j=0) = \theta_{k0}$

$E(\ln E_j |\ Tk_j=1, Y1=1, D_j=0) = \theta_{k1}$ $\qquad$ $E(\ln w |\ Tk_j=1, Y1=1, D_j=0) = \theta_{k1} + \ln\lambda_1$

$E(\ln E_j |\ Tk_j=1, Y2=1, D_j=0) = \theta_{k2}$ $\qquad$ $E(\ln w |\ Tk_j=1, Y2=1, D_j=0) = \theta_{k2} + \ln\lambda_2$

where k = 0,1,2.

The efficiency units are the efficiency units actually *supplied* which, of course, can be different from the worker's total stock. The θ parameters reflect the optimizing behaviour of the workers as outlined in the previous section. The mean efficiency units of any experience group (and hence, for a given year, any cohort) can be different in different years to reflect the differences in both the optimal choices of human capital investments and the set of human capital production functions that the cohort faced. That is, the conditional means can be different not only because the output from the production functions can change over time but also because the optimal time inputs for on-the-job training can change and the efficiency units that are paid for are those that are *supplied* in a given period. The relation between these θ parameters and an underlying structural model is complicated and dependent on an explicit version of the structural model. However, for the purpose of identifying the price series $ln\lambda$, it is not necessary to specify a full structural model.

There are 11 parameters to estimate - the 9 conditional means of efficiency units for each of the three experience groups for each of the three years and the log prices for year 1 and year 2 (the log price for year zero being normalized to zero). Pooling the observations for all years and groups: (the idiosyncratic error terms are suppressed for simplicity)

$$
\begin{aligned}
\ln w_j = {} & \theta_{00} + (\theta_{10} - \theta_{00})T1_j + (\theta_{20} - \theta_{00})T2_j \\
& + [(\theta_{01} - \theta_{00}) + \ln\lambda_1]Y1_j + [(\theta_{02} - \theta_{00}) + \ln\lambda_2]Y2_j \\
& + [(\theta_{11} - \theta_{10}) - (\theta_{01} - \theta_{00})]T1_jY1_j + [(\theta_{12} - \theta_{10}) - (\theta_{02} - \theta_{00})]T1_jY2_j \\
& + [(\theta_{21} - \theta_{20}) - (\theta_{01} - \theta_{00})]T2_jY1_j + [(\theta_{22} - \theta_{20}) - (\theta_{02} - \theta_{00})]T2_jY2_j
\end{aligned}
$$

This yields 9 equations in the 11 unknowns. The prices are not identified because changing the year of observation, holding experience constant, changes the cohort. In this three period model define the cohorts as Y-T, then for the years Y0, Y1 and Y2, the cohort representation and experience level in the sample is:

Cohort	Y0	Y1	Y2
-2	T2		
-1	T1	T2	
0	T0	T1	T2

1		T0	T1
2			T0

Thus, θ_{10} and θ_{21} are both cohort -1; θ_{00}, θ_{11} and θ_{22} are all cohort 0, θ_{01} and θ_{12} are cohort 1; θ_{20} is cohort -2 and θ_{02} is cohort 2.

If there were no cohort effects, $\theta_{00} = \theta_{01} = \theta_{02}$, $\theta_{10} = \theta_{11} = \theta_{12}$, and $\theta_{20} = \theta_{21} = \theta_{22}$. The equation would then reduce to:

$$\ln w_j = \theta_{00} + (\theta_{10} - \theta_{00})T1_j + (\theta_{20} - \theta_{00})T2_j + \ln\lambda_1 Y1_j + \ln\lambda_2 Y2_j$$

and the prices would be identified. This would be an extremely strong assumption since, among other things, it rules out any technological change in the human capital production functions or endogenous selection effects in response to any changes over time that affect educational choice.[13] In fact, it is much stronger than is needed for identification. Consider the two approaches discussed in Section 2: the standard unit method and the flat spot method.

Standard Unit Method

The requirement for identification of the price using the standard unit method is that the conditional mean for the initial endowment only group ($D_j = T1_j = T2_j = 0$) is time invariant, i.e. that $(\theta_{01} - \theta_{00}) = 0$ and $(\theta_{02} - \theta_{00}) = 0$. This defines the initial endowment group as the standard unit. Thus cohorts could face different school and post-school production functions and have different selection into higher schooling levels as long as this condition is met. The equation imposing only this assumption becomes:

$$\ln w_j = \theta_{00} + (\theta_{10} - \theta_{00})T1_j + (\theta_{20} - \theta_{00})T2_j + \ln\lambda_1 Y1_j + \ln\lambda_2 Y2_j$$

[13]In effect, however, this is the implicit assumption in the construction of many forms of aggregate wage index.

$$+ (\theta_{11} - \theta_{10})T1_jY1_j + (\theta_{12} - \theta_{10})T1_jY2_j + (\theta_{21} - \theta_{20})T2_jY1_j + (\theta_{22} - \theta_{20})T2_jY2_j$$

Since this specification is completely general with full interactions between all the cells, the identical price series is estimated from the coefficients on the year dummy variables either using the initial endowment sample only in a regression that excludes all but the year dummies, or by pooling all the observations for all the experience groups and estimating the full equation.[14]

The pooled estimates also estimate changes over time in the conditional means of all the experience groups other than the initial endowment group. The pattern of these changes reflect, among other things, the pattern of production technology changes over time in the post-school investment production function which are of interest in themselves. The T1 coefficient ($\theta_{10} - \theta_{00}$) shows the amount added to efficiency units for those that acquire a unit of experience in period 0. By definition this can only be one cohort. The sum of the T1 and T1Y1 coefficients ($\theta_{11} - \theta_{00}$) shows the amount added to efficiency units for those that acquire a unit of experience in period 1. Again, by definition this can only be one cohort, and in fact a different cohort from the previous one. The difference between the two amounts ($\theta_{11} - \theta_{10}$) shows the improvement in the post-school technology (or the difference in the actual amounts invested) faced by the later cohort. It is not, of course, necessary to pool the data to obtain estimates of these technology changes, since they can be obtained from wage data for the other groups once the price has been estimated on the initial endowment group observations. The pooled estimation simply provides all the estimates simultaneously.

The above model applies to the "zero" schooling group, but this may be pooled with other schooling groups to jointly estimate the prices and the pattern of production function changes and/or selection effects associated with schooling. The addition of schooling adds the minor complication that schooling takes time and shifts the relation between cohorts and experience, but does not affect identification of the price series.

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[14]The advantage of pooling is only smaller standard errors that follow from a common variance in the error term; the point estimates by construction are the same.

Suppose we have a "positive" schooling level indicated by D=1 and that schooling takes one period. Assume for simplicity that schooling has the same effect on the efficiency units of all individuals in the same cohort. Then define the relevant conditional means for the D=1 group as:

$E(\ln E_j | Tk_j=1, Y0=1) = \delta_{k0}$ $\quad$ $E(\ln w | Tk_j=1, Y0=1) = \delta_{k0}$

$E(\ln E_j | Tk_j=1, Y1=1) = \delta_{k1}$ $\quad$ $E(\ln w | Tk_j=1, Y1=1) = \delta_{k1} + \ln\lambda_1$

$E(\ln E_j | Tk_j=1, Y2=1) = \delta_{k2}$ $\quad$ $E(\ln w | Tk_j=1, Y2=1) = \delta_{k2} + \ln\lambda_2$

Pooling just the D=1 observations, and assuming restrictions on the sample by experience, the wage equation is:[15]

$$\begin{aligned}\ln w_j = {} & \delta_{00} + (\delta_{10} - \delta_{00})T1_j + (\delta_{20} - \delta_{00})T2_j \\ & + [(\delta_{01} - \delta_{00}) + \ln\lambda_1]Y1_j + [(\delta_{02} - \delta_{00}) + \ln\lambda_2]Y2_j \\ & + [(\delta_{11} - \delta_{10}) - (\delta_{01} - \delta_{00})]T1_jY1_j + [(\delta_{12} - \delta_{10}) - (\delta_{02} - \delta_{00})]T1_jY2_j \\ & + [(\delta_{21} - \delta_{20}) - (\delta_{01} - \delta_{00})]T2_jY1_j + [(\delta_{22} - \delta_{20}) - (\delta_{02} - \delta_{00})]T2_jY2_j\end{aligned}$$

This again yields 9 equations in the 11 unknowns. The prices as before are not identified from this sample because changing the year of observation, holding experience constant, changes the cohort. For this sample (D=1) it is not appropriate to impose any restrictions on the cohort effects since in this case they pick up changes in schooling technology and selection effects for schooling. Instead we pool this sample with the sample for D=0 where identification was

[15]If the sample is restricted by age at the upper end, this is a restriction by cohort and will reduce the range of experience for the D=1 group in this three period model to 0 and 1. The (Y2) observations are deleted since these workers are above the age range. If the sample is restricted by years of experience the observations are included. For large number of periods these will be approximately the same. The equations above include the observations -i.e. working lives are the same across schooling groups. For a multi-period model, only the end periods would be affected by this assumption.

