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Wage Fairness, Growth and the Utilization of R&D Workers*

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Abstract

In 1999, only one of three US scientists and engineers was employed to do R&D and, in several countries over the last forty to fifty years, employment of skilled workers for R&D purposes appears not to have kept pace with the overall increase in the supply of skilled workers. Low utilization of R&D personnel implies low growth per human capital endowments. To analyze the low R&D utilization/low growth equilibria, we set up an endogenous growth model in which firms set fair wages and which allows for an analysis of changes in the utilization rate of R&D workers. We find that the rise in under utilization and the fall in growth per human capital to be consistent with the increase in the demand for higher education. This could be interpreted as the "consumption" element in higher education has received an increased importance yielding a low growth effect of higher education. The results also point at problems of correctly measuring actual human capital inputs in firms.

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1. Introduction

Much of the research on the determinants of economic growth has focused on the inputs of R&D workers in research departments. Given the importance that central contributions in the growth literature place on R&D inputs for economic development, it is surprising to find that only low shares of all educated R&D workers are actually employed to perform R&D. For instance, in the US in 1999 almost 11 million scientists and engineers were employed in the US labor market but of these less than a third, only 3,5 million, were active in science and engineering (S&E).[1] The corresponding figures are not available for the European union. However, figures based on "human resources in science and technology" (HRST), a considerably broader definition than "scientists and engineers" reveals that utilization rates are low also in Europe. In 1999, 65 million workers were classified as being educated for employment in science and technology (S&T) but of these only 42.3 million, or less than two out of three, were actually employed in S&T.[2]

An important issue is also if there is an increasing trend in under utilization. Data do not allow us to explore the long run trends in shares of workers in S&E or in S&T. However, for forty to fifty years back we may compare trends in workers having acquired higher education to workers actually employed in R&D. *Figure 1* compares the total number of workers above age 25 with higher education to the number of scientists and engineers engaged in R&D, for the US, West Germany[3], UK, France and Japan from 1960 to 2000.[4] With the exception of Japan, 'Scientists and engineers in R&D' does not keep pace with the number of workers with higher education. Particularly in the UK and in recent decades the US, there is a widening gap between the two curves. In four cases, observations are available also for single years during the 1950:s. *Figure 2* show that the trends remain for the UK, and France. For the US, R&D employment starts to lag behind overall higher education rates in the 1960:s. For Japan, R&D employment grew faster than overall higher education in the 1950:s, which is consistent with this country's high growth period.

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[1] See Science and Engineering Indicators-2002.

[2] That S&T is a much broader concept than S&E is shown by the fact that of workers in S&T only 19 % are classified as workers in S&E. See for instance OECD (2002).

[3] Germany after unification 1990.

[4] Data on scientists and engineers are taken from http://elsa.berkeley.edu/~chad/Sources50.asc and the number of workers with higher education from ftp://ftp.worldbank.org/pub/decweb/grthdata/barro&lee1993.

The low utilization rates of R&D workers in the research departments in recent years in the US and the EU, that we reported above, together with Figures 1 and 2, suggest a long-term decrease in the utilization rates. While for Japan the two time series grow at approximately the same rate during the last forty years, the trend that employment of workers in R&D does not keep pace with higher education is most clear in the case of United Kingdom.

Certainly, this is suggestive evidence and it is not clear that the utilization of R&D workers as a share of the supply of 'scientists and engineers' has shown a similar trend over the last fifty years as in Figure 1. It appears quite clear, however, that supply is not a restrictive variable since less than a third of 'scientists and engineers' in the US is used for R&D purposes.

The purpose of this paper is to present a theoretical model that is consistent with the long run decrease in the rate of utilization of R&D personnel for R&D tasks. The strategy is to explore an endogenous growth model with fair wage setting. Firms have incentives to raise the wage above the market clearing level but unlike the standard efficiency wage model where this generates unemployment, in this model the higher wage lowers the utilization rates of R&D workers as R&D workers are relegated to production with consequences for growth and welfare.

The study is also intended to increase our understanding of how incentive systems to promote R&D workers' efficiency affect economic growth. A growth model with fair wage setting is shown to involve mechanisms that hamper the positive growth effects of increases in the number of R&D workers. As supply of R&D workers increases, firms' utilization of R&D workers decreases, human capital per R&D worker drops as does their work effort.[5]

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[5] Several arguments favor the idea that efficiency wage setting is of particular significance to workers like researchers, civil engineers and others that are directly involved in improving the quality of goods. First, efficiency wage theory assumes some latitude in workers' effort which seems easy to accept for R&D workers since their effort to a lesser degree than that of workers on the factory floor depends on technological factors and cannot easily be monitored. Secondly, efficiency wage setting is particularly important for researchers since the performance of individual R&D workers must be crucial to the firm. Without any breakthroughs in the research lab of the medical company or in the design department in the auto company, firms' survival is threatened in the long run. The likelihood of a research breakthrough, in turn, hinges on the incentives that R&D workers have to work hard and it is not surprising that studies show that management is most concerned with maintaining good relations with workers as a way to prevent workers from slacking off. See in particular Campbell and Kamlani (1997).

We investigate the effects of long run changes that characterize developed countries, including changes in demography, in demand for higher education, in the quality of teaching and in retirement ages. Of these, we find that workers' increased preferences for higher education is consistent with the stylized fact that growth is lower than suggested by the increases in human capital. A long run fall in the utilization rate of R&D workers is consistent with improved productivity in tertiary education.

