

ARTICLES

OPTIMAL EDUCATION IN AN AGE-STRUCTURED MODEL UNDER CHANGING LABOR DEMAND AND SUPPLY

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We introduce a model of the optimal education policy at the macro level, allowing for heterogeneity of the workforce with respect to its age and qualification skills. Within this framework we study the optimal education rate in the context of changes in labor demand (as represented by the elasticity of substitution across ages and qualification) and labor supply (as represented by a change in the population growth rates). Applying an age-structured optimal-control model, we derive features of the optimal age-specific education rate. Our results show that the relation between the elasticities of substitution of labor across ages plays a crucial role in the way the demographic changes affect (both in the short and in the long run) the optimal educational policy. We also show that under imperfect substitutability across age and qualification groups, the optimal educational policy is adjusted in advance to any change in the labor supply.

Keywords: Human Capital, Age Composition of Labor, Age-Structured Model, Optimal Control

1. INTRODUCTION

Changes in the age distribution of the workforce—as caused by changes in the cohort size of entering labor flows—and its implications for labor market outcomes such as wages and unemployment have been extensively discussed in the empirical economic literature [Freeman (1979); Welch (1979); Katz and Murphy (1992); Murphy and Welch (1992)]. Besides the age structure, the skill level constitutes

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a further important heterogeneity of workers in the labor market. Labor market outcomes for different skill groups (in particular wage dispersion) have been extensively studied [e.g., Katz and Autor (1999)].

In a seminal paper, Card and Lemieux (2001) reconcile the work of Welch (1979) and of Katz and Autor (1999). They introduce an aggregate production function that accounts for imperfect substitutability of workers across age and education. Their aim is to explain the empirical fact that the rise in education-related wage differentials in the United States from 1959 to 1995 is mainly due to a rise in the college–high school wage gap for younger men, whereas the gap for older men has remained fairly constant over the same time period (1959–1995). Within their framework, the authors show “that the increase in the college–high school wage gap over the past two decades is attributable to steadily rising relative demand for college-educated labor, coupled with a dramatic slowdown in the rate of growth of the relative supply of college-educated workers.”

As argued in Rojas (2005), the implications of these empirical studies have not yet been integrated into formal macroeconomic models except in Lam (1989) and in Kremer and Thomson (1998). Whereas Lam considered the effect of the change in age structure on life-cycle wage profiles in a stable population, Kremer and Thomson study the role of imperfect substitution across workers of different age in explaining the speed of convergence of per capita output between countries.

The assumption that workers of different ages are not perfectly substitutable across age within educational groups is also empirically verified by Stapleton and Young (1988). According to them, there is empirical evidence that the elasticity of substitution across ages of unskilled labor is higher than that for skilled labor. Recently Roger and Wasmer (2009) also indicated the importance of controlling for age and skill heterogeneity for explaining labor productivity. The fact of imperfect substitutability across age and education implies that there is an optimal age–education mix of the workforce (in terms of output maximization). Our aim is to provide a model of the optimal education/training policy, i.e., optimal assignment of resources to transform unskilled into skilled labor, at the macro level allowing for heterogeneity of the workforce with respect to its age and qualification skills. Within this framework we study the optimal education/training rate in the context of alternative labor demand and labor supply effects. The degree of substitutability across workers of different age and education characterizes the labor demand pattern. Labor supply is determined by the inflow of low- and high-skilled workers. Because we assume zero mortality and full employment, labor supply is determined by a change in the demographic factors in our model.

Our paper is motivated by the fact that population aging, as caused by decreasing fertility and increasing survival to older ages, implies a change in the age and educational composition of the workforce and, hence, requires a change in the optimal age-specific education policy. Obviously the substitutability of workers across age and across qualifications, together with increasing demand for educated workers and technological progress, constitute key factors explaining the relation between demographic change and educational investment at the macro level.

According to the theory of optimal life-cycle human capital investment, human capital accumulation is concentrated at the beginning of life [Weiss (1986)]. An economy characterized by population aging might therefore exhibit an “older vintage” of human capital. It is therefore of interest how a social planner will react in terms of its age-specific human capital investment under conditions of labor force aging and faced with alternative labor demand patterns.

So far, formal models of population aging and human capital formation have concentrated on explaining educational activities at the individual level, e.g., Bouccekine et al. (2002) and Heijdra and Romp (2009), and its implication for long-run economic growth. Increased longevity will increase educational activities at the individual level and may boost economic growth at the aggregate level. In this literature, the pattern of labor demand and its interrelationship with changing demographic supply are not considered. In contrast to these models, we start at the macro level and consider the optimal age-specific education policies if workers of different age and skill are not perfectly substitutable in the work process and if labor supply is determined by the prevailing demographic structure.¹

In summary, our paper is intended to raise and address the following questions:

- (i) Compared to the case of perfectly substitutable labor across ages and across education, how will the optimal age-specific educational policy change under conditions of imperfectly substitutable labor across age and across qualification groups?
- (ii) Compared to the case of a stationary population, how will increasing or decreasing population (hence change in the labor supply) affect the optimal educational policy?
- (iii) Will the long-run and short-run effects of a change in the demand and supply factors of labor differ? In particular, will a change in demographic factors be anticipated in the optimal educational policy in advance of the time point where the actual change takes place?

The main methodological instrument employed in the paper to answer the above questions is that of intertemporal dynamic optimization in a model in which time and age change continuously. The dynamics of human capital is then described by an *age-structured system of differential equations*, in contrast to overlapping-generations (OLG) models involving a presumably small number of coexisting generations. The paper exhibits several advantages of the continuous age framework. First, the obtained results are independent of the number of age groups (in contrast to OLG models, where the number of age groups may have an effect on the results). Second, working in continuous time/age allows to use standard analytic tools such as derivatives and integrals more efficiently. Third, some of the results (that in Section 4, in particular) cannot be established at all in the OLG framework unless a rather fine differentiation of age groups is used (above ten age groups for the result in Section 4, for example). Finally, the continuous time/age model is advantageous also from a numerical point of view, because it allows more profound time/age aggregation (discretization) than the a priori discretization involved in the OLG models [see, e.g., Section 5 in Veliov (1997)].

Optimality conditions for the continuous-time/age dynamic optimization problem are presented and discussed in Section 3. The conditions are derived in Appendix B using the general result in Feichtinger et al. (2003).