obtained using the standard unit method by imposing $(\theta_{01} - \theta_{00}) = 0$ and $(\theta_{02} - \theta_{00}) = 0$:[16]

$$
\begin{aligned}
\ln w_j = {} & \theta_{00} + (\theta_{10} - \theta_{00})T1_j + (\theta_{20} - \theta_{00})T2_j + \ln\lambda_1 Y1_j + \ln\lambda_2 Y2_j \\
& + (\theta_{11} - \theta_{10})T1_jY1_j + (\theta_{12} - \theta_{10})T1_jY2_j + (\theta_{21} - \theta_{20})T2_jY1_j + (\theta_{22} - \theta_{20})]T2_jY2_j \\
& + (\delta_{00} - \theta_{00})D_j + [(\delta_{10} - \delta_{00}) - (\theta_{10} - \theta_{00})]T1_jD_j + [(\delta_{20} - \delta_{00}) - (\theta_{20} - \theta_{00})]T2_jD_j \\
& + (\delta_{01} - \delta_{00})Y1_jD_j + (\delta_{02} - \delta_{00})Y2_jD_j + [(\delta_{11} - \delta_{10}) - (\delta_{01} - \delta_{00}) - (\theta_{11} - \theta_{10})]T1_jY1_jD_j \\
& + [(\delta_{12} - \delta_{10}) - (\delta_{02} - \delta_{00}) - (\theta_{12} - \theta_{10})]T1_jY2_jD_j \\
& + [(\delta_{21} - \delta_{20}) - (\delta_{01} - \delta_{00}) - (\theta_{21} - \theta_{20})]T2_jY1_jD_j \\
& + [(\delta_{22} - \delta_{20}) - (\delta_{02} - \delta_{00}) - (\theta_{22} - \theta_{20})]T2_jY2_j\, D_j
\end{aligned}
\tag{2}
$$

The advantage of computing estimates in this way is that it is largely independent of any specific structure and is non-parametric in the sense of being based only on cell means. The underlying behavioral model implies that higher schooling choice is positively related to an individual's initial endowment and therefore that the mean of the initial endowment group cannot be expected to be generally time invariant if the equilibrium outcome results in some cohorts having a smaller fraction in the "zero" schooling group. A variety of factors including the expected time path of the price of human capital will affect the schooling choice and hence the path of the equilibrium fraction in the initial endowment group. The identification strategy requires the mean initial endowment of the initial endowment group to be time invariant. If the fraction in the initial endowment group varies substantially by cohort over the observation period, there would have to be some doubt over the validity of the identifying assumption. This is examined below.

Flat Spot Method

The flat spot method is equivalent to an alternative set of restrictions on the θ and δ parameters. In terms of the three period illustrative model for the zero schooling group, suppose

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[16]Again, it is obviously not necessary to actually pool the data from the higher schooling groups since all these parameters can be recovered from the wage data for these groups once the price series is obtained from estimation on the initial endowment observations.

the flat spot occurs in the last two experience periods, T1 and T2. The price change from Y0 to Y1 can then be estimated by aging the -1 cohort from T1 to T2 over Y0 and Y1 since, by assumption, efficiency units for this cohort will be the same across T1 and T2. Similarly, the price change from Y1 to Y2 can be estimated by aging the 0 cohort from T1 to T2 over Y1 and Y2. In terms of the conditional means:

$$E(\ln w|\ T2_j{=}1, Y1{=}1, D_j{=}0) - E(\ln w|\ T1_j{=}1, Y0{=}1, D_j{=}0) = (\theta_{21} - \theta_{10}) + \ln\lambda_1 = \ln\lambda_1$$

and

$$\begin{aligned} E(\ln w|\ T2_j{=}1, Y2{=}1, D_j{=}0) - E(\ln w|\ T1_j{=}1, Y1{=}1, D_j{=}0) &= (\theta_{22} - \theta_{11}) + \ln\lambda_2 - \ln\lambda_1 \\ &= \ln\lambda_2 - \ln\lambda_1 \end{aligned}$$

where the flat spot method assumes $(\theta_{21} - \theta_{10}) = (\theta_{22} - \theta_{11}) = 0$.

In principle, the flat spot method, unlike the standard unit method, could be used for any schooling group so that all observations across schooling groups could be pooled. Indeed, a comparison of the series obtained by applying the flat spot procedure to different schooling groups provides a test of the single price assumption. However, theoretical considerations suggest that any flat spot that exists may not be the same for all schooling groups, and in some cases a flat spot may not exist at all. This is the major problem for the flat spot approach. Moreover, in practice the flat spots, if they exist, are unknown and errors from an incorrect assumption on the position of the flat spot will typically cumulate, resulting in potentially large errors for secular analysis over several decades.[17]

Comparison of the Methods

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[17]Heckman, Lochner and Taber (1998) propose a flat spot method that yields a price series in our notation of $\lambda_0, \lambda_1(1-\sigma), \ldots, \lambda_T(1-\sigma)^T$, where σ is the rate of depreciation, assumed to be zero. If this rate was not in fact zero, the cumulative error over the 27 years of our data period in estimating the 2001 price compared to the 1975 price would result in an underestimate of the true 2001 price by 42% if the rate of depreciation was actually .02, and 24% if it was as small as .01.

For the homogeneous human capital model, the two methods are complementary. They represent alternative ways of estimating a single price series by placing different restrictions on the θ and δ parameters. The standard unit method is valid if restrictions placed *across* cohorts are valid: specifically, that there is a group whose human capital is closely proxied by their initial endowment, and whose mean initial endowment, and therefore total human capital, is constant. The group chosen is a group that is assumed either not to be exposed to human capital production functions, retaining only their initial endowment, or a group that would have negligible optimal accumulation of further human capital relative to the initial endowment so that variation across cohorts in this accumulation could be ignored.[18] The constant mean initial endowment can be checked in part by examining whether the fraction of successive cohorts in the initial endowment group for the relevant data period is constant. However, the method remains vulnerable to the possibility that the wrong group has been chosen in the sense that optimal accumulation of human capital beyond the initial endowment for the chosen group may both vary across cohorts and not be negligible.

The flat spot method is valid if restrictions placed *within* cohorts are valid: specifically, that there is a known flat spot on optimal human capital profiles. This method is particularly vulnerable to errors in specifying the unknown flat spot. Within the homogeneous human capital model, this method can provide a further check on the standard unit method through an examination of whether there exists a credible flat spot region for the initial endowment group that generates the same price series as the standard unit method.

In addition, the flat spot method applied to groups other than the initial endowment group can provide some evidence on whether the single price applicable to the standard unit is the relevant price for all human capital - i.e. whether it is necessary to specify more than one type of human capital. Since *ex ante* the price, or prices, are not known, the flat spot or spots cannot be

[18]If the average on-the-job accumulation for the group was 10% or less of the initial endowment, any change in this accumulation across the period of observation would bias the price change by a maximum of one tenth of the accumulation change.

known. Indeed, a general optimizing framework suggests that the flat spots will be different for different groups and will change over time. The test of more than one price from the flat spot method applied to different groups is therefore vulnerable to mis-specification of the flat spot regions. However, an examination of whether there exist credible patterns of flat spot regions that are consistent with a single price provides useful evidence on the issue, even if it is not a definitive test. This is examined briefly below and in more detail in Bowlus and Robinson (2004).

4 Estimates of the Price of Labor

Standard Unit Method

The data sources for the application of this method are the repeated cross sections in the 1976-2002 March files of the Current Population Survey (MCPS). Given the basic structure of the estimating equations specified above, a number of decisions have to be made to implement the standard unit procedure. The first is the empirical counterpart to the initial endowment group. The trade off here must weigh the objectives of minimizing contact with human capital production functions that may have been subject to technological change; choosing a group where the changes in the selection effects over the time period of the earnings data (1975-2001) are small; choosing a group where the worker's human capital stock is closely proxied by the amount supplied and whose addition through on-the-job training is relatively small; and choosing a group such that the sample size is sufficiently large to yield reasonably precise estimates. The group adopted here are males that have less than 12 years of schooling and are 19-21 years old.[19]

[19]As noted above, exploring the assumption of a group that is exposed to minimal change in initial endowment or human capital production functions is ongoing, and a variety of evidence on test scores and early IQ measures may be useful. There is some argument that important technological improvements have occurred in the early grades. To the extent that this is true, the price series computed here will be upward biased. The estimates of technological change in human capital production are relative to the standard unit, so these estimates would be lower bounds.

As noted earlier, the identification strategy requires the mean initial endowment of the initial endowment group to be time invariant. If the fraction in the initial endowment group varies substantially by cohort over the observation period, there would have to be some doubt over the validity of the identifying assumption. Examination of the cohort patterns shows that the equilibrium choices of the various cohorts resulted in substantial changes in the initial endowment group prior to 1975, but a stable path thereafter. In effect, there was a large reduction in the cohort fraction in the dropout group across the pre-war cohorts which had stabilized by the time of the post-war cohorts. Since the initial endowment group is "zero" experience as well as "zero" schooling, only the postwar cohorts contribute to the initial endowment group for the 1975-2001 period, so the cohort fractions for the initial endowment group are stable.[20]

The second is the functional form. For ease of comparison with much of the literature, and to avoid imposing functional form restrictions wherever possible, dummy variable sets were used for education and experience in the preferred specification, though a large variety of alternatives were explored in analyzing robustness.[21] The third is the treatment of a variety of variables that appear in wage equations, including sex, region, industry, occupation, union status, etc. This, and other details of the estimation are dealt with in detail in the appendix.[22]

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[20]Figure A1 in the Appendix shows the time path of the cohort fraction in the high school dropout group.

[21]Four education categories were used. These correspond to the usual groupings found in the previous literature. Since there is a change in the form of the education question in the January 1992 CPS, the construction of a consistent measure is important. We have followed Jaeger (1997) in generating our series. For the purpose of identifying the price series, the main concern is a consistent definition of the lowest schooling group. Inconsistency in the series for the other groups affects estimates of the magnitude of selection effects or technology change but does not bias the price estimates.

[22]The treatment of sex is particularly interesting, but from the point of view of estimating the price, restricting the initial endowment group to males avoids the necessity of deciding between a discrimination or omitted ability story for the female wage differential.

The estimated price series from the preferred specifications are shown in Figure 1. These are obtained from the most general specifications. The price series labelled *eup* uses the most general specification, which is equivalent to estimating the price series using the initial endowment group only and no regressors other than the year dummy variables, while *eups* is obtained from a slightly restricted specification. This uses all observations for both sexes and smooths the permitted path of technological change and selection effects over time by using three year grouped dummy variables for all the experience, education and education/experience interactions with time instead of single year dummy variables. Education and experience are in dummy variable form. The two series are very similar, and a wide variety of other specifications that permit reasonable flexibility for the technology/selection effects produce similar series. The price series *eup* shows a very strong decline to the early 1990s followed by a recovery. The percentage drop from 1975 to 1993 is 26% and the recovery reduces the overall drop over the 1975-2001 period to 15%. The smoother *eups* is similar with a trough one year earlier in 1992 that is 25% down from 1975, and a recovery to 2001 that reduces the overall drop to 14%.