2 The model

Some general comments

We assume a continuum of industries that are indexed by $\omega \in [0,1]$. Firms allocate R&D workers to participate in R&D races to improve quality in perfect competition with other firms. In each industry, firms are distinguished by quality j of the products they manufacture. The higher the integer value of j the higher is the quality. R&D workers' innovation implies that the firm acquires the ability, represented by a blue-print, to manufacture a higher quality product. If the state-of-the-art quality in an industry is j, the next firm to win an R&D race becomes the single manufacturer of a j+1 quality product. Since firms are Bertrand price-setters, a winner of an R&D race will price lower quality competitors out of business and take over the market in its industry. Over time, as new innovations push industries up the quality ladder the economy grows. These are the basic ideas of the Grossman-Helpman (1991a) growth model.

Labor is, in our model, of two kinds: R&D workers, L_r, and production workers, L_p. The number of workers in each category as well as the length of R&D workers' education is determined endogenously. While R&D workers can work as production workers, production workers cannot work as R&D workers. Assume that a share u of L_r is allocated to production, we will have $L_p + uL_r$ workers in production and $(1-u)L_r e$ workers in the labs where e is R&D workers' effort. At each instant firms make a decision about how many of the R&D workers that should be employed in the lab and how many should be employed in production. One unit of production workers is required to produce one unit of output, regardless of quality. We treat the wage rate of production workers as the numeraire and let w denote the relative wage of R&D workers.

Utility maximizing consumers

All consumers live forever and maximize discounted utility from consumption of goods:

$$U \equiv \int_0^{\infty} e^{-\rho t} \log U^s(t)dt, \tag{1}$$

where ρ is the subjective rate of discount and log $U^s(t)$ is each consumer's static utility at time t, which is given by an additive utility function:

$$\log U^s(t) = \int_0^1 \log \sum_j \lambda^j d(j,t,\omega) d\omega \, . \tag{2}$$

$d(j,\omega,t)$ denotes the quantity consumed of a product of quality j produced in industry ω at time t. The parameter $\lambda > 1$ represents the extent to which higher quality products improve on lower quality products, i.e., the size of the step on the quality ladder.

At each point in time t, each consumer allocates expenditure E to maximize, log $U^s(t)$, given the prevailing market prices and that the second term is zero, i.e. at its equilibrium value. Solving this budget allocation problem yields a unit elastic demand function

$$d = E/p, \tag{3}$$

where d is quantity demanded and p is the market price for the product in each industry with the lowest quality adjusted price. The quantity demanded for all other products is zero.

Given this static demand behavior, each consumer chooses the path of expenditure over time to maximize (1) subject to the usual inter-temporal budget constraint. Solving this optimal control problem yields[6]

$$\frac{dE(t)}{dt} / E(t) = r(t) - \rho, \tag{4}$$

i.e., a constant expenditure path is optimal if and only if the market interest rate, r, equals ρ. As we restrict attention to steady state properties of the model, ρ is the equilibrium interest rate throughout time and

[6] See Grossman and Helpman (1991a).

consumer expenditure is constant over time. We let E denote aggregate steady state consumer expenditures.

The behavior of firms

a) The product market

One unit of labor produces one unit of output regardless of quality. Since production workers' wage rate has been normalized to one, every firm has a constant marginal cost equal to one. When the researchers have innovated, the firm becomes the single producer of the state-of-the-art quality in its industry.

We consider now the profits earned by a firm that has innovated successfully and become the state-of-the-art producer. With the previous state-of-the-art producer charging a price of 1, which is the lowest price such that losses are avoided, the new quality good producer earns instantaneous profits

$$\pi(p)=\begin{cases}(p-1)E/p, & p\leq\lambda\\ 0, & p>\lambda\end{cases} \tag{5}$$

where p is the price set by the producer. Equation (5) implies that profits are maximized by choosing $p=\lambda$. Therefore, this producer earns as a reward for its innovative activity a profit flow equal to $(1\text{-}1/\lambda)E$. None of the other firms in the industry can do any better than break even by selling nothing at all.

b) R&D inputs

So far, we have followed a standard Grossman-Helpman set-up of a growth model. In industry ω at time t, we let ℓ_i denote the number of R&D workers employed by firm i. In a model with fair wage setting, however, it is the employment of R&D workers in efficiency units that matters and the amount of human capital of the R&D workers. Hence, $eh(S)\ell_i$, where *e* is effort exerted by the R&D workers and *h(S)* is the human capital per R&D worker which is a function of the number of years, *S*, that the worker has spent in tertiary school. $eh(S)\ell=eh(S)\sum_i \ell_i$ is then the industry-wide R&D

employment in efficiency units as well as the *instantaneous* probability that some firm will be rewarded for R&D success. Both *e* and *h(S)* will be defined later. Individual R&D firms behave competitively and treat p as given, not influenced by their choice of ℓ_i.

Let υ denote the expected discounted rewards for winning an R&D race. For a given effort e, each firm chooses its R&D employment ℓ_i to maximize instantaneous profits that equal $\upsilon e\ell_i - w\ell_i$. For a steady state profit maximization equilibrium, the optimal level of inputs of R&D workers implies that $\upsilon = w/e$.

c) R&D workers' effort and firms' wage setting

The empirical literature offers much support for the fair wage approach to efficiency wage setting.[7] In this section we derive its crucial behavioral element, the effort function, from the utility maximizing behavior of R&D workers.