Although a (continuous) age structure has been introduced into the neoclassical theory of optimal investment in several recent contributions [e.g., Barucci and Gozzi (2001); Feichtinger et al. (2005, 2006)]; we are aware only of the paper by Christiaans (2003) and our own work [Prskawetz and Veliov (2007)] that augmented the classical theory of labor demand by modeling the age structure of the workers. The vintage structure of human capital has been integrated into a model of growth and technological diffusion by Chari and Hopenhayn (1991). The authors assume that different vintages coexist in each time period and operate with technology-specific skilled and unskilled human capital. The equilibrium distribution of skilled workers across the vintages is derived endogenously, depending on consumers' optimal supply of unskilled and skilled labor force and vintage-specific optimal demand for skilled and unskilled workers. Similarly to our model, new and old human capital may not be perfectly substitutable in the production process. Although Chari and Hopenhayn allow only young unskilled and old skilled or unskilled labor, and differentiate between vintages of production, we ignore the latter assumption but allow for continuous age-specific labor. More recently, the vintage structure of human capital has also been introduced into a model of endogenous growth by Boucekine et al. (2002).

In the model we present in Section 2, the aggregate production depends on the age- and skill-specific supply of labor. A general production function of CES type is employed, which reflects the imperfect substitutability between different age groups and between labor with different qualification.

In Section 4, we prove that in the case of perfect substitutability of workers across age and qualification, the optimal educational rate is independent of demographic changes. Furthermore, we show that it might be nonmonotonic in age; that is, it might be profitable to postpone education to somewhat greater ages in order to benefit from cost-free "learning by doing" and to take advantage from the more advanced knowledge that one can obtain at a later time.

The situation substantially changes in the case of nonperfect substitutability of workers across age and qualification, and this is a key point in the paper. In Section 5 we show that the effect of demographic changes on the formation of human capital critically depends on the elasticity of substitution across ages and across qualifications. In addition, this effect may be qualitatively different in the short versus the long run. Changes in the age-specific supply of workers together with the prevailing demand structure of the economy—as reflected by the parameters of the elasticity of substitution—determine the evolution of the human capital. The analysis clearly exhibits the importance of the relation between the elasticities of substitution across age and qualification, which may lead to different (opposite) impacts of the demographic change on the optimal educational policy. Moreover, it is shown that a change in the labor supply influences the optimal education policy already in advance of the time point when the change takes place.

The data specifications and the derivation of the optimality conditions are given in two appendices. The longer proofs are presented in Research Report 2010-09, ORCOS, TU-Wien, 2010, http://www.eos.tuwien.ac.at/OR/research/reports_list.html.

2. THE MODEL

Below, $t \in [0, T]$ denotes the time, and T is the end of the (presumably large) planning horizon. In our model the workers will be distinguished by their “active” ages, s . It is assumed that all individuals start working at the same age, $s = 0$ (which corresponds to, say, twenty years of biological age) and retire at age $s = \omega$. We distinguish the workers also by their skills, considering for simplicity two levels of qualification: low-skilled and high-skilled workers. We denote by $L(t, s)$ the number of low-skilled workers of age s at time t , and similarly, by $H(t, s)$ the number of high-skilled workers resulting from the government’s investment in human capital.

Upgrading of low-skilled workers into high-skilled workers takes place at a rate $l(t, s)u(t, s) + e(s)$. Here $u(t, s)$ denotes the educational rate at time t for workers of age s . The function $l(t, s)$ reflects the dependence of the learning abilities of the workers on time and age, and $e(s)$ represents learning by doing, which depends on the years spent working. At the same time, due to technological progress or for other reasons, high-skilled workers of age s may lose their skills at a rate $\delta(t, s)$.

The dependence of learning abilities on age is investigated in Pfeiffer and Reuß (2007). As the authors demonstrate, though older persons might already have high levels of skills as opposed to younger persons, their learning ability is slower than that of younger persons. They also show that skill depreciation accelerates with age. Besides the age-specific dependence of learning and depreciation, learning ability may also depend on time, due to technological progress.

The equations for the dynamics of the stock of low- and high-skilled workers are therefore

$$L_t + L_s = \delta(t, s)H(t, s) - e(s)L(t, s) - l(t, s)u(t, s)L(t, s),$$

$$L(t, 0) = L_0(t),$$

$$H_t + H_s = -\delta(t, s)H(t, s) + e(s)L(t, s) + l(t, s)u(t, s)L(t, s),$$

$$H(t, 0) = H_0(t),$$

$$L(0, s), H(0, s): \text{ given initial data.}$$

The left-hand side, $L_t + L_s = \lim_{h \rightarrow 0} (L(t+h, s+h) - L(t, s))/h$, represents the change in one unit of time of the low-skilled labor that is of age s at time t . This change is composed of downgrading high-skilled to low-skilled workers (decay of human capital) at rate $\delta(t, s)$ and of upgrading low-skilled to high-skilled workers at rate $e(s)$ due to costless on-the-job learning by doing and at rate $l(t, s)u(t, s)$

due to costly education. Similarly, the left-hand side, $H_t + H_s$, represents the change in one unit of time of the high-skilled labor. This change is composed of the same components as the change of the low-skilled labor, but with the opposite sign.

At age $s = 0$ the number of those who enter the work force at time t is $L_0(t)$ for the low-skilled and $H_0(t)$ for the high-skilled. We assume throughout the paper that $H_0(t)$ for each t is relatively small compared with $L_0(t)$. This reflects the fact that all but a few high school graduates enter the work force as low-skilled workers and have to undergo additional education/training in order to become high-skilled.

We assume also that there is no unemployment and there is no mortality at working ages; therefore the sum $L(t, s) + H(t, s)$ equals the total working-age population, which is determined by the exogenously given total inflow, $N_0(t)$. Thus $L_0(t) + H_0(t) = N_0(t)$. This makes it possible to exclude the variable $H(t, s)$ from the model and to pass to a single differential equation for $L(t, s)$. However, for better transparency of the exposition, we shall work with equations for both $L(\cdot, \cdot)$ and $H(\cdot, \cdot)$.