Flat Spot Method

Consider first the use of the flat spot method as a check on the robustness of the standard unit method. This requires examination of whether there exists a credible flat spot region for the initial endowment group that generates the same price series as the standard unit method. The flat spot regions examined are chosen to correspond to the approach in Heckman, Lochner and Taber (1998). The region is chosen to be between the middle and the end of the working life, avoiding regions that may be influenced by retirement behaviour. In order to implement the method it is necessary to chose the length of the flat spot, and hence the number of cohorts that can be used to identify price changes between any pair of years, as well as its position (or, possibly, changing position over time). There is a tradeoff between the length of the flat spot and the sample size. The analysis reported in this section uses a flat spot length of 10 years, allowing the averaging of 9 cohort pairs across any two years. This is, perhaps, the minimum length that is feasible since the resulting sample sizes are not large.

Figure 2 shows the price series obtained from the flat spot method applied to the initial endowment group (*flatspot*), compared to that obtained from the raw (*eup*) and minimally smoothed (*eups*) standard unit method. The flat spot region for this group is assumed to be over the age range of 47-56. The series show strong secular similarity, differing substantially only during the recession in the early 1980s. Since the standard units method uses young workers and the flat spot method uses older workers, different behaviour of these two age groups over the cycle is a potential explanation for the observed difference over the cycle. For long run secular analysis, the series show the same basic picture. The overall 1975-2001 change is virtually identical.

In Figure 3 evidence on the single price assumption is presented. Figure 3 plots the series obtained from the flat spot method applied to the college group (*college*) compared to dropouts (*dropout*). The flat spot region for college is assumed to be over the age range of 51-60.[23] These two groups provide the strongest contrast of skilled and unskilled workers. Remarkably, the series show a very similar pattern. The correlation between the series is 0.91. The age range for the flat spot is consistent with the approach of Heckman, Lochner and Taber (1998) in choosing a period relatively late in the working life, but not too late to be contaminated by retirement behaviour. The single price assumption would be inconsistent with the data if it was not possible to generate similar price series for the college graduate and dropout groups for credible age ranges for the flat spots. The close equivalence in the series in Figure 3 is therefore evidence that the single price assumption can pass this test.

In fact, the flat spot method estimates are sensitive to the choice of age range. Figure 4 illustrates this sensitivity by plotting the series for four different potential candidates for the age range: 45-54 (*college3*); 48-57 (college2); 51-60 *(college)* and 52-61 (*college4*). The oldest group *(college4)* still has a mid-point well before age 60, yet appears substantially different from the others, even the one year younger group *(college)*. This pattern is consistent with a true

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[23]This later age range for the college group reflects the standard approach that compares experience rather than age profiles.

profile that peaks in the early 50's and declines thereafter. The earlier age series would then be biased upward due to averaging changes within a cohort over a mainly still increasing portion of the life-cycle human capital profile, and the latter series would, conversely, be biased downward because it averages over a mainly declining portion. This sensitivity suggests that the flat spot method should be used with great caution.

In summary, except for the issue of the precise cyclical pattern, the price series for the lowest schooling group obtained from the standard unit method appears completely consistent with the series obtained using the flat spot method.[24] Equally important, the series can also be approximated closely using the flat spot method applied to the highest schooling group with a credible age range. This provides evidence that the homogeneous human capital framework explored in this paper, that allows for selection and technological change in human capital production and which retains the major advantages of simplicity and readily interpretable aggregation, is a credible alternative to heterogeneous models in explaining human capital price paths.[25]

Comparison with Aggregate Wage Measures

In Figure 5 the efficiency units price is contrasted with the time path of a sophisticated measure of the aggregate wage that takes into account the changing weights of each

[24]The estimates presented in this paper abstract from issues of potential refinement such as participation and treatment of other typical wage regression variables. Participation issues are likely to be particularly important for cyclical patterns but may also affect secular paths. Blundell, Reed and Stoker (2003) examine participation effects on measures of aggregate wages for the British labour market. In addition, institutional factors such as unions and minimum wage laws may be important. These issues will be explored in future work.

[25]As noted earlier, neither the single price assumption, nor for that matter a two price model are intended as exact representations of reality. The cost of such simplifying assumptions depend on how good an approximation they provide for the relevant level of aggregation of data. The evidence presented above suggests this cost is low, at least for this period of data for the United States. This evidence is also consistent with Gould (2002) which emphasizes the increasing importance of general skills in the US economy.

schooling/experience type. In constructing aggregate wages the previous literature has been concerned with the fact that workers are different and the composition of the labor force has changed over time. The composition bias literature was especially concerned with variation in these weights over the cycle as this was a potentially important source of bias in estimates of the true wage cyclicality over business cycles.[26] The interpretation of this corrected price in the homogeneous human capital model is the efficiency unit's price. However, this price will be incorrectly estimated using any standard form of correction that uses constant weights, if there is technological change in human capital production and/or selection effects of the type discussed earlier. The interpretation in a heterogeneous human capital model is that of a price index of a basket of inputs. This again will be incorrectly estimated using a constant weights correction, if there is technological change in human capital production and/or selection effects because the qualities of the inputs in the basket will be changing. In fact, the fixed weights approach is equivalent to imposing fixed coefficients over time on the education and experience variables in our basic estimating equation (2), reducing it to: [27]

$$\begin{aligned} \ln w_j = \theta_{00} + (\theta_{10} - \theta_{00})T1_j + (\theta_{20} - \theta_{00})T2_j + \ln\lambda_1 Y1_j + \ln\lambda_2 Y2_j \\ + (\delta_{00} - \theta_{00})D_j + [\,(\delta_{10} - \delta_{00}) - (\theta_{10} - \theta_{00})]T1_jD_j + [\,(\delta_{20} - \delta_{00}) - (\theta_{20} - \theta_{00})]T2_jD_j \qquad (3) \end{aligned}$$

In Figure 5 the price series obtained from this form of estimation, denoted *adjwage*, is contrasted with the efficiency units price, *eups*. Both series show an initial decline followed by a recovery after 1993, but the magnitudes are very different. The aggregate wage or wage index shows a much smaller decline in the 1980s than the efficiency units price and remains

[26] See, for example, Bils (1985) and Solon, Barsky and Parker (1994). In earlier work (Bowlus, Liu and Robinson, 2002) we set this literature in a homogeneous human capital framework to permit a symmetric approach to correcting both the labor price and the labor quantity over the cycle, rather than correcting only the price as in the previous literature.

[27]This equivalence is discussed at length in Bowlus, Liu and Robinson (2002) where the estimating equations for a corrected labor input price found in the previous wage cyclicality literature are derived from a continuous form of equation (3).

substantially higher during the recovery in the 1990s. The overall decline in the aggregate wage or wage index from 1975 to 2001 is 8%. The overall decline of *eup* is 15%, almost double that of the decline in the composition adjusted aggregate wage. Accounting for technological change in human capital production (and/or selection into the various education groups) can therefore produce a major difference in the time path of the price of the labour input over the 1975-2001 period.

5 Estimates of the Total Quantity of Efficiency Units

Total efficiency units in any period t, for any observation j, are, by definition:

$$N_t = \sum_j E_{jt}h_{jt}$$

where E_{jt} are the efficiency units supplied per hour by observation j in period t and h_{jt} are the hours for which those efficiency units are supplied. All firms pay the same price, λ_t, for efficiency units in period t, so the hourly wage paid to observation j is:

$$w_{jt} = \lambda_t E_{jt}$$

and hourly earnings for observation j are:

$$w_{jt}h_{jt} = \lambda_t E_{jt}h_{jt}$$

hence $N_t = \sum_j (w_{jt}h_{jt})/\lambda_t$. Thus to compute a total efficiency units series the total wage payments are simply divided by the price series.

The time path of total efficiency units, *euss*, using the moderately smoothed price series, *eups,* is given in Figure 6. Not surprisingly, given increasing population and an increasingly educated workforce, the labor input shows a strong upward trend. However, some of this path is due to the combination of technological change in human capital production and selection effects. The magnitude of these effects can be estimated by comparing the path of *euss* with an aggregate labour input measure that does not take these effects into account, but which otherwise corrects for the changing education/experience composition of the labor force. A variety of approaches have been taken to construct such a labor input series that accounts for changes in composition.[28] Logically, there is always an input series corresponding to any aggregate wage series that follows from dividing the total expenditure on the labor input by the aggregate wage index. The aggregate wage indices found in the previous literature that adjust for observed composition changes follow from our basic estimating equation by imposing zero coefficients on all the time interaction terms in equation (2), so the composition corrected aggregate hours measures follow from dividing the total expenditure on the labor input by the aggregate wage index obtained from this restricted form of equation (2) given in equation (3).[29]

The comparison labor input, corresponding to the aggregate wage index obtained from estimating equation (3), is plotted as *adjhours* in Figure 6. This measure also, of course, increases with population and the increasingly educated labour force, but does not take account of technological change in human capital production and selection into the various education levels. It shows a slower rate of increase. Over the 1975-2001 period, *adjhours* increases by 109%. The measure using the unsmoothed price *eup* increases by 126%, and the smoother *euss* measure shown in Figure 6 increases by 124%. Allowing for selection and technological change results in a total labour input that is larger by 16-18 %. The underestimate of the increase in the labor input by standard composition adjusted measures has important implications for the sources of growth over this period. Technological change in human capital production may be adding more than half a percent a year to the true labor input.

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[28]See, for example, Jorgenson, Gollop and Fraumeni (1987), Kydland and Prescott (1989), Hansen (1993).