Rather than allowing for open unemployment (as in for instance Akerlof (1982)), we assume that when firms for efficiency wage reasons raise the R&D workers' wage above the competitive level, some R&D workers, determined by a random draw, are relegated to the factory floor. Since this share in efficiency wage models is formally identical to the unemployment rate, we represent this under utilization rate by u, which defines the share of R&D workers that is unemployed in their capacity of R&D workers.

The worker supplies a higher effort level, e_i, the higher is the offered wage relative other R&D workers' wage w_i/w. This comparison with peers is uncontroversial.

For reasons of tractability we assume that work outside the R&D lab is homogeneous. However, to recognize the existence of a number of qualified work tasks, like in top administration, comparable to the ones that R&D workers perform in the lab, we assume that R&D workers compare

[7] See Bewley (1998) who finds much support for the "fair wage" version of efficiency wage theory. The fair wage efficiency wage model is also supported by a large number of other studies like Blinder and Choi (1990) and Campbell and Kamlani (1997) for the US, Kaufman (1984) for the UK, and Agell and Lundborg (1995) for Sweden. All theses studies are based on interviews (or questionnaires) with the people that actually set the wages in firms. Interestingly, using an experimental approach, Fehr and Falk (1999) corroborates the finding from the survey studies. The consistent message in these studies, carried out in countries with highly diverging labor market institutions (like the US, UK and Sweden) and based on different methods (like interviews or questionnaires, and experiments), justifies the specification of a growth model on the principal finding that fair wage considerations determine effort of R&D workers.

their wage to the outside wage. Thus, also the relative wage w_i enters.[8] We shall show, however, that our results do not hinge on this assumption.

In the study by Campbell and Kamlani (1997), 13.3 percent of firms claim that high wages is the most important factor to stimulate effort of white-collar workers and high wages is ranked as the second most important factor to prevent workers from slacking off on the job. The first two arguments w_i/w and w_i that determine effort are therefore related to the individual R&D worker's place in the wage hierarchy.

Moreover, the higher is the under utilization rate, u, the more anxious will the R&D worker be to keep the job in the lab, and hence the higher effort level is expected by the firm. The unemployment rate is a standard argument in efficiency wage theory and almost ten percent of the firms in the Campbell and Kamlani study claim that high unemployment is the most important factor that raises effort of white-collar workers. The unemployment (under utilization) argument is in their study somewhat more important to white-collar workers than to other workers.

We consider the following effort function[9]

$$e_i = -a + (\frac{w_i}{w})^{\alpha} w_i^{\beta} + u^{\phi} \tag{6}$$

where $\alpha + \beta < 1$ (to ensure that effort is declining in the wage) and $a > 0$ (to ensure that a zero wage is not optimal).[10]

As firms set the wage by minimizing w_i / e_i. From the first order condition and after imposing $w_i = w$, we get:

[8] Agell and Lundborg (1995) find first that workers compare their wages to others not only in the same firm but also in other firms and secondly that firms consider reduced work effort to be a likely reaction to "unfair" wages. Since inter-firm comparisons are particularly common among white-collar workers for which education as well as work content is heterogeneous, this might suggest the existence of non-peer comparisons.

[9] Assume for R&D worker i an effort utility function $U_i^{\ell} = -(1/2)e^2 - e(a - (w_i^{\alpha}/w^{\alpha})w_i^{\beta} - u^{\phi})$ where utility falls in effort and rises in the individual's relative wage. Utility of having a job is also high when under utilization is high. The worker determines effort to maximize U_i^{ℓ} which yields $\delta U/\delta e = -e - (a - (w_i^{\alpha}/w^{\alpha})w_i^{\beta} - u^{\phi}) = 0$.

[10] See Akerlof (1982) for these requirements. Equilibrium utility of effort becomes $U_i^{\ell *} = -e^2/2$ which, as in the main text, is assumed negligible compared to the utility derived from consumption, U_i^S.

$$w = \left(\frac{e}{\alpha+\beta}\right)^{1/\beta} \qquad (7)$$

and for equilibrium effort we obtain (from $w_i = w$ in (6)):

$$e = -a + w^{\beta} + u^{\phi} \ . \qquad (8)$$

Endogenous labor supplies and education

While several studies have shown that schooling is of empirical importance to growth, we have, so far, said nothing about how much education workers demand.[11] To find inner solutions, we need to ensure that not everyone chooses the same vocation. We therefore assume that individuals are heterogeneous as they value education differently. While the monetary gains are identical for all workers with the same vocation, workers may value education differently in terms of social status, of having an intellectual work, of the personal development that education may offer etc. Let V denote this value of education discounted over the period of education and work.[12] V is uniformly distributed on the interval $\left[0,\bar{V}\right]$.

Each individual compares the present value of an optimal number of years of schooling to the present value of no education.[13] Working life is T years. With S years of schooling, the individual accumulates human capital amounting to $h(S)$ which is an increasing and concave function. S years of education yields (besides the value V) a flow salary of $wh(S)$ when employed as an R&D worker and where w now is the reward to one unit of human capital. If relegated to the factory floor, the human capital has no extra value and the worker receives a unit wage.

To determine the optimal number of years of schooling, the individual must consider the benefits and costs of marginal additional schooling, dS. The gains to be made from extra schooling equal the probability of working as an R&D worker $(1-u)$ times the extra return in this state $wh'(S)$. Thus, the

[11] For the relation between education and growth, see, for instance, Hall and Jones (1999) and Bils and Klenow (2000).

[12] We let V include the period in school so that V does not vary with the number of years in school.