The price of education per capita, $u(t, s)$, is $p(s, u(t, s))$, where $p(\cdot, \cdot)$ is a given function of (s, u) . The total cost $P(t)$ of the educational effort for the society at time t is therefore represented as

$$P(t) = \int_0^\omega p(s, u(t, s))L(t, s) ds.$$

We allow for imperfect substitutability across age groups for both low-skilled and high-skilled labor. If $\pi_L(\cdot)$ and $\pi_H(\cdot)$ are the respective relative-efficiency parameters (assumed to be fixed over time), the two subaggregates of low-skilled and high-skilled labor at time t , $\tilde{L}(t)$ and $\tilde{H}(t)$, are given by the following two CES functions:

$$\begin{aligned} \tilde{L}(t) &= \left(\int_0^\omega \pi_L(s)(L(t, s))^{\lambda_L} ds \right)^{1/\lambda_L}, \\ \tilde{H}(t) &= \left(\int_0^\omega \pi_H(s)(H(t, s))^{\lambda_H} ds \right)^{1/\lambda_H}. \end{aligned}$$

Here $\lambda_L \in (-\infty, 1]$ and $\lambda_H \in (-\infty, 1]$ give the respective partial elasticities of substitution $1/(1 - \lambda_i)$ for $i = L, H$. In the limiting case of perfect substitutability across age groups, λ_L and λ_H are equal to 1 and the aggregate of low-skilled and high-skilled labor is simply a weighted sum of age-specific supply.

We assume that the production technology depends only upon labor. The aggregate output at time t is given by a CES function of the two subaggregates of low-skilled and high-skilled labor, in which the technological level is represented by the two efficiency parameters $\theta_L(t)$ and $\theta_H(t)$:

$$Y(t) = (\theta_L(t)(\tilde{L}(t))^\rho + \theta_H(t)(\tilde{H}(t))^\rho)^{1/\rho}.$$

Here again $\rho \in (-\infty, 1]$ gives the partial elasticity of substitution, $\sigma_W = 1/(1 - \rho)$, between high-skilled and low-skilled labor. Note that the marginal product of labor for a given age–education group depends on the group’s own supply of labor and the aggregate supply of labor in the education category.

The net revenue of the society at time t is the aggregate output $Y(t)$ minus the cost of education, $P(t)$, i.e., $Y(t) - P(t)$.

The formal problem of a central planner is to maximize the accumulated discounted net revenue by choosing optimally the educational rate $u(t, s)$.² Discounting the future at a rate $r \geq 0$, we come up with the following dynamic optimization problem with state variables $L(t, s)$, $H(t, s)$, $\tilde{L}(t)$, $\tilde{H}(t)$, and $P(t)$ and control variable $u(t, s)$:

$$\max \int_0^T e^{-rt} [(\theta_L(t)(\tilde{L}(t))^\rho + \theta_H(t)(\tilde{H}(t))^\rho)^{1/\rho} - P(t)] dt \tag{1}$$

subject to

$$L_t + L_s = \delta(t, s)H(t, s) - e(s)L(t, s) - l(t, s)u(t, s)L(t, s), \tag{2}$$

$$L(t, 0) = L_0(t),$$

$$H_t + H_s = -\delta(t, s)H(t, s) + e(s)L(t, s) + l(t, s)u(t, s)L(t, s), \tag{3}$$

$$H(t, 0) = H_0(t),$$

$L(0, s), H(0, s)$: given initial data,

$$\tilde{L}(t) = \left(\int_0^\omega \pi_L(s)(L(t, s))^{\lambda_L} ds \right)^{1/\lambda_L}, \tag{4}$$

$$\tilde{H}(t) = \left(\int_0^\omega \pi_H(s)(H(t, s))^{\lambda_H} ds \right)^{1/\lambda_H}, \tag{5}$$

$$P(t) = \int_0^\omega p(s, u(t, s))L(t, s) ds, \tag{6}$$

$$u(t, s) \geq 0. \tag{7}$$

Because our model does not include education as a separate sector [cf. Lucas (1988); Boucekkine and Ruiz-Tamarit (2008)], the control u is directly interpreted as on-the-job training. However, the results are not limited to this interpretation. Indeed, let the workers of different qualification be perfectly substitutable ($\rho = 1$) and let the unskilled workers of different ages also be perfectly substitutable ($\lambda_L = 1$). Then an amount of labor, uL , of age s allocated at time t to education instead of production has a total cost consisting of the opportunity cost $\pi_L(s)\theta_L uL$ (from lost production) and the cost of education. Both costs may be included in $p(s, u)L$; therefore our model completely covers the case of college/university education in the case of a linear production function. In the case of nonperfect

elasticity of substitution either across ages or across qualifications, the learning should be (strictly speaking) interpreted as costly “training.”

The next assumptions will be assumed to hold throughout the paper.

Standing Assumptions. All exogenous functions are continuous as well as the derivatives that appear later on in the text, excluding the population inflow data $L_0(t)$ and $H_0(t)$, which are assumed only to be piecewise continuous. The cost function $p(s, u)$ is monotonically increasing and strongly convex with respect to u . The initial and boundary data $L(0, s)$, $H(0, s)$, $L_0(t)$, and $H_0(t)$, as well as the efficiency coefficients θ_L , θ_H , π_L , and π_H , are strictly positive.

The strong convexity assumption for $p(s, \cdot)$ provides substantial mathematical convenience, as usual. At the same time, it can be economically justified: the greater the fraction of the low-skilled workers of a certain age that are involved in education, the larger the per capita educational cost due to the heterogeneity of people with respect to their abilities (the best are taken first in the educational process).

For a precise definition of the notion of a solution to system (2)–(6) and the appropriate space settings, we refer to Webb (1985) and to Feichtinger et al. (2003).

3. OPTIMALITY CONDITIONS

The necessary optimality conditions for problem (1)–(7) follow from the Pontryagin-type maximum principle obtained in Feichtinger et al. (2003). A sketch of the derivation is given in Appendix B, where the following result is obtained.

PROPOSITION 1. *If $(L, H, \tilde{L}, \tilde{H}, P, u)$ is a solution of the optimal control problem (1)–(7) then the equation*

$$\Delta_t + \Delta_s = (r + e(s) + \delta(t, s) + l(t, s)u(t, s))\Delta - p(s, u(t, s)) - f(t, s), \quad (8)$$

$$\Delta(t, \omega) = 0, \quad \Delta(T, s) = 0$$

with

$$f(t, s) = Y(t)^{1-\rho}\theta_H(t)\pi_H(s)\tilde{H}(t)^{\rho-\lambda_H}H(t, s)^{\lambda_H-1}$$

$$- Y(t)^{1-\rho}\theta_L(t)\pi_L(s)\tilde{L}(t)^{\rho-\lambda_L}L(t, s)^{\lambda_L-1}$$

has a unique solution $\Delta(t, s)$ and for (almost) every $(t, s) \in [0, T] \times [0, \omega]$ the optimal $u(t, s)$ maximizes the function $\Delta(t, s)l(t, s)u - p(s, u)$ over all $u \geq 0$.