[29]The composition correction in this case implicitly uses relative wages as weights for the hours of various worker "types" where the relative wages of worker "types" are computed from averaging over 1975-2001, rather than averaging over a sub-period or choosing a base year.

The price series *eup* assumes that the standard unit had the same mean initial endowment and was not exposed to any technological improvement. Since the cohort fraction in this group was roughly constant over the period, there is some evidence to support the constant mean assumption. However, it is unlikely that the standard unit group was not exposed to any production function change. To the extent that technological improvement has occurred in the lower grades, the estimates of *euss* in Figure 6 are lower bounds. They represent the effects of technological change in the production functions relative to those in the lower grades. If, as is sometimes suggested, early education has been substantially improved, the total effect of technological change in human capital production may be considerably larger than the 16-18% estimate.

6 The Quantity of Efficiency Units per Worker by Education Group and The College Wage Premium

Efficiency units for any sub-group can easily be calculated since there is a single price. Efficiency units for any subgroup, therefore, follow from dividing total wage payments to the subgroup by this price. The strongly declining efficiency units price implies that any group that does not show equally strong growth in the efficiency units they are supplying will have a declining wage. Further, *differential* change in efficiency units supplied will result in changes in relative wages. The dropout group had no strong growth in average efficiency units to counter the price decline and suffered a decline in real wages. For example, for dropouts aged 24-65 the average real wage in the sample of paid workers dropped from $7.58 in 1975 to $6.17 in 2001. The college group increased average efficiency units enough to offset the price decline. College graduates aged 24-65 in the sample of paid workers increased from $12.88 in 1975 to $15.52 in 2001.

A detailed analysis of the source of the increase in the average efficiency units for the college group is beyond the scope of this paper. Brief examination of the cohort patterns, however, shows that the later cohorts have more efficiency units. Moreover, an inspection of the time path of the increasing efficiency units for college graduates shows that this was a slow increase while the cohort fractions of college graduates increased, and accelerated when the cohort fractions stabilized. The timing of this stabilization led to the timing of the increase in the college premium in the 1990s.

This stabilization of the cohort fractions going to college is apparent in Figure 7. Figure 7 shows a dramatic increase in the fractions going to college for the pre-war cohorts, going from .1802 in the birth cohort 21-23 to .3251 in the 45-47 cohort - an 80% increase. From that point on there is some decline. Roughly speaking there was a move into college by the pre-war and immediately post-war cohorts which then abruptly stopped and began a reversal. Assuming, as most models would predict, a positive correlation between initial endowment and college attendance, this time path of the cohort fraction going to college would produce a declining, and eventually zero negative selection effect on the college group. In the presence of technological improvement in human capital production this would produce an increase in the college premium in the 1990s since the later cohorts would be exposed to superior production functions. In the period of the pre-war cohorts, successive cohorts had increasingly larger fractions of the cohort in the college graduate group, continuously lowering the average initial endowment of this group. This reduction in initial endowment would have masked the technological improvement at the college level in the 1970s and 1980s. By 1990, however, the negative selection effect was largely eliminated by the earlier stabilization of the cohort fractions going to college and the dominance of the newly stabilized cohorts in the total labour force so that the technological improvement would become apparent.

This explanation implies that careful examination of the increased college premium would show that it was largely confined to the most recent cohorts, which is also the case. The evidence on the increase in the measured college premium has, of course, been widely known for some time and has spawned a large literature to explain it. However, as Card and Lemieux (2001) point out "A less known fact is that *virtually the entire rise* [in the premium; our italics] is attributable to changes in the relative earnings of *younger* college educated workers." (p. 705) In order to explain this less known fact in a heterogeneous human capital model with no technological change in human capital production functions, Card and Lemieux (2001) have to assume that college educated workers from different cohorts are different factors of production. In the simpler homogeneous human capital model employed here the results are a predictable consequence of secular technological improvements in human capital production functions and the selection effects implied by the actual time path of college enrollment.

7 Discussion and Conclusions

The evidence presented in the previous sections suggests that technological change in human capital production functions could be an important source of growth. Together with endogenous human capital investment decisions this technological change provides a new explanation for the changes in the wage patterns in the United States for the period 1975-2001. An important difference in the approach presented in this paper from previous models is that the role of relative demands and supplies of skills is diminished and is replaced by the role of the total demand and supply of human capital. College workers faced downward pressure on their wages when the supply of college workers increased. However, this was not because of an increase in the relative supply of college workers, but because of a large increase in the total supply of efficiency units of human capital. All workers felt the same downward pressure. The different relative wage patterns for college and other workers, instead of being due to exposure to different price paths, was due to different human capital technology and endogenous selection effects reflected in the time path of the fraction of individuals going to college.

The presence of technological change and selection effects complicates identification of human capital prices and quantities. In this paper we have proposed a “standard units” approach and complemented this with a “flat spot” approach based on an assumed flat spot in experience profiles. The evidence from US data for 1975-2001 is consistent with a homogeneous human capital model amended to include technological change in human capital production and selection into education groups dependent on initial endowments. The arguments presented for the use of the single price assumption appear to be justified for the period of data examined. However, the homogeneous human capital model, even amended to allow for technical change in human capital production and selection, remains a restrictive model that may not apply for other periods. In particular, part of the case for the applicability of this assumption for pricing purposes relies on marginal arguments - that is, technical change at the level of output production functions may favor workers with a particular level of human capital in some production processes, but not all at once. Periods in which technological change is widespread and all in the same direction in favoring a particular level of human capital could see some deviation from a single price.

Discussion of recent technological change has focussed on the argument that it has favored skilled workers. However, technological change in earlier periods, such as the industrial revolution often saw the invention of machinery to replace expensive skilled workers with inexpensive unskilled workers. A process of endogenous technological change in the product production functions biased toward saving on relatively expensive “packages” of human capital, together with supply side responses, could have the effect of re-establishing the efficiency units process as the marginal production function and “correcting” any large deviations from a single price.

Technological change in human capital production functions is difficult to identify since, compared to other production functions, the output is not directly observable. Since significant technological change in human capital production functions has major implications for growth, wage inequality and education policy, it is important to study this issue. This paper represents an initial attempt at tackling this problem. There are many refinements that have been postponed for future work. A key refinement concerns the precise nature of what might be identified as technological change. No claims have been made in this paper for the identification of the actual magnitude of technological change in human capital production functions, only the potential for the magnitude to be significant.

As discussed earlier, under the identification strategy for the price, it is possible to identify the efficiency units *supplied* for any group of workers. From this kind of data there remains the difficulty of identifying technological change in human capital production functions from changes in initial endowments, changes in optimal on-the-job investment induced by the human capital price time path, and changes in the prices of other inputs in the human capital production function. Of relevance here is the literature on school quality. These school quality measures are inputs in the human capital production function, and changes in these inputs, if not controlled for, could appear as technological change, i.e. shifts in the human capital production function. While much of the literature finds that measured school quality has little direct effect on student achievement, evidence from this literature can be important in identifying technological change.[30] A full decomposition of these effects is an important task for future structural modeling.

An important feature of historical development is the almost universal increase in schooling. Human capital models explain levels of schooling by reference to costs and returns in a life-cycle setting. Technological change in human capital production functions may be an important part of this process. Even if the price of human capital was constant, the average level of education in a country would increase if there was technological improvement in human capital production since this would lower the cost of production of a standard unit. This would not be apparent from cost measures that focussed on input costs. Technological improvement could also provide insight into the adoption of increasing minimum schooling standards over time, and government subsidization of education at increasingly higher levels.

Technological change in human capital production functions has important implications for the transmission of technological change across economies. As discussed in Section 5, if technological change is not taken into account it is possible to substantially under-estimate the labor input, which results in the appearance of technological change in the output production

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[30]See, for example, Hanushek (1986), Hanushek, Rivkin and Taylor (1996) and Dearden, Ferri and Meghir (2002).

function. Similar mis-attribution can happen with capital mis-measurement.[31] If a significant part of apparent improvements in the output production function are in fact due to improvements in the human capital production functions that characterize a country's education and on-the-job training environment, adopting "state of the art" output production functions will not generate the expected growth. Policy initiatives on innovation could be mis-directed. Technological improvements in the output production function or the capital input production function may be relatively easily available to countries outside of where such innovations originated. The latest machinery can be imported so full advantage can be taken by all countries of technological change in producing machinery. In contrast, the "latest labor input" can only be imported to a very limited extent so that improvements in human capital production functions may be less easily transmitted internationally, given the link to a country's education and on-the-job training systems. And, in any case, the import of a few newly produced workers would not change the human capital of the domestic workers. This has important implications for growth and convergence.

The empirical evidence presented in this paper is based on United States data for 1975-2001. However, the analysis is applicable to other countries and time periods and can be used to inform the policy debate on a wide variety of issues. For example, it is possible to assess the contribution of a country's post-secondary system to the total stock of human capital in the country and to compare this across countries. For international comparisons of human capital stocks, quite apart from any "quality" differences, the problem of adding different levels of education is often avoided by choosing a measure such as the fraction of the population who have graduated high school (for comparison across developing countries) or the fraction of the population with post-secondary education (for comparison across developed countries). However, this can result in misleading conclusions. According to the latter measure, Canada has higher per capita human capital than the US. However, the US has a higher fraction of the

[31]Greenwood, Hercowitz and Krusell (1997) investigate this issue and provide estimates to suggest that the magnitudes in the capital input case are important. Our estimates can be used to provide a similar analysis for the labor input. This is left for future work.

population with a university degree. If this measure was used instead of the fraction with post-secondary education the ranking would be reversed. The methods developed in this paper can help to resolve this issue.[32]

[32]A preliminary analysis of the contribution of post-secondary systems is carried out for the US and Canada in Bowlus, Liu and Robinson (2003) and shows a much larger contribution for the US. Comparison of total stocks under various comparability assumptions for Canada and the US at the elementary and high school level shows higher per capital human capital in the US, reversing the OECD ranking based on its measure A1 which the OECD characterizes as "traditionally used to proxy the stock of human capital." (*Education at a Glance - OECD Indicators,* OECD 1998, p. 7.)