[13] Our formulation of the determination of the optimal years of schooling is inspired by Grossman and Helpman (1991) who, though, assume homogenous labor. See also Findlay and Kierzkowski (1983).

marginal benefits $[(1-u)wh'(S)]dS$ can be reaped during the period $t+S$ to $t+T$ and the present value of these earnings equal $(e^{-\rho S}-e^{-\rho T})[(1-u)wh'(S)]dS/\rho$. During dS the student has no income and had he worked, income would have been $(1-u)wh(S)+u$ such that the marginal cost of an extra unit of schooling is the forgone earnings $e^{-\rho S}[(1-u)wh(S)+u]dS$ during the period $t+S$ to $t+S+dS$. The first-order condition, i.e. marginal benefits equal to marginal cost, yields

$$(1-e^{\rho(S-T)})=\frac{\rho}{h'(S)}\left[h(S)+\frac{u}{(1-u)wh(S)}\right]. \qquad (9)$$

The optimal *S* solves (9). The present value of lifetime earnings of an unskilled worker equals $\Lambda_u=\int_t^{t+T}e^{-\rho(\tau-t)}d\tau=\frac{1}{\rho}(1-e^{-\rho T})$. This value should be compared to the alternative of spending the first *S* years in school and then receiving, for the remaining years, a flow salary of *wh(S)* when employed as an R&D worker and 1 when at the factory floor. Add to this the subjective value of education, *V*, discounted and we get a total present value of optimal education as

$$\Lambda_e=\int_{t+S}^{t+T}e^{-\rho(\tau-t)}[(1-u)wh(S)+u]d\tau+\int_t^{t+T}e^{-\rho(\tau-t)}Vd\tau=\frac{1}{\rho}(e^{-\rho S}-e^{-\rho T})[(1-u)wh(S)+u]+\frac{1}{\rho}(1-e^{-\rho T})V$$

The worker prefers optimal education to no education if $\Lambda_e\geq\Lambda_u$. The *marginal* worker is indifferent between optimal education (obtained from (9)) and no education ($\Lambda_e=\Lambda_u$) and it follows that for this worker, *V* equals:

$$V^*=1-\frac{(e^{-\rho S}-e^{-\rho T})}{(1-e^{-\rho T})}[(1-u)wh(S)+u]. \qquad (10)$$

For this *marginal* worker, discounted money income from being unskilled exceeds expected discounted money income from optimal education. If, for a worker, $V\geq V^*$ he then chooses education and if $V<V^*$ he chooses no education. The share of the fixed labor force *N* that opts for higher education is then determined as $m=(\bar{V}-V^*)/\bar{V}$ yielding

$$L_r=mN \qquad (11)$$

and

$$L_p = (1 - m)N\ . \tag{12}$$

At each instant, a share S/T of the total number of L_r is in school, a share $(1-S/T)(1-u)$ of L_r is working in the R&D departments, and a share $(1-S/T)u$ of L_r is working as production workers.

Labor market equilibrium

We assume that R&D workers can work in the lab and on the factory floor while production workers only can work on the factory floor, but not in the lab. If demand for R&D workers drop, R&D workers are driven down on the factory floor and have to accept lower pay.[14] With production workers' wage equal to 1, each producer employs E/λ workers for production. Full employment in the labor market for production workers then implies that

$$L_p + (1 - S/T)uL_r = E/\lambda, \tag{13}$$

holds. Supply of production labor, i.e. L_p plus the number of workers that are not hired in the R&D lab, uL_r, equals demand for labor. As firms do R&D they demand ℓ workers per industry. Thus, full employment of R&D labor in terms of number of workers $(1-u)L_r$ implies that

$$(1 - S/T)(1 - u)L_r = \ell. \tag{14}$$

We may now also determine the rewards for winning R&D races, υ. We know from equation (4) that in any steady state equilibrium the market interest rate must equal ρ. The profit flow $(1-1/\lambda)E$, derived from (5), must be discounted by ρ, and we must also consider that producer of the state-of-the-art commodity eventually is driven out of business by other firms' further innovations. As noted in section "*R&D inputs*" this occurs with instantaneous probability $eh(S)\ell$ during time span dt. Since $\upsilon = w/e$ we obtain, as an equilibrium R&D condition, that υ equals:

[14] We could have assumed that R&D workers get unemployed. However, with competitive wages for production workers these workers would be fully employed and it seems to go against empirical facts to allow for unemployment among researchers while full employment holds for production workers.

$$\frac{(1-1/\lambda)E}{\rho + eh(S)\ell} = w/e \qquad (15)$$

where the right hand side represents the costs and $eh(S)\ell = eh(S)(1-u)L_r(1-S/T)$ is the overall human capital actually used for R&D.[15]

Growth

We now can derive a growth equation that is considerably richer in nature than in standard models of this type. Growth obtains derived as $g = eL_r(1-S/T)(1-u)h(S)\log\lambda$. We shall denote $L_r(1-S/T)$ the "measurable" educated R&D workers since this is the variable to be found in statistics on the number of R&D workers that firms employ. As before, effort, e, must be considered and that firms need not fully utilize all R&D workers, but only the share $1-u$. With endogenous education, we must also recognize that the relevant measure of R&D should also consider that years of schooling may change the amount of R&D actually used by firms.