Here $\Delta(t, s)$ represents the difference between the marginal values (“shadow prices”) of skilled and nonskilled labor, that is, the marginal benefit of transforming one unit of low-skilled labor into one unit of high-skilled labor. In the above equation, $(r + \delta(t, a))\Delta(t, s)$ represents the opportunity cost and f is the age-specific marginal gain in productivity from this transformation. The remaining terms $(e(s) + l(t, s)u(t, s))\Delta(t, s) - p(s, u(t, s))$ on the right-hand side of (8) represent the fact that by being skilled the educational cost $p(s, u)$ is saved, but

with it the worker loses the opportunity of becoming skilled later at the rate $e(s) + l(t, s)u(t, s)$.

According to the standing assumptions, the derivative $p_u(s, u)$ exists and is invertible with respect to u . Denote by $z \rightarrow p_u^{-1}(s, z)$ the inverse and define

$$p_{u+}^{-1}(s, z) = \begin{cases} p_u^{-1}(s, z) & \text{if } z > p_u(s, 0), \\ 0 & \text{elsewhere.} \end{cases}$$

Then the unique maximizer of $\Delta(t, s)l(t, s)u - p(s, u)$ subject to $u \geq 0$ can be written as

$$u(t, s) = p_{u+}^{-1}(s, l(t, s)\Delta(t, s)). \tag{9}$$

Notice that if $l(t, s)\Delta(t, s) > p_u(s, 0)$ for some (t, s) , then $u(t, s) > 0$ and (9) reads as $p_u(s, u(t, s)) - l(t, s)\Delta(t, s) = 0$. Otherwise, $u(t, s) = 0$. For example, with the usual specification $p(s, u) = b(s)u + 0.5cu^2$ the optimal control takes the form

$$u(t, s) = \begin{cases} (\Delta(t, s) - b(s))/c & \text{if } \Delta(t, s) > b(s), \\ 0 & \text{elsewhere.} \end{cases} \tag{10}$$

Thus educational effort is applied only for those ages for which the marginal cost of education at $u = 0$ is exceeded by the benefit of the education, measured by the difference between the shadow prices of skilled and unskilled labor.

Substituting u from (9) in (8), we obtain that

$$\begin{aligned} \Delta_t + \Delta_s &= (r + e(s) + \delta(t, s) + l(t, s)p_{u+}^{-1}(s, l(t, s)\Delta))\Delta \\ &\quad - p(s, p_{u+}^{-1}(s, l(t, s)\Delta)) - f(t, s), \tag{11} \\ \Delta(t, \omega) &= 0, \quad \Delta(T, s) = 0. \end{aligned}$$

It is important to notice that the function $p_{u+}^{-1}(s, \cdot)$ is Lipschitz continuous; therefore (8), together with the side conditions $\Delta(t, \omega) = 0$ and $\Delta(T, s) = 0$, uniquely determines the solution $\Delta(t, s)$, and hence also the optimal control u by (9).

4. THE CASE OF PERFECT SUBSTITUTABILITY OF LABOR

In this section we consider the simplest case, in which problem (1)–(7) becomes linear with respect to the state variables:³ the case of perfectly substitutable labor across ages and across qualifications, $\rho = \lambda_L = \lambda_H = 1$.

PROPOSITION 2. *The optimal educational rate $u(t, s)$ is independent of the initial data $L(0, s)$, $H(0, s)$ and of the low- and high-skilled worker inflows $L_0(t)$ and $H_0(t)$. If all data are time-invariant [except for $L_0(t)$ and $H_0(t)$] then $u(t, s) = u(s)$ is also time invariant in the time interval $[0, T - \omega]$.*

The proposition implies, in particular, that a demographic change (represented by $L_0(t)$ and $H_0(t)$)⁴ would not have any influence on the optimal educational rate. Moreover, in the stationary case, the end of the time horizon T may influence

the optimal control no longer than one generation before the end of the horizon, that is, on $[T - \omega, T]$ only.

Proof. To prove the first claim of the proposition we note that now $f(t, s) = \theta_H(t)\pi_H(s) - \theta_L(t)\pi_L(s)$ in (8) and the right-hand side of (8) and the side conditions do not depend on L and H , and therefore on the data $L(0, s)$, $H(0, s)$, $L_0(t)$, and $H_0(t)$. Because Δ does not depend on the demographic data, u does not too, because of (9).

In the time-invariant case we have $f(t, s) = f(s)$. Let us denote $z(\tau; a) = \Delta(\tau - a, \omega - a)$, where $\tau \in [0, T]$ is a parameter and $a \in [0, \min\{\tau, \omega\}]$. Then, denoting $a' = \omega - a$, we have

$$-\frac{d}{da}z = (r + \delta(a') + e(a') + l(a')p_{u+}^{-1}(a', l(a')z))z - f(a') - p(a', p_{u+}^{-1}(a', l(a')z)).$$

Clearly, the right-hand side is independent of τ , and because we have $z(\tau, 0) = \Delta(\tau, \omega) = 0$, the solution $z(\tau; a) = z(a)$ is independent of τ . For $t \in [0, T - \omega]$ and $s \in [0, \omega]$ we have

$$\Delta(t, s) = z(t + \omega - s; \omega - s) = z(\omega - s)$$

and the right-hand side is independent of t (because $t + \omega - s \in [0, T]$ if $t \in [0, T - \omega]$). Using (9), we complete the proof. ■

Several papers on optimal education and human capital formation [cf. Weiss (1986) and Boucekine et al. (2002) for a review of the theoretical literature on optimal life-cycle human-capital investment] assume or conclude that educational efforts are optimally allocated to youngest ages and decrease with age. We established numerically that this is not always true in our model; namely, the optimal educational rate, $u(s)$, may strictly increase at certain ages. Below we analyze mathematically the reason for this effect and give some economic explanations. To make the analysis more transparent, we present it in the case of time-invariant data and a quadratic cost function $p(u)$. Moreover, it is clear that decreasing learning ability $l(s)$ encourages learning at young ages and cannot be a reason for increasing learning with age. Therefore we assume learning ability to be constant.