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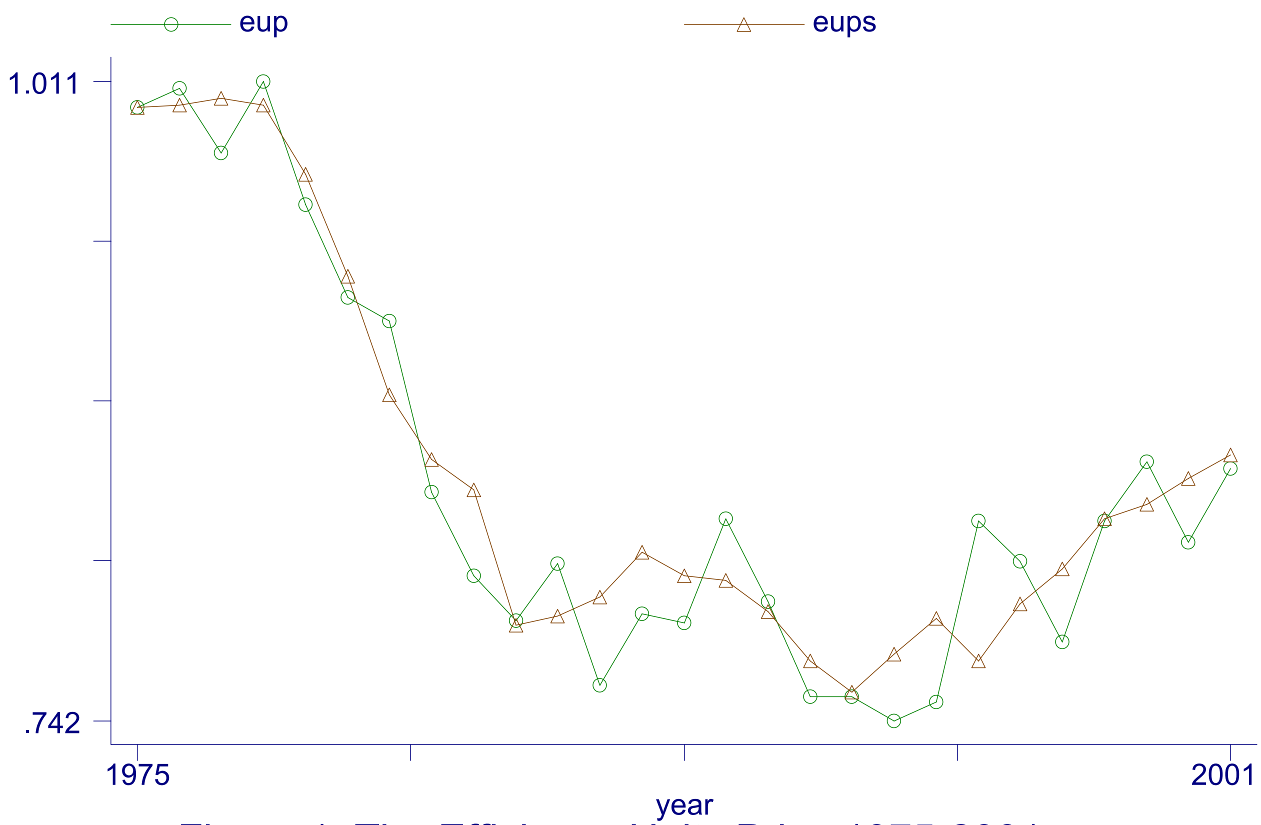