In their empirical study, Bils and Klenow (2000) specify a human capital function consistent with mincerian wage equations. As do Hall and Jones (1999) and others we follow their approach and assume that each individual worker's human capital is a function of the efficiency of education and of the individual's schooling years. We assume that the efficiency in higher education is a function of the stock of human capital, hL_r, which is raised to a parameter η. If this parameter is positive, the quality of schooling is increasing in human capital. The number of school years affects human capital depending on the university premium. We then have a human capital stock of the individual determined as $h = (hL_r)^{\eta} e^{\log((1-u)w+u)S}$ or

$$h = L_r^{\eta/(1-\eta)} e^{(\log((1-u)w+u)S)/(1-\eta)} \qquad (16)$$

where the term $\log((1-u)w+u)$ in the exponent is the endogenous university premium.[16]

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[15] There is a "potential" supply of human capital of $L_r(1-S/T)eh$.

[16] An advantage with this formulation is that we can calibrate the model so as to make it consistent with empirically relevant university premiums. Note that the university premium is here defined in terms of the wage per unit of human capital, i.e. *w,* rather than in terms of the flow salary of educated workers, *wh*. Two deviations from the Bils and Klenow model should be pointed out: First, as cohorts do not change over time in

Expenditures

Steady state consumer expenditure E must equal total wage incomes plus interest income on assets owned. The value of all assets equals the stock market value of all producers of state-of-the-art goods, i.e. $\upsilon = w/e$ in equilibrium and $\rho\upsilon$ are the interest incomes. Consumer expenditures then become

$$E = L_p + uL_r(1 - S/T) + w(1-u)L_r(1 - S/T) + \rho w/e. \qquad (17)$$

3 The simulations

We assume the following parameter values and factor supplies: λ =1.2, implies that an innovation represents a 20% improvement and that consumers are willing to pay 20% more for the improved good. The rate of discount is 5%, ρ= .05. The parameters of the effort function cannot be settled on empirical grounds but are set to α = .25, β = .25, ϕ= .5 and a =1.0 while η is set equal to 0.1 and $\bar{V}$ =1.46. These values are determined so as to yield what appears to be a reasonable basic solution. Parameters α and β determine the curvature of the effort-wage relation. The total number of workers in the economy, *N*, is 10.0 and the number of active work years, *T* is set to 50.

We want to capture economic changes of a very long run nature. The model allows for a study of long run changes in for instance population size (*N*), number of work years *T* (i.e. retirement age), taste for higher education $\bar{V}$, and, finally, in the quality of higher education η. We are particularly interested to see if any of these changes are consistent with the stylized facts that R&D workers over time get under utilized and that growth in the OECD area has not kept pace with the number of R&D workers employed. *Table 1* reports the results of these changes.

The first column gives the basic solution. While we do not expect population increases to be able to explain the stylized facts, we start by analyzing the effects thereof to illustrate some basic workings of the model.

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model, the individual's work experience does not enter in the determination of human capital and, secondly, the university premium is endogenous.

Table 1 Simulation results

	Bench-mark solution **1**	**Population increase** **2**	**Education demand increase** **3**	**Retirement age decrease** **4**	**Teaching quality increase** **5**
1) Wage, w	1.164306	1.164088	1.164357	1.164765	1.163932
2) Effort, E	0.519382	0.519358	0.519388	0.519433	0.51934
3) School years, S	4.476104	4.487253	4.204502	4.709702	4.472637
4) Human Capital/capita, h	1.416278	1.418231	1.396431	1.434497	1.417032
5) Total Human Capital, H	1.283457	1.297531	1.281651	1.284382	1.283947
6) Under utilization, u	0.230994	0.231017	0.230988	0.230945	0.231034
7) R&D workers in labs, $L_r(1-S/T)(1-u)$	1.744801	1.761589	1.767091	1.723714	1.744679
8) University premium, $\log((1-u)w+u)$	0.051674	0.051608	0.05169	0.051813	0.051561
9) Growth, g	0.234002	0.236568	0.233673	0.234171	0.234091
10) Production workers, L_p	7.508009	7.583339	7.491159	7.522984	7.508242
11) Total R&D workers, L_r	2.268903	2.290803	2.297872	2.241339	2.268864
12) R&D workers in school, $L_r(S/T)$	0.223088	0.225858	0.210969	0.235677	0.222895
13) Share of population to higher education, m	0.249199	0.249174	0.250884	0.247702	0.249176
14) Growth/(active R&D worker), $g/L_r(1-S/T)$	0.103134	0.103269	0.101691	0.104478	0.103176
15) Grwth/R&D worker in Labs, $g/L_r(1-S/T)(1-u)$	0.134114	0.134292	0.132236	0.135852	0.134174

We raise the population size by one percent (Column 2). *Ceteris paribus* this raises supply of both production workers and R&D workers (Rows 10 and 11). An increase in the supply of production workers lowers the under utilization rate, while an increase in supply of R&D workers raises under utilization.[17] More workers imply that expenditures (i.e. $E = L_p + uL_r + w(1-u)L_r + \rho w/e.$) (not shown) go up which raises *demand* for both types of workers. In the new equilibrium, the number of productionworkers increases by 1.00 % and R&D workers by .97 % and we

[17]The relative increase in production workers is also manifested in a decrease in the *share* of total population opting for higher education, from 24.9199 to 24.9174 %. This drop in the share *m* implies an increase in the marginal worker's value of education (*V**) (not shown).

obtain a net increase (from 23.099 to 23.102%) in the under utilization rate.[18]

The increased demand for R&D also spills over into an increase in students' optimal schooling years, which rises to 4.487. With a larger number of R&D workers that each spend more time for education, human capital rises and growth is up. Thus, the standard result that population increases raise growth carries over to this model with an endogenous determination of education.