PROPOSITION 3. *Assume that all data [except for $L_0(t)$ and $H_0(t)$] are time-invariant and continuous in s , $l(s) = l$, $p(u) = bu + \frac{c}{2}u^2$. Let there exist some s for which $u(s) > 0$ and such that one of the following conditions holds:*

$$(i) \quad d(s) - \frac{b}{c}l \geq 0 \quad \text{and} \quad \theta_H\pi_H(s) - \theta_L\pi_L(s) < \frac{b^2}{2c};$$

or

$$(ii) \quad d(s) - \frac{b}{c}l < 0 \quad \text{and} \quad \theta_H\pi_H(s) - \theta_L\pi_L(s) < \frac{b}{l}d(s) - \frac{c}{2l^2}(d(s))^2,$$

where $d(s) = r + \delta(s) + e(s)$. Then there exists $s_0 \in (0, \omega)$, where u is differentiable and $u'(s_0) > 0$.

Proof. According to (10), in the time-invariant case

$$u(s) = \max \left\{ 0, \frac{1}{c}(l\Delta(s) - b) \right\}, \tag{12}$$

$$\Delta'(s) = (r + \delta(s) + e(s) + lu(s)) \Delta(s) - f(s) - \left(bu(s) + \frac{c}{2}(u(s))^2 \right), \tag{13}$$

where as before $f(s) = \theta_H \pi_H(s) - \theta_L \pi_L(s)$. Hence, the optimal control is a continuous function. Let a be the minimal number such that $u(s) = 0$ on $(a, \omega]$. Because u is not identically zero, we have $a > 0$. Clearly $u(s) > 0$ on some maximal (to the left) interval (a_0, a) . Then

$$u(s) = \frac{1}{c}(l\Delta(s) - b) \quad \text{for } s \in (a_0, a).$$

In particular, u is differentiable on (a_0, a) .

Assume that $u'(s) \leq 0$ on (a_0, a) . Apparently this implies that $a_0 = 0$. Moreover, $\Delta(s)$ must satisfy $\Delta'(s) \leq 0$ on $(0, a)$. On this interval Δ satisfies the equation [resulting from (13) after substitution of $u(s)$ from (12)]

$$\begin{aligned} \Delta'(s) &= \left(r + \delta(s) + e(s) + \frac{l}{c}(l\Delta(s) - b) \right) \Delta(s) \\ &\quad - f(s) - \frac{b}{c}(l\Delta(s) - b) - \frac{1}{2c}(l\Delta(s) - b)^2. \end{aligned} \tag{14}$$

Rearranging the terms, we obtain

$$\Delta'(s) = q_2(\Delta(s))^2 + q_1\Delta(s) - q_0,$$

where

$$q_2 = \frac{l^2}{2c}, \quad q_1(s) = r + \delta(s) + e(s) - \frac{bl}{c}, \quad q_0 = f(s) - \frac{b^2}{2c}. \tag{15}$$

Because $\Delta'(s) \leq 0$, for every $s \in (0, a)$ the quadratic form $q_2x^2 + q_1(s)x - q_0(s)$ takes a nonpositive value for some $x \geq 0$. This means that

$$\min_{x \geq 0} \{q_2x^2 + q_1(s)x - q_0(s)\} \leq 0.$$

Calculating this minimum, we obtain two possibilities.

Case (i): If $-q_1(s)/2q_2 \leq 0$ then $q_0(s) \geq 0$.

Case (ii): If $-q_1(s)/2q_2 > 0$ then $(q_1(s))^2 + 4q_0(s)q_2 \geq 0$.

Substituting from (15), one obtains that Case (i) contradicts assumption (i) and Case (ii) contradicts the alternative assumption (ii) of the proposition. This completes the proof. ■

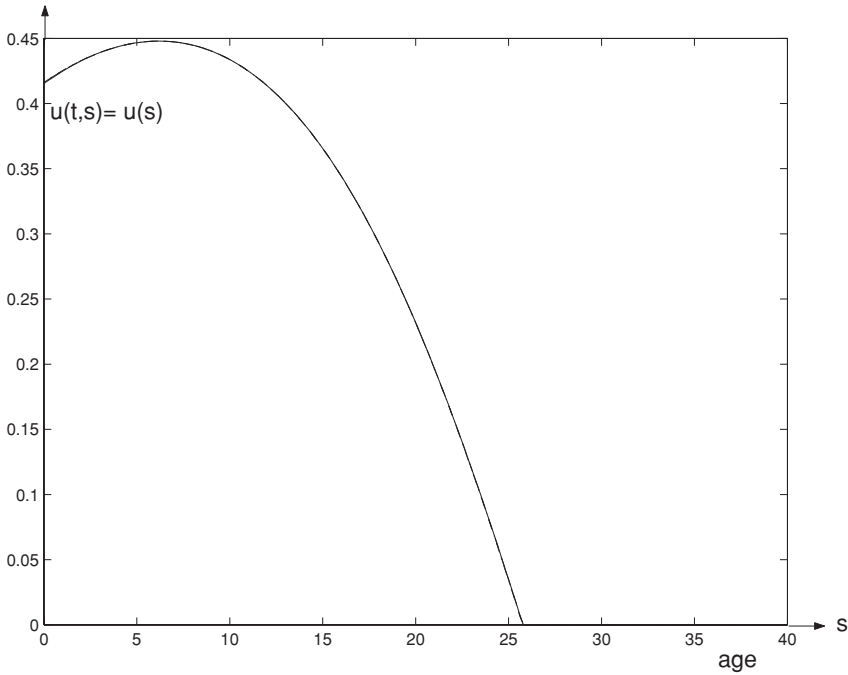


FIGURE 1. Age distribution of the optimal training rate.

The sufficient conditions for nonmonotonic behavior of the optimal educational rate are fulfilled if

- (i) $d(s) = r + \delta(s) + e(s)$ is sufficiently large for some s (larger than bl/c) and $f(s) = \theta_H \pi_H(s) - \theta_L \pi_L(s)$ is sufficiently small for this s (smaller than $b^2/2c$);
- (ii) $d(s)$ is not that large, but $f(s)$ is small enough, now depending on the value of $d(s)$.

In economic terms, an increase of the educational rate with age would happen if for some age the sum of depreciation (r), dequalification [$\delta(s)$], and “learning by doing” [$e(s)$] rates is large relative to the productivity differential f . If in a certain age interval the productivity differential is small, this may lead to postponement of learning because in the short run the returns to education are small. The returns to education may be reduced by the fact that people can lose their costly qualification [with rate $\delta(s)$] and can make use of costless “learning by doing” [with rate $e(s)$]. In addition, a higher depreciation rate diminishes the role of the length of the time interval in which the worker exercises his qualification, and therefore increases the chances for nonmonotonic learning. We have numerically found the optimal educational policy for the perfect substitutability case (the respective data are presented in Appendix A). Figure 1 shows that increasing learning with age may happen even when $\delta = e = 0$. We mention that a higher value of δ can be associated with a higher rate of technological progress. Thus higher technological

progress may lead to postponement of learning to older ages in order to take advantage of more advanced knowledge.