Figure 1: The Efficiency Units Price 1975-2001

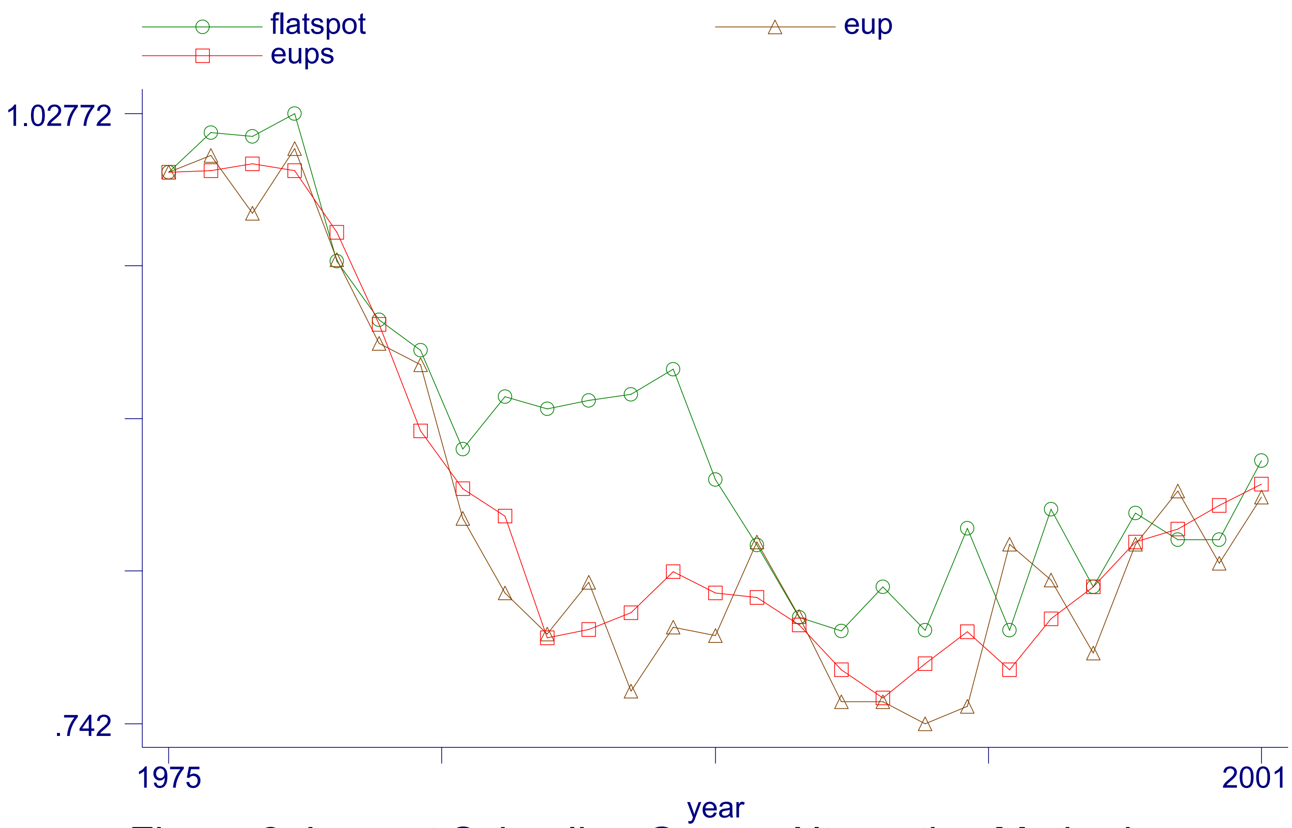

Figure 2: Lowest Schooling Group: Alternative Methods

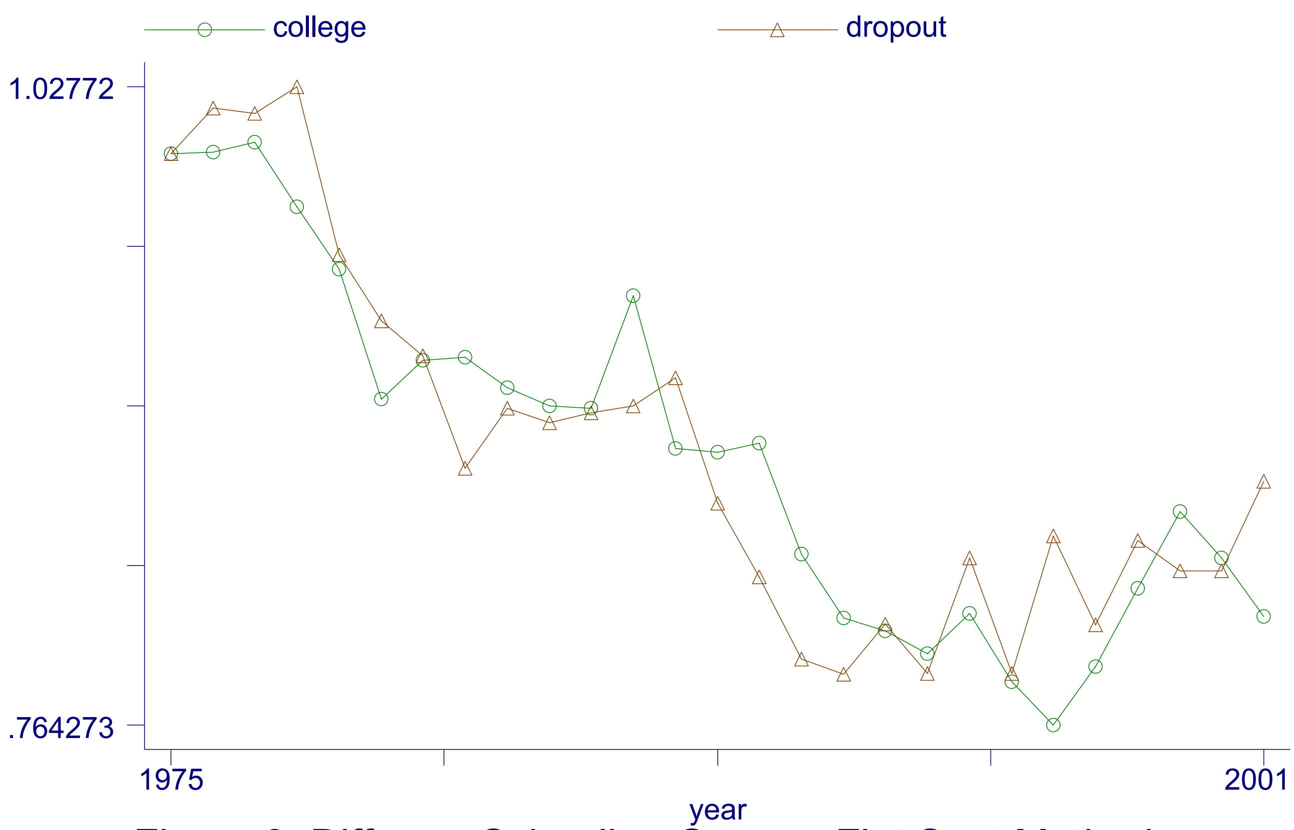

Figure 3: Different Schooling Groups: Flat Spot Method

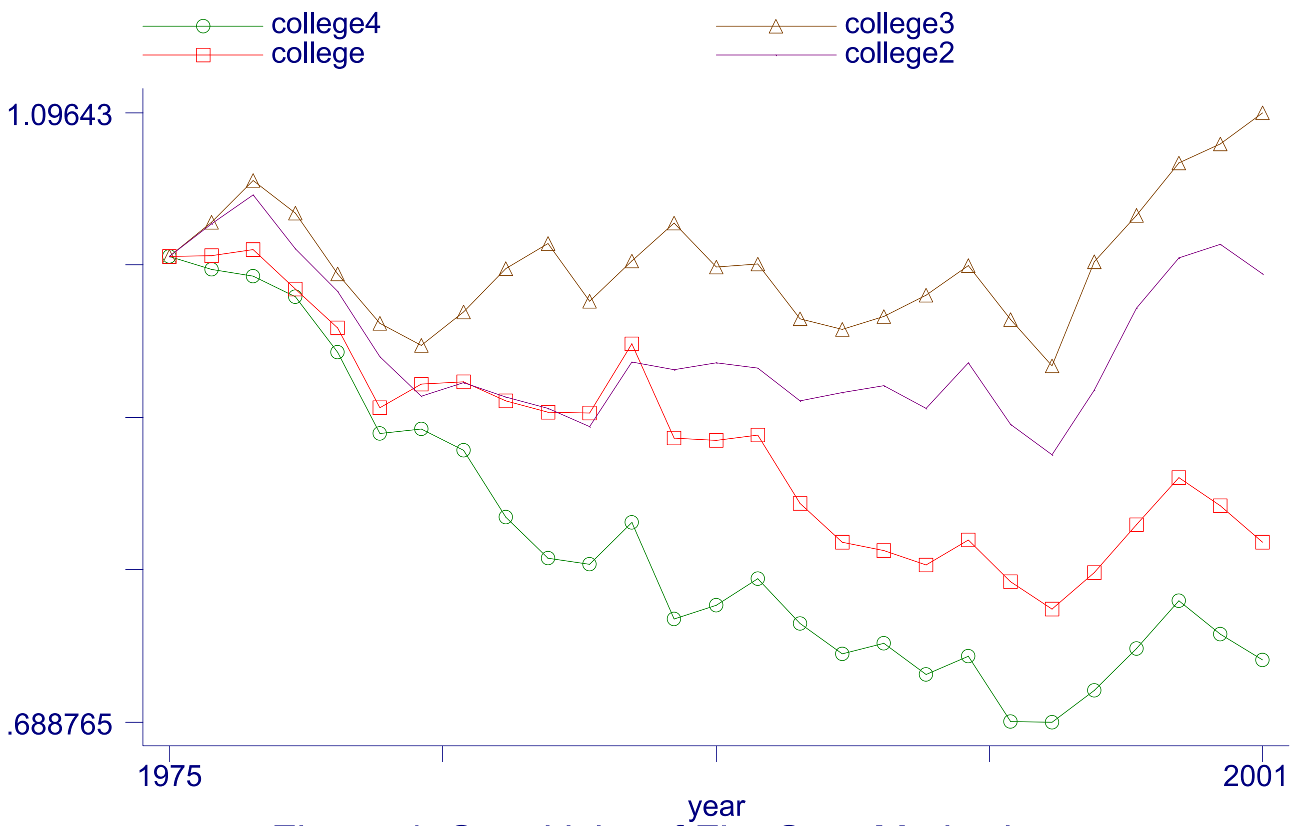

Figure 4: Sensitivity of Flat Spot Method

Note: The flat spot age ranges are:

51-60 college

48-57 college2

45-54 college3

52-61 college4

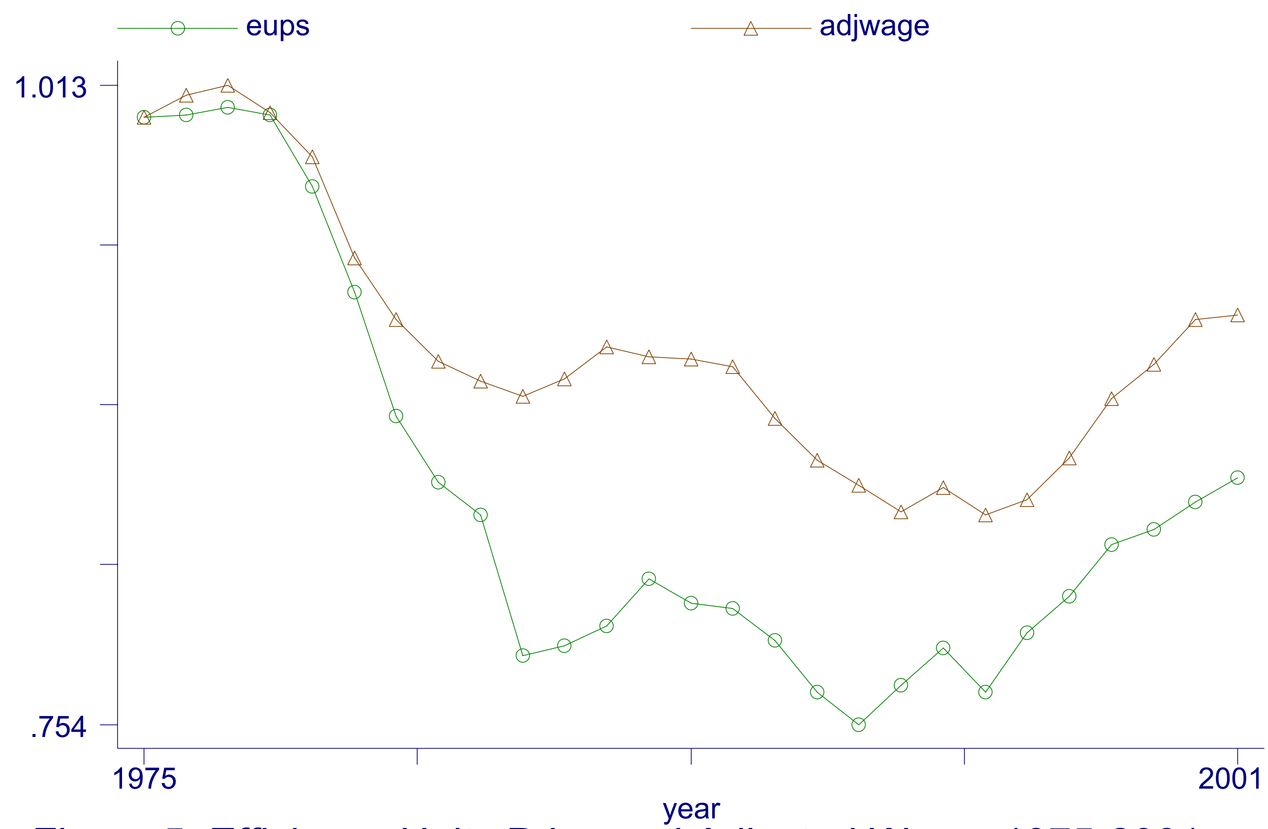

Figure 5: Efficiency Units Price and Adjusted Wage: 1975-2001

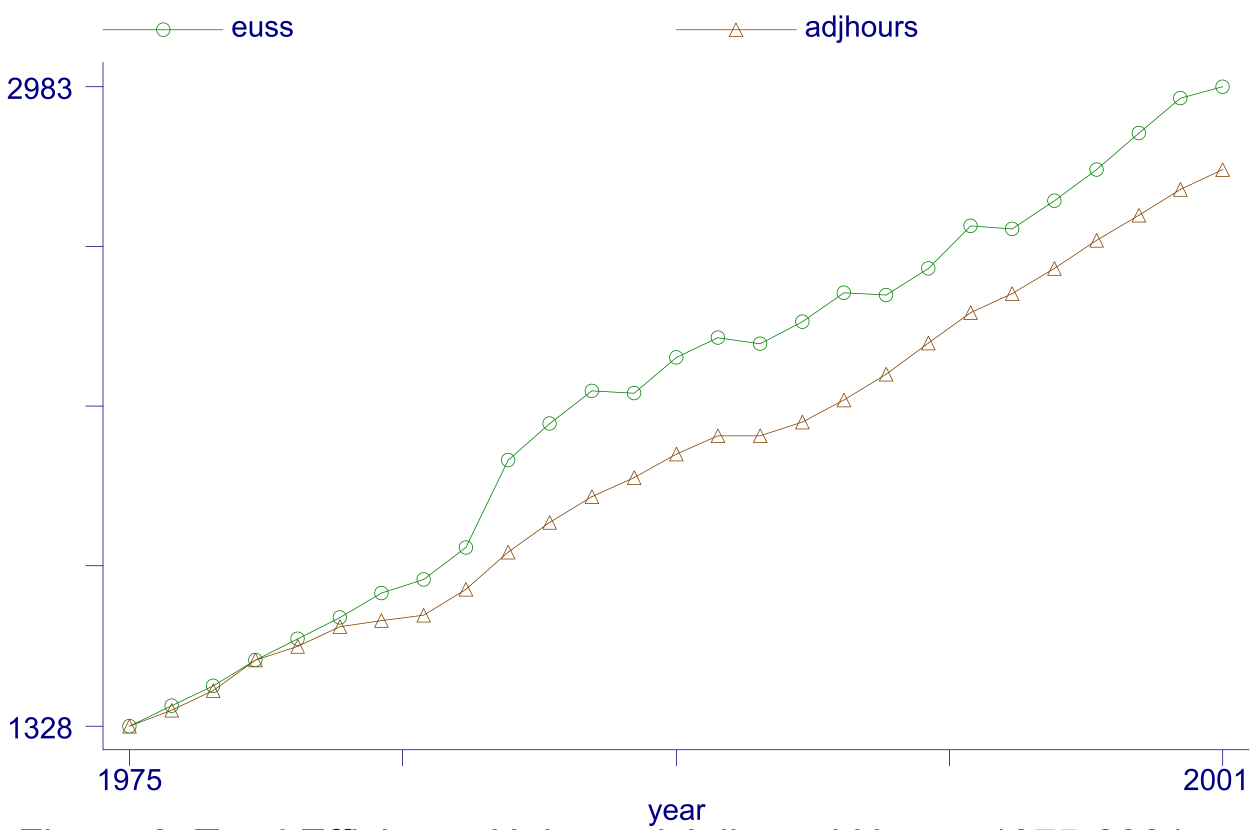

Figure 6: Total Efficiency Units and Adjusted Hours: 1975-2001

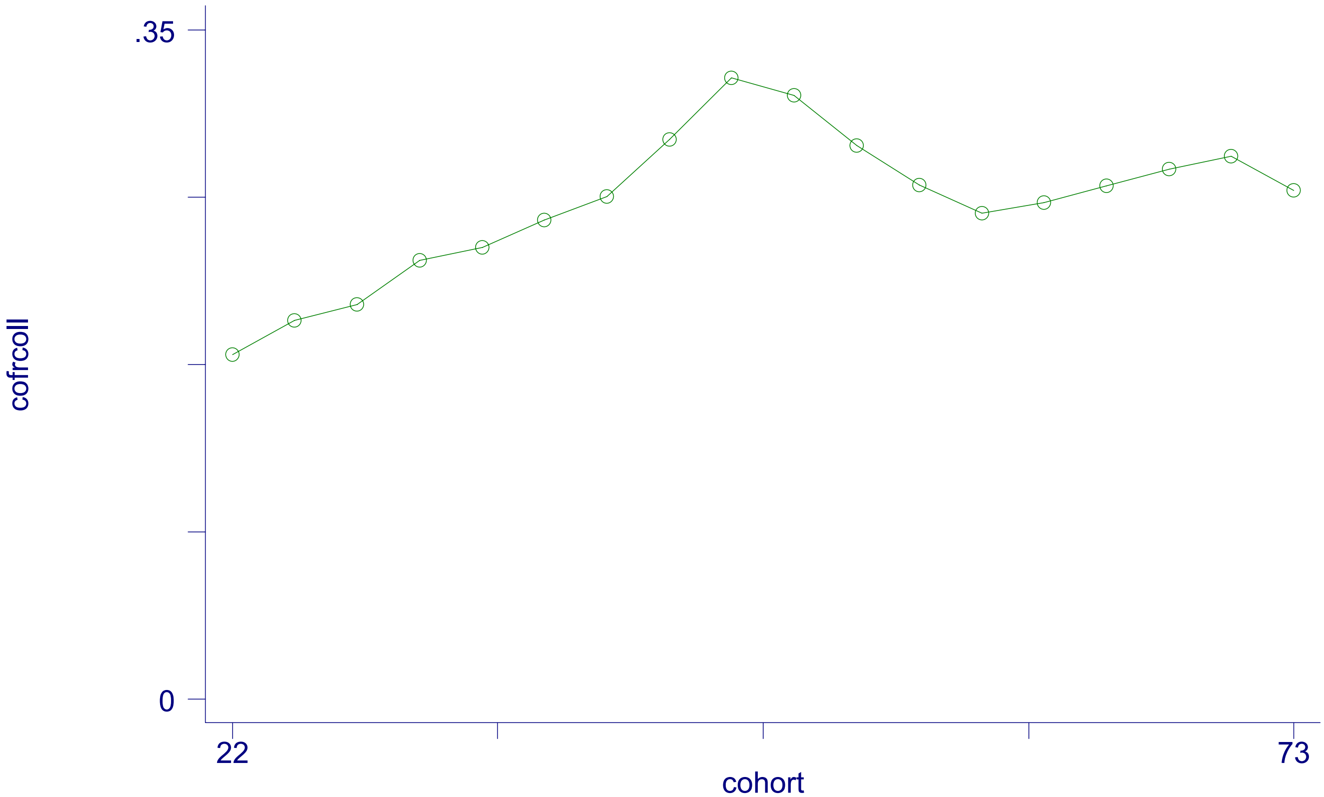

Figure 7: Fraction College Graduates by Cohort

Appendix

AI. Data Sources, Definitions and Restrictions

The March CPS (MCPS) annual labour incomes are for the year preceding the survey. Prior to the 1976 survey (1975 earnings) reported working hours in the survey could not be related to the previous year's earnings. The data were thus restricted to start from the earnings year 1975. Hourly wages were constructed as the ratio of annual labor income to annual working hours. Annual working hours were constructed as the product of weeks worked per year and usual hours worked per week.

Restrictions on the sample were made primarily on the basis of the availability of wage observations and considerations of possible measurement error in these observations. The sample for estimating the price series was restricted to paid employees aged 19-63. It also excluded workers who worked less than 50 hours in the year.

Measurement of Education and Experience

The main variables are education and experience. The education variables in the MCPS have a break at the survey year 1992, when a new set of questions are introduced. The issue of consistency of the education measure across this break is studied in Jaeger (1997) who compared the education answers from the same respondents at different points in their CPS rotation who were asked the old education questions in their earlier rotation and the new questions in their later rotation. Jaeger offers solutions of two types. First is a linearization of the new educational attainment question that approximates the old "highest grade completed." In addition Jaeger considers 4 category matches rather than linearization. These are dropouts, 12^{th} grade, some college and college graduates.

An important feature of the Jaeger assignment is that after the break he assigns "12^{th}

grade, no diploma" to his 12th grade group rather than to dropouts. This is due to the use of the median rather than the mean in Jaeger's Table 2. The mean of the "12th grade, no diploma" group is actually 11.38 but the median is 12. The cumulative fraction up to and including 11 years over the 1986-1991 survey period in our analysis was 17.76, 17.36, 17.31, 16.86, 16.68 and 16.09. Jaeger's definition takes it to 13.40 for 1992 and the alternative of assigning "12th grade, no diploma" to the dropouts group takes it to 15.12, suggesting that this assignment might be causing an unwanted break. Further inspection, however, shows that the big drop is actually in the cumulative to 10 years which is common to drop out measures under both assignments. For this paper we adopted Jaeger's definitions.

The actual assignment of Jeager's schooling groups takes place for all individuals in the sample in the calender year of the survey. The preferred regression specifications impose an age restriction of 19. This is done because the reference group must include only those whose *completed* education is dropout, but this is not directly observable in the data. That is, it is obviously possible that in different years the group that are in the "dropout" education group may differentially go on for more education - i.e. they may be from different points in the true initial

endowment distribution. Analysis of the MCPS shows substantial numbers of 17-18 year old dropouts eventually move out of this category, but by 19 the problem is minimal. A similar problem applies to other schooling groups, and the age cutoff to align completed and contemporaneous observations on schooling will be higher for the higher schooling groups, but this will not affect the price estimates - only the interpretation of the other coefficients.

The experience measure is based on the standard potential experience definition but is amended as follows. The standard form is age minus schooling minus 6. This is fine for a general use of experience in some continuous form but is inappropriate for our purposes at the point of the "initial endowment" group which identifies the price. In particular, the initial endowment schooling group is essentially 0-11. For individuals with zero on the education variable this would imply 11 years of experience for a 17 year old - i.e. they would apparently have started working when they were 7 years old. At a minimum it makes sense to impose legal age restrictions to prevent too much experience. The form adopted here imposes this and is very convenient for cohort analysis. The definition is ex=age-16 if the individual is in Jaeger's "dropout" category and the remaining schooling groups are shifted in age by 1, 2 and 5 years respectively.

Experience is used in both continuous and dummy variable form. The dummy variable form was preferred for flexibility. In addition, this form is very convenient for cohort analysis since the age restriction on the data for the regressions (19-63) together with this definition of experience puts exactly the same age range in the initial endowment group in each year which corresponds to an exact 3 year birth cohort group that moves by one year for each successive calender year of data. The experience groupings were 0-5 years, 6-10 years, 11-20 years, 21-30 years, 31-40 years and 41 or more years. This makes the initial endowment group very easy to compare over time: it is the 19-21 year old dropouts in any year.

A2. The Interpretation of Dummy Variables for Sex, Industry, Occupation and Region

Male-Female Dummy Variables

In principle, any sub-group can be used to estimate the price series. Thus a male only or female only sample should produce the same results. In fact the results will be different, reflecting the declining male-female wage differential over time for given schooling and experience. The interpretation of this change in the efficiency units framework can take two forms. The first is a standard employer discrimination story that leads to females receiving a lower price for their efficiency units. The alternative model is that males and females have different initial endowments of human capital. There is no discrimination, so the model retains the single price assumption. One interpretation is that the female initial endowment is less market oriented human capital than that of the male. The relative difference between home and market orientation could differ over time and across countries at different stages of development and at different levels of female labour force participation.