We also see that growth per R&D worker rises, from .1031 to .1033 and that growth per R&D worker employed in the laboratories rises as well, from .1341 to .1343. This is as expected since each R&D worker acquires more schooling. From this we conclude that the stylized fact that growth has not been able to keep pace with available supplies of R&D is *not* due to population increases. On the contrary, population increases tend to *raise,* not lower, growth per R&D worker.

A second phenomenon that we may analyze is an *increase in the taste for higher education* (Column (3)). We assume a one percent increase in the difference between $\bar{V}$ and the V^* we obtain in the benchmark solution and it implies that the value of education, beside the university premium, rises. Given the normal distribution of the value of education, an increase in $\bar{V}$ implies that the share of the population opting for tertiary education rises. We can think of this as an increase in the perceived social status of higher education. Of course, the share of workers preferring (optimal) education to no education rises, in this case from 24.9199% to 25.0884%. Since the valuation does not depend on the number of years of schooling, the injection to human capital formation is counteracted by a decrease in the optimal number of schooling years, from 4.48 to 4.20 years. Since more people prefer the high wage work, expenditures rise (not shown), profits from R&D also rise and demand for R&D workers goes up relative to demand for production workers. A consequence is that the under utilization rate goes down (from 23.0994% to 23.0988%). Hence, as more and more people over time go to higher education, we find that they choose fewer years of education and that firms employ an increasing share of them in R&D. With the parameter values assumed, the negative effect of the decrease in schooling years dominates and human capital formation drops. Consequently, the growth rate goes down at the same time as the number of workers in R&D rises. This case is therefore in line with the stylized fact

[18] This increase in u implies that effort rises but, as firms then adjust the R&D wage per unit of human capital downwards, effort is reduced and the net effect is negative. This qualitative effect depends on the selected parameter values and the effect on effort is theoretically ambiguous.

mentioned in the introduction that over time growth has not kept pace with the increase in the number of employed R&D workers.

We turn now to analyzing the effects of *higher efficiency in tertiary education* (Column 4). Since human capital, here hL_r is assumed to reflect teachers' human capital, a higher η, which we raise by 1 percent, implies that human capital per R&D worker is increasing more in the human capital of teachers.

Each R&D worker's human capital (*h*) rises (here from1.416278 to 1.417032). This increase leads to several adjustments. As there is no direct effect on R&D demand, and *h* has increased, the share of workers that go to higher education, *m,* drops (from 24.9199 to 24.9176%) and the optimal number of school years falls (from 4.4761 to 4.4726). These effects counteract the initial human capital increase. Moreover, the increase in η implies that a given level of R&D may be produced by a lower number of R&D workers and we find that the under utilization rate of R&D workers increases (from 23.0994 to 23.1034%). While this tends to raise effort, a drop in the R&D wage reduces effort and we find that the net effect on effort is a decrease, (from .519382 to .51934). While there are several mechanisms that counteract the initial increase in human capital that a higher η gives rise to, the net effect is, as expected, a human capital and growth increase. As noted on the last two lines of *Table 1*, growth per R&D worker rises.

The last long run change of modern economies that we analyze is *reductions in retirement ages*. Such reductions took place in most OECD countries during the 20:th century. Earlier retirement implies that the remaining number of years during which the educated worker can benefit from the return to his education falls. As we reduce *T*, we expect higher education to become less attractive and we see that the share of the population that acquires higher education drops from 24.92 to 24.77%. With this reduction in the supply of human capital and no change in the demand for R&D, we obtain an increase, to 4.71, of the optimal number of years of education. Thus, following a reform in the retirement age, higher education will be more unequally distributed to a lower number of workers that educate themselves for a longer period of time. It should then come as no surprise that human capital per R&D worker, *h*, rises.

The under utilization of R&D workers drops slightly as the supply of R&D workers falls. This, in turn, tends to lower effort but the wage goes up implying a marginally higher effort. With increases in the share of highly educated employed in R&D labs and a higher wage, the equilibrium university premium is up.

With the parameter values chosen, the overall supply of human capital, *H*, rises as does the growth rate and growth per employed R&D worker rises. Hence, like population increases, drops in the retirement age *cannot* explain the stylized fact that growth does not keep pace with R&D supplies.

To summarize, we have found only one long run change that is consistent with the stylized fact that growth does not keep pace with increases in the employment of R&D workers. This change is the increase in demand for higher education which, among other things, leads reduces utilization rates of R&D. In the next section, we shall consider some empirical evidence of the model, in particular the utilization of R&D.

4 Empirical evidence and concluding remarks

Due to increased demand for higher education most OECD countries should have experienced long run increases in their supplies of R&D workers. One prediction of the model is that while the number of R&D workers increases relative to production workers, *actual* R&D inputs have grown less since i) utilization of R&D workers falls, and ii) the optimal number of schooling years drops. The first prediction implies that while the number of R&D workers employed in firms has increased, *the number of R&D workers employed for R&D purposes may have increased much less*. This may have prevented growth from increasing to the extent suggested by basic endogenous growth theory and as explored in Jones (1995a) and in several other papers.