5. EFFECTS OF THE DEMOGRAPHIC FACTOR IN THE CASE OF IMPERFECT SUBSTITUTABILITY OF LABOR

5.1. Long-Run-Effects

The demographic factor is represented in our model by the exogenous inflow of new labor, $N_0(t)$, split into $L_0(t) + H_0(t) = N_0(t)$. Because we assume full employment a change in the demographic factor is equivalent to a change in the labor supply. To investigate the impact of a demographic change on the optimal educational policy, we compare three scenarios, constant, increasing, and decreasing population, by choosing $L_0(t) = L_0e^{\gamma t}$, $H_0(t) = H_0e^{\gamma t}$, where γ is a zero, positive, or negative growth rate, respectively. Because all the equations in the model and the objective function are homogeneous of first order, the optimal solution is independent of the size of the population. Hence, it is not the different population sizes that are responsible for the different solutions in the three scenarios that we encounter below, but rather *the differences in the age distribution* of the populations with different growth rates.

The elasticity of substitution across ages for low- and for high-skilled labor are determined by λ_L and λ_H , respectively. We focus our investigation in this section on how the demographic factor influences the optimal learning rates in different ages in the case of nonperfect substitutability of workers, taking $\lambda_L < 1$ and/or $\lambda_H < 1$. Therefore, to shorten the formulas, we assume perfect substitutability across qualifications: $\rho = 1$. Moreover, we assume that all data [except for $L_0(t)$ and $H_0(t)$] are time-invariant.

We change the variables $L^\gamma(t, s) = e^{-\gamma(t-s)}L(t, s)$, $H^\gamma(t, s) = e^{-\gamma(t-s)}H(t, s)$ in equations (2) and (3) (in which the boundary data $L_0(t)$ and $H_0(t)$ are specified as explained above). In fact, L^γ and H^γ satisfy exactly the same equations (2), (3), except that the boundary conditions become constant: L_0 and H_0 , respectively. Also, the initial conditions change correspondingly. We next discuss the long-run behavior of the optimal solution, in which the initial data are irrelevant.

Substituting (L^γ, H^γ) for (L, H) also in equations (4)–(6) and in the objective function (1), we obtain the following equivalent problem:

$$\max \int_0^T e^{-(r-\gamma)t} [\theta_L \tilde{L}^\gamma(t) + \theta_H \tilde{H}^\gamma(t) - P^\gamma(t)] dt \tag{16}$$

subject to

$$L_t^\gamma + L_s^\gamma = \delta(s)H^\gamma(t, s) - e(s)L^\gamma(t, s) - l(s)u(t, s)L^\gamma(t, s), \tag{17}$$

$$L^\gamma(t, 0) = L_0,$$

$$H_t^\gamma + H_s^\gamma = -\delta(s)H^\gamma(t, s) + e(s)L^\gamma(t, s) + l(s)u(t, s)L^\gamma(t, s), \tag{18}$$

$$H^\gamma(t, 0) = H_0,$$

$L^\gamma(0, s), H^\gamma(0, s)$: given data,

$$\tilde{L}^\gamma(t) = \left(\int_0^\omega e^{-\gamma\lambda_L s} \pi_L(s) (L^\gamma(t, s))^{\lambda_L} ds \right)^{1/\lambda_L}, \tag{19}$$

$$\tilde{H}^\gamma(t) = \left(\int_0^\omega e^{-\gamma\lambda_H s} \pi_H(s) (H^\gamma(t, s))^{\lambda_H} ds \right)^{1/\lambda_H}, \tag{20}$$

$$P^\gamma(t) = \int_0^\omega e^{-\gamma s} p(s, u(t, s)) L^\gamma(t, s) ds, \tag{21}$$

$$u(t, s) \geq 0. \tag{22}$$

Thus we obtain that (L, H, u) solves our initial problem with an exponentially changing population [$L_0(t) = L_0 e^{\gamma t}, H_0(t) = H_0 e^{\gamma t}$] if and only if (L^γ, H^γ, u) solves the same problem for a constant population [$L_0(t) = L_0, H_0(t) = H_0$], but with modified data:

$$\begin{aligned} \pi_L^\gamma(s) &= e^{-\gamma\lambda_L s} \pi_L(s), & \pi_H^\gamma(s) &= e^{-\gamma\lambda_H s} \pi_H(s), \\ p^\gamma(s, u) &= e^{-\gamma s} p(s, u), & r^\gamma &= r - \gamma. \end{aligned}$$

The above simple transformation deserves some comments. First, we established that the optimal educational policy for an exponentially changing population is exactly the same as that for a stationary population with the above modified data. Assume for a moment that $\gamma > 0$. The modified per capita cost of learning, $p^\gamma(s, u)$, decreases with age compared to $p(s, u)$. This does not imply that there would be more learning at old ages, because the efficiency coefficients $\pi_L^\gamma(s)$ and $\pi_H^\gamma(s)$ decrease with s , too. However, we point out that $\pi_L^\gamma(s)$ and $\pi_H^\gamma(s)$ decrease with age at different rates. For instance, if $\lambda_H < \lambda_L$, then the efficiency of high-skilled labor decreases with age less than that of low-skilled labor. This observation leads to the suggestion that for $\gamma > 0$ and $\lambda_H \ll \lambda_L$ there would be a relative shift of learning from younger to older ages. This means that the normalized distribution of the optimal learning, $v(t, s) = u(t, s) / \int_0^\omega u(t, \sigma) d\sigma$, will be shifted to older ages compared with the stationary case $\gamma = 0$. The situation is similar for a decreasing population ($\gamma < 0$), except that “increase” and “decrease” should be interchanged. This is seen in Figure 2, where $\lambda_H = 0.1, \lambda_L = 0.9$. Both the absolute (left plot) and the normalized (right plot) learning rate shift to older ages for the increasing population, and to younger ages for the decreasing population.

The situation is the opposite if $\lambda_H \gg \lambda_L$. This is clearly supported by Figure 3, which shows that the learning age-density, v , shifts to older ages if the population decreases, and to younger ages if it increases [the right plot gives $v(40, \cdot)$]. The left plot represents the optimal learning $u(t = 40, s)$ for the three populations, showing that in addition to the age-shift, there is an increase of learning at all ages for the decreasing population.