The estimating equations for this model and the discrimination model are the same, including a dummy variable for female. The coefficients on the time dummies yield the same full price series in both cases, but the calculation of the efficiency series is different. In the no discrimination model the efficiency series follows in the usual way from dividing the total wage payments by the (single) dollar price estimated from the coefficients on the time dummies. If the discrimination model was true and this procedure for calculating efficiency units was followed it would result in an underestimate of the total efficiency units, and the degree of underestimation would vary over time as the degree of discrimination varied. In the discrimination model the true efficiency series is calculated separately for males and females by dividing total wage payments for each sex by the relevant (and different) dollar prices for each sex, and then adding the efficiency units of both sexes.

Industry, Occupation and Region

If industry wage differentials are due to unobserved individual heterogeneity this implies differences in the unobserved mean efficiency units of workers in different industries. As long as the overall mean of the initial endowment of efficiency units is time invariant (say, for males) industry can then be ignored in the estimating equation. The differences in unobserved heterogeneity by industry would show up in the calculation of efficiency units by industry, i.e. by dividing total industry wage payments by the single price for different industries would show different per worker hour efficiency units across industries.

If industry wage differences were due to compensating differentials, industry information would be relevant. This is similar to the discrimination case where here the price paid to workers can include a psychic cost which results in different prices being paid for an efficiency unit in different industries. To deal with this requires the equivalent of the non-discriminated against group (males) - i.e. an industry with zero compensating differential. As in the discrimination case, the various price series can all be identified as long as the initial endowment is time invariant, though again construction of the total efficiency units series would have to proceed by group (in this case industry) and then aggregated across groups. Otherwise there will be a biased estimate of the total efficiency units and the degree of bias would be sensitive to the industry mix.

Occupational and regional wage differentials can be considered similarly to industry. To the extent that the differences are unobserved individual heterogeneity and that the assumption of time invariant initial endowments overall can be maintained, the occupation and region information can be ignored. Suppose, however, that initial endowments were “caused” by region in the sense of the effects of the regional environment. This would have to be treated similarly to the male-female differences when female efficiency units had different market orientation since changes over time in the region mix would change the mean overall initial endowment. As in the male-female case, a group (in this case region) where the initial endowment was time invariant would have to be identified.

A3. Functional Forms

Education and experience were both defined in continuous year and dummy variable form. The preferred specification was the dummy variable form. The most general specification includes interactions between all dummy variables - education, experience, sex and year - which is equivalent to estimating each cell sub-group separately. This places no restriction on selection or technological change effects on any group other than the identifying assumption implicit in the standard unit. In particular, the price is equivalently estimated by restricting the sample to the standard unit group and regressing the log wage on year dummies. The moderately restricted specification restricts the technological change and selection effects by interacting the education, experience and sex dummies, together with their interactions, with three year grouped year dummies instead of annual year dummies.

A4. Top-coding

Top coding is a serious problem in the CPS, especially for analysis involving high earners such as college graduates. The top-code correction procedure we adopted is as follows.

The earnings years 1975-1987 use a variable value top-coding cutoff (1975-1980: 50,000; 1981-1983: 75,000 and 1984-1987: 99,999) on a *total* earnings. Thus, the observed total cannot exceed the cutoff value. 1988-1994 uses a constant cut-off value (99,999) separately on two components of the total, hence the observed total can be above the cut-off of 99,999. Our analysis is only sensitive to top coding for the flat spot method, since "standard unit" workers are in practice never top-coded. The flat spot method applied to college graduates, however, used highly experienced college graduates which are disproportionately top-coded. The requirement is primarily that the procedure be consistent from year to year rather than that the level be exactly correct. For consistency across the whole period, the procedure adopted is simple. Assume a log normal distribution for total wage and salary income (denoted *_incwag* in the Unicom version of the March CPS files). Consistently estimate the mean of ln(*_incwag*) using Tobit with the relevant year known cutoff. (Some observations in some years are identifiable as not top-coded, but this is not consistent across years.) Given the log normal assumption for the total, the estimate of the mean is consistent if any fixed number is chosen for the cutoff and the maximum number that can be used for the cutoff is the top-code cutoff. Hence this number is chosen and any other information, i.e. an inconsistent indication of whether some of the values at the cut-off are actually uncensored, is discarded.

For 1975-1987 there is a single cut-off for the total, and hence no observed values above the cut-off, so this is straightforward. For 1988-1994 there are two cut-offs, but a consistent procedure with the earlier years can be adopted by mimicking a total cut-off. (In any case, almost all the censoring is due to one component.) Consider the imposition of a cut-off of 99,999 on the reported total, i.e. any observation above the single component cut-off of 99,999 is recoded to 99,999. Estimate the mean using Tobit as before. This is equivalent to the procedure for the earlier years. If, in the reported *_incwag* total, the two components were uncensored, the total would have been a true total that under a single cutoff procedure would have had observations top-coded at 99,999, i.e. any observation above 99,999 would have been recoded to 99,999. If both components were censored the true value of the total would have been above 199998 and the reported value would be 199998. A single cut-off of 99,999 would have top-coded this observation at 99,999. Finally, if one component had been censored and one uncensored, both the observed and true values will be above 99,999 and a single cut-off procedure would have recoded these observations to 99,999. There is some true information in this case both at, and above the 99,999 value for a small number of observations. That is, there are a some observations between 99,999 and 199998 that could be identified in some years as being unconstrained, but ignoring this information does not affect statistical consistency of the mean estimate, whereas trying to use it treats different years differently and risks relative inconsistency across years.

The Tobit on ln(_*incwag*) where observations on _*incwag* above 99,999 are recoded to 99,999 for earnings years 1987-1994 yields an estimate of the predicted mean of ln(_*incwag*) denoted *princ75-94*. Denote the overall mean of ln(_*incwag*) using the censored values as *lninc*, and define:

tpcdincr = (*princ* - *lninc*)/*frcens*

where *frcens* is the fraction of "censored" observations, i.e. observations at the cutoff. The amount *tpcdincr* is then the value such that if it is added to the value of observed (recoded) ln(_*incwag*) for all observations at the cutoff, the mean of the observed ln(_*incwag*) would then equal the predicted mean under log normality for _*incwag*. Equivalently, *tpcdincr* is the value such that multiplying _*incwag* by exp(*tpcdinc*) for all observations at the cutoff, the mean of the observed ln(_*incwag*) would then equal the predicted mean under log normality for _*incwag*. Since log wages are used to estimate all the price series, deriving the top-code adjustment to match the true and actual log-earnings means is a logical benchmark.

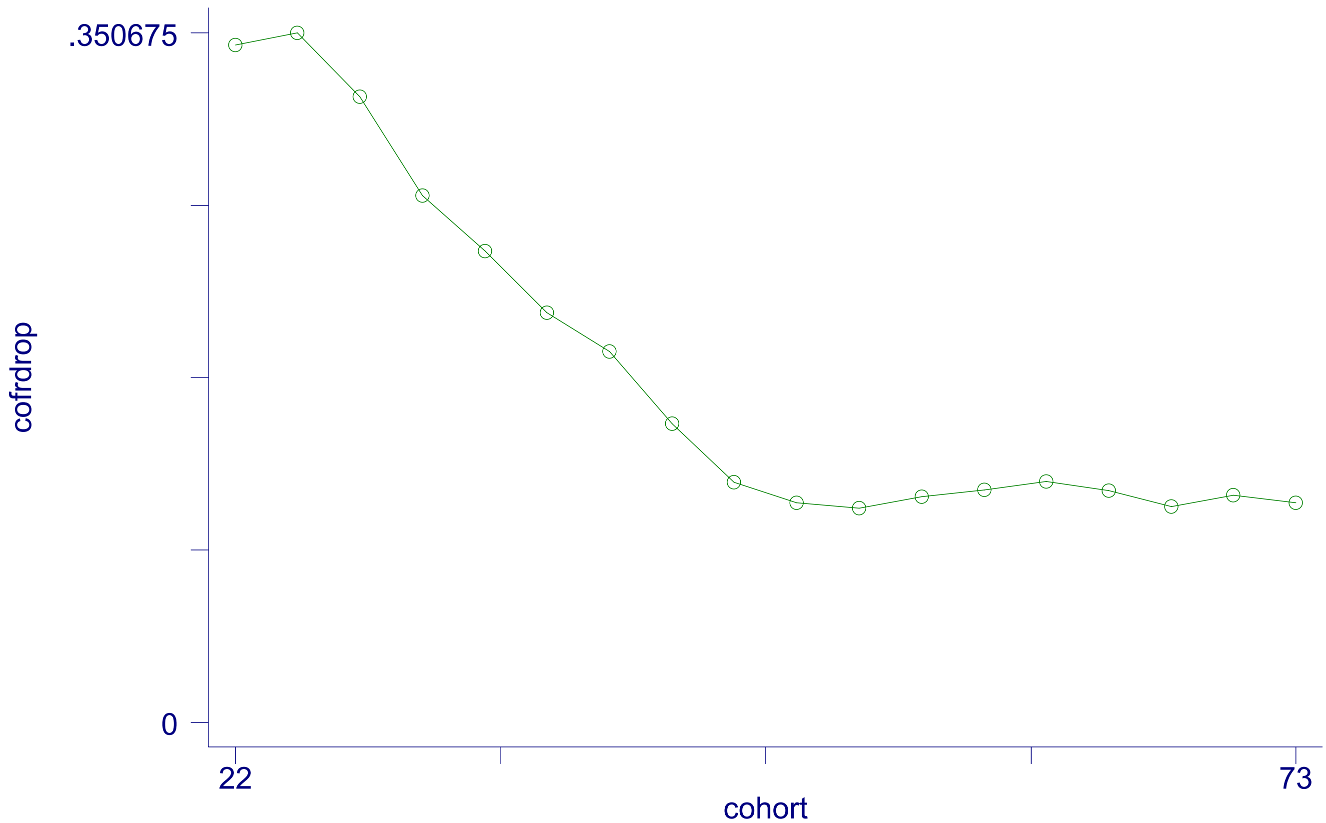

Figure A1: Fraction Dropouts by Cohort