Our model also predicted that years of schooling should drop as the number of workers opting for higher education rises. It is a fact that the rich countries' university reforms, that mainly and gradually took place during the 1960:s and 1970:s, implied the possibility for individuals to limit the number of years necessary for a PhD. Moreover, in many countries students may enter university and take courses that raise their human capital without completing a full degree. No long run data for completion times are available, however.[19]

[19] This is according to the OECD:s statistical bureau. Note also that since the number of years in mandatory schooling has increased, the number of years to complete a Ph.D. or

Many have argued that a basic reason that growth has not kept pace with R&D inputs is that R&D workers' productivity has fallen. The most common measure of R&D productivity is the number of patents per worker. Machlup (1962) showed that the rate of patents per R&D worker declined from 1920 to 1960 and Kortum (1996) reported that the number of patents per research worker shows a clear downward decline in the US from the 1960:s into the 1990:s. These findings are not restricted to the US; Evenson (1984) documents a worldwide decline. Moreover, Kortum (1993) reports a decline in patents per R&D expenditures across all manufacturing industries. According to Mansfield (1986), the decline is not caused by a falling propensity to patent innovations.[20] While this evidence does not constitute proofs that effort has fallen over time, they are nevertheless consistent with our model's predictions since, for instance, population growth lowers R&D workers' effort. Other possible explanations for the drop in R&D workers' productivity have been offered by, for instance, Kortum (1996) and Segerstrom (1999).

Arguments could be made both for and against the view that changes in effort matter. In favor of this view are the convincing sociological and psychological evidence that fair wage considerations matter to workers' behavior. Moreover, it is a fact that firms in R&D races have very strong incentives to extract top performance out of their R&D workers. Firms also go a long way to find compensation policies that serve the purpose of stimulating hard work, particularly among workers in key positions. Firms would hardly invest in such policies unless they considered effort to be a key variable for the performance of the firm or if they thought that changes in effort were of a short run nature. Agell and Lundborg (2002) shows that employees in Sweden improved the work performance during the 1990:s. There is also evidence, albeit of an anecdotal nature, that people work very hard in "tiger economies" which appears consistent with our model. Stafford and Duncan (1980) analyzed time diaries from the mid-1970s in the US and showed that effort varied a great deal across worker categories and that workers spent a fair amount of their work time not working. While these facts do not directly corroborate our results they still suggest that effort may vary considerably also over time.

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civil engineer degree *relative* to years of mandatory schooling has fallen a great deal over the last 60-100 years.

[20] This productivity drop may of course have several explanations of which lower effort is just one candidate. For instance, Segerstrom (1999) presents a model based on increasing difficulties of innovating that is able to theoretically account for this phenomenon and the present model offers another explanation.

Mechanisms that reduce the positive growth effect show up in our model. In particular, an increase in demand for higher education is consistent with the stylized fact that growth rises less than inputs of R&D. As more and more workers prefer higher education, the relative supply of R&D workers increases over time which not only raises the under utilization rate of R&D workers, but it also tends to reduce schooling years of individual R&D workers. Human capital per R&D worker thus drops suggesting deviations between *measurable* inputs of R&D workers and actual human capital employed by firms in their laboratories. The results point to the problems of correctly measuring R&D inputs as human capital. Obviously, simply counting the number of workers employed in firms is not enough; knowledge about the share of R&D workers that firms actually allocate to R&D and the level of R&D workers' human capital, as measured by for instance years of schooling, seems imperative.

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Figure 1. Scientists & Engineers employed in R&D and workers with higher education. 1960-2000. 1960=100.