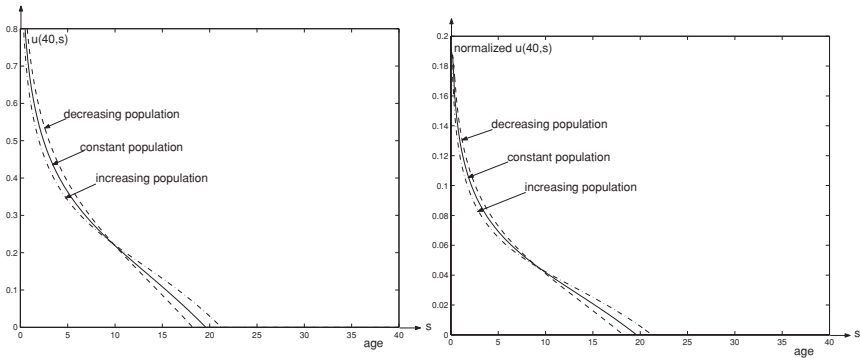


FIGURE 2. Optimal training rate u (left) and normalized age-density v (right) at $t = 40$ for the three scenarios. Here $\lambda_L = 0.9, \lambda_H = 0.1$.

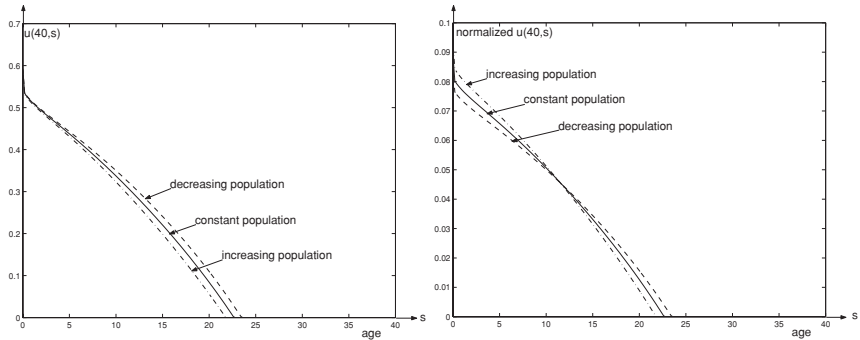


FIGURE 3. Optimal training rate u (left) and the normalized age-density v (right) at $t = 40$ for the three scenarios. Here $\lambda_L = 0.1, \lambda_H = 0.9$.

Intuitively, this change in the age-specific learning rate can be explained as follows. In the case of an increasing population, the additional labor entering the market would lead to a shift from the optimal age composition for the stationary case toward an excessive amount of young unskilled labor. If the educational rate remains unchanged, then this shift will result in a shift toward lower ages of the age distribution of skilled labor too. Thus keeping the educational rate the same as for the stationary population leads to an excessive number of young workers in both qualification groups. Now we have to distinguish two cases. If $\lambda_H \ll \lambda_L$, then the distortion of the optimal age distribution of high-skilled labor would be the dominant problem due to the smaller elasticity of substitution. Counteraction to restore the age balance of high-skilled labor is to increase the educational rate for older ages. In contrast, if $\lambda_H \gg \lambda_L$, then it is more important to restore the age distribution of low-skilled labor, because its elasticity of substitution is smaller. The way to do this is to increase learning more for young ages, which is to decrease

the young low-skilled labor by educating it. In the case of a decreasing population the arguments are exactly the reverse.

Although the theoretical arguments that we presented above are supported by the numerical experiments, they do not provide a formal proof of the established dependence of the age-distribution of learning on the demographic factor and on the elasticities of substitution. However, we are able to obtain a rigorous result in a somewhat simplified situation. Namely, we assume that $\delta(s) = e(s) = 0$, $\lambda_H = 1$, $\lambda_L < 1$, $p(s, u) = \frac{\epsilon}{2}u^2$. Also, we assume here that the control constraint $u \geq 0$ is not binding, which, due to the specific form of $p(s, u)$, is equivalent to assuming that for each (t, s) the shadow price of a high-skilled worker is higher than the shadow price of a low-skilled one. Let $u^\gamma(t, s)$ be the optimal control. Because in this subsection we are interested in long-run behavior, we consider the optimal steady-state control $u^\gamma(s) = \lim_{t \rightarrow +\infty} u^\gamma(t, s)$. To investigate how it depends on γ , we define

$$\Gamma(s) = \frac{du^\gamma}{d\gamma}(s)|_{\gamma=0}.$$

PROPOSITION 4. *The function Γ has the following form: there exists $\bar{s} < \omega$ such that $\Gamma(s) \geq 0$ on $[0, \bar{s}]$ and $\Gamma(s) < 0$ on (\bar{s}, ω) . It may happen that $\bar{s} < 0$, that is $\Gamma(s) < 0$ for all $s \in (0, \omega)$.*

The interpretation is that in an increasing population with nonperfect substitutability of nonskilled labor and perfect substitutability of skilled labor there will be more learning at young ages and less at old ages than for the stationary population. The higher learning in young ages, however, may be absent. Clearly, the result is completely consistent with those in Figure 3.

The other “extreme” case, $\lambda_L = 1$, $\lambda_H < 1$, is technically more complicated and we do not present its analysis. As Figure 2 (left plot) shows, the effect of demography on learning at older ages is just the opposite in this case, compared with the case $\lambda_L = 0.1$, $\lambda_H = 0.9$. However, for young ages the increasing population learns less in both cases.

The situation is even more complicated if both the high-skilled and the low-skilled labor are not perfectly substitutable across ages. Here the relation between λ_L and λ_H plays a role in the qualitative dependence of the optimal learning rate on demography in the same direction as in the two “extreme” cases considered above. However, if both λ_L and λ_H are strictly smaller than one, and if the difference between them is “small,” then the particular data θ_L , θ_H , $\pi_L(s)$, and $\pi_H(s)$ may have a decisive role in the qualitative impact of demography on the optimal educational policy.