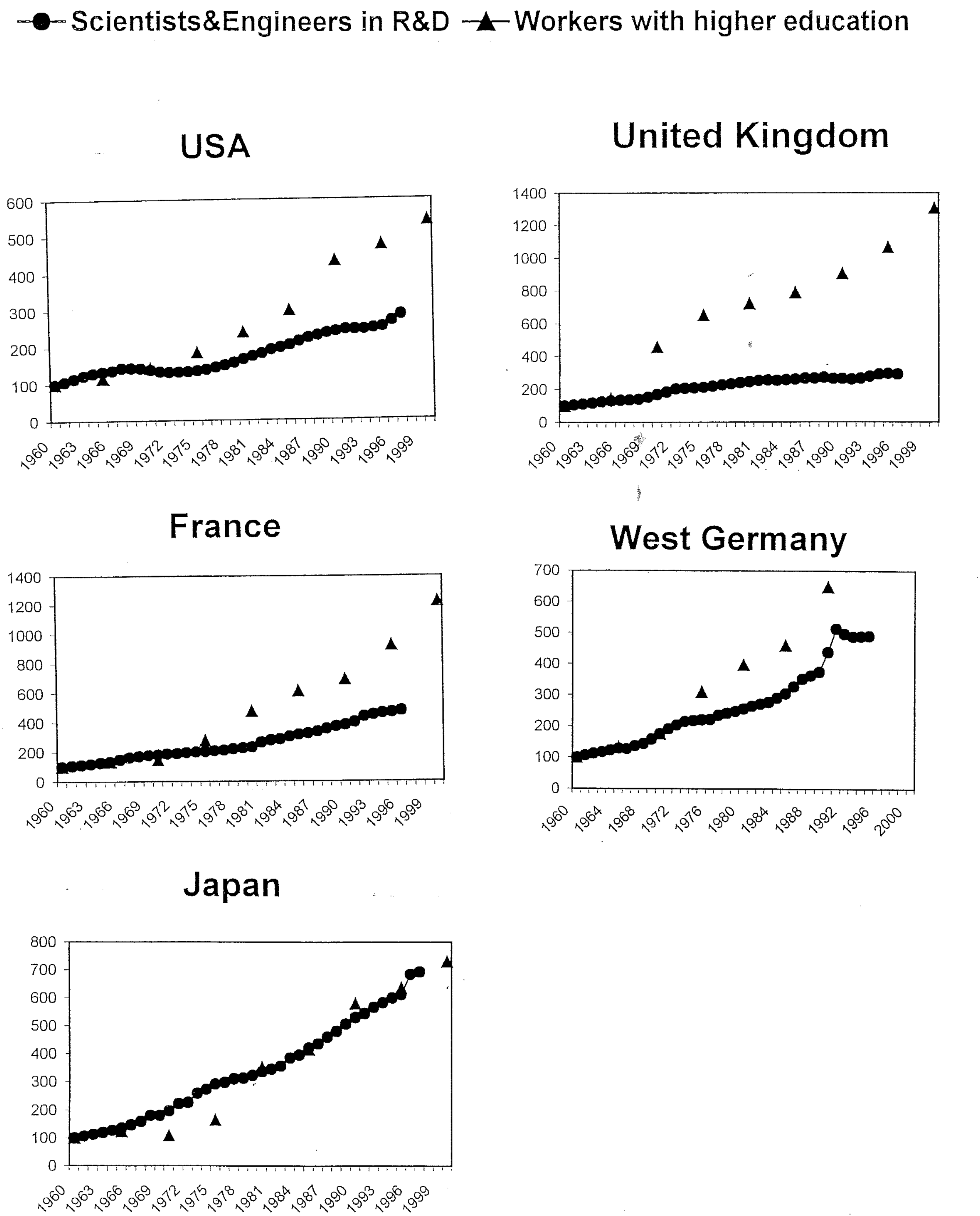
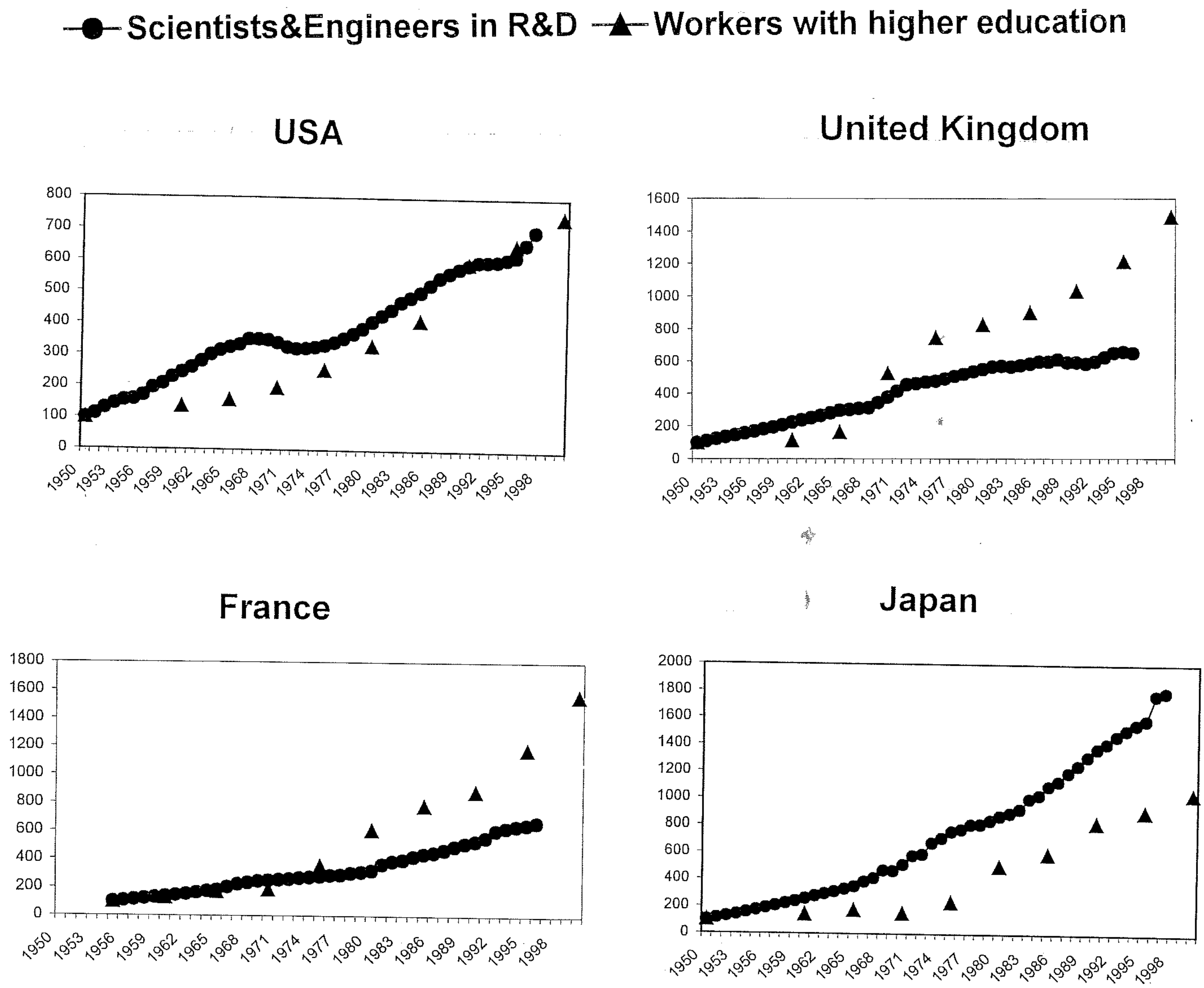


Figure 2. Scientists & Engineers employed in R&D and workers with higher education. 1950-2000. 1950=100.



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