5.2. Short-Run and Anticipation Effects of a Demographic change

In this subsection we investigate (theoretically and numerically) the short-run effects of a demographic change on the optimal learning rate. That is, if a stationary population began to increase or decrease, we examine how this demographic

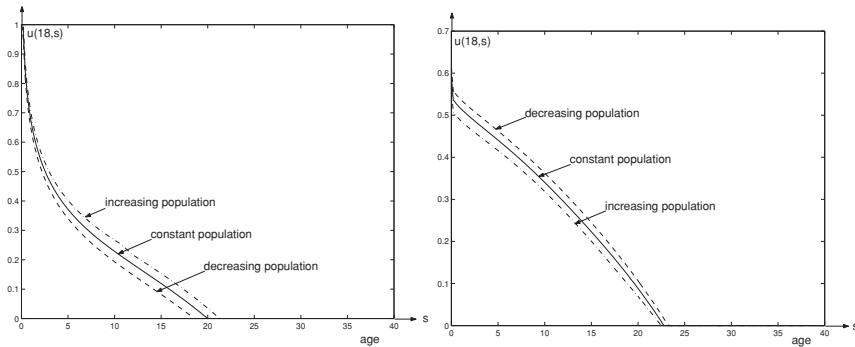


FIGURE 4. Age distribution of the optimal training rate in the anticipation phase ($t = 18$) for the three scenarios and for $\lambda_L = 0.9$, $\lambda_H = 0.1$ (left plot) and $\lambda_L = 0.1$, $\lambda_H = 0.9$ (right plot).

change would influence the optimal educational rate shortly after the change took place. Moreover, we establish that in the case of imperfect substitutability of labor (either across ages or across qualifications), a change in the demographic factor influences the optimal education policy not only afterward but also before the change takes place. That is, contrary to the case of perfect substitutability of labor, here the expectation of a future change in the supply of labor influences human-capital building even before the labor market becomes affected by this change.

We start with the three scenarios from the previous section—constant, increasing, and decreasing population—by choosing a constant growth rate γ , where γ is zero, positive, or negative, respectively. We then assume that till the year $\bar{t} = 20$ the population is stationary in all the three scenarios, but starting at time $\bar{t} = 20$ the three populations grow differently: $N_0(t) = N_0 e^{\gamma(t-\bar{t})}$ for $t > \bar{t}$. We shall compare the optimal learning rates in the three scenarios at time $t \in [\bar{t}, \bar{t} + \omega)$ (that is, shortly after the growing/shrinking population enters the labor market), but also at time $t < \bar{t}$, when the labor market is still not affected by the demographic change, but is already aware of this future change in labor supply. In the numerical results presented below,⁵ the constant-size population is simulated numerically before time $t = 0$, and the end time T is sufficiently large (we have used $T = 180$), so that the optimal solution for the constant scenario is close to the steady state [does not change with time in the interval $(0, 30)$]. We have chosen $\lambda_L = 0.9$, $\lambda_H = 0.1$ (alternatively $\lambda_L = 0.1$, $\lambda_H = 0.9$), $\gamma = 0$, or $\gamma = \pm 0.0072$ in the three scenarios; the rest of the data are as specified in Appendix A.

Figure 4 presents the age distribution of the optimal education rate at $t = 18$ (two years before the demographic change starts to influence the labor market). The expectation of an increasing/decreasing population leads to a change in the optimal education rate before (in fact, also shortly after) the change at time $\bar{t} = 20$. The direction of change is different for different combinations of λ_L and λ_H . We

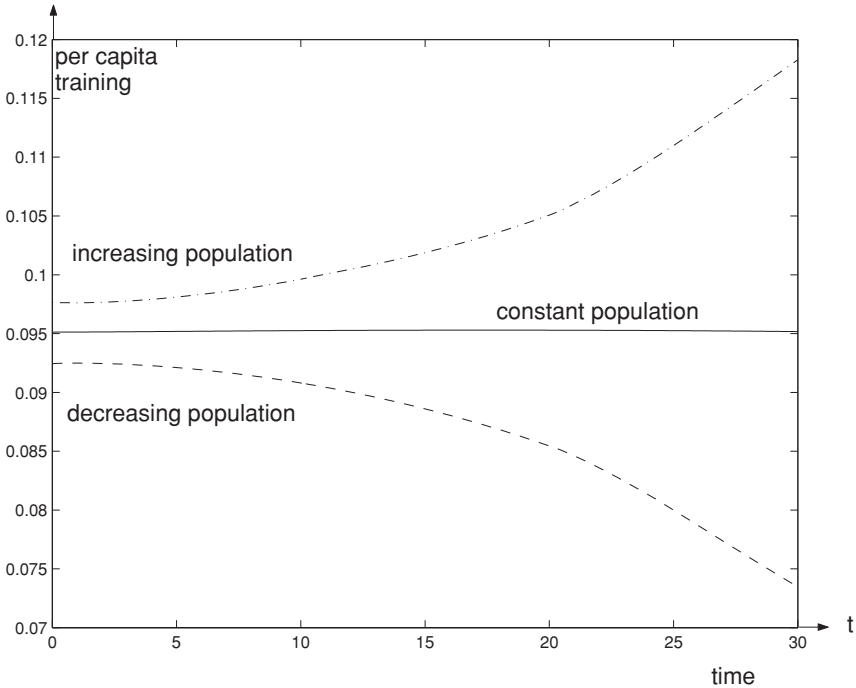


FIGURE 5. Per capita training effort in the anticipation phase ($t \in [0, 20]$) for the three scenarios and for $\lambda_L = 0.9, \lambda_H = 0.1$.

see in the left plot of Figure 4 that if $\lambda_H = 0.1 < 0.9 = \lambda_L$, then the expectation of increasing population leads to a higher education rate before the time of change, whereas for the decreasing population the education rate is lower. The situation is just the opposite for $\lambda_L = 0.1 < 0.9 = \lambda_H$ (the right plot).

The anticipation effect is not restricted just to the few years before \bar{t} . In Figure 5 we plot the time path of the aggregate per capita education effort, defined as $\int_0^\omega L(t, s)u(t, s)ds / \int_0^\omega N(t, s)ds$. Because the population before \bar{t} is of the same size for all t , this is a relevant indicator of the educational effort. Clearly, the educational effort is highest for the population for which the labor market is expected to expand at \bar{t} , and this happens in the whole plotted interval (at least twenty years before the demographic change results in a change of the labor supply).

The anticipation effect, discussed above, is rigorously proved in the next proposition. To simplify the consideration somewhat, we compare the following two scenarios: the constant-inflow case, $N_0(t) = N_0$, and

$$N_0(t) = N_0^*(t) = \begin{cases} N_0 & \text{for } t \leq \bar{t}, \\ N_0^* & \text{for } t > \bar{t}, \end{cases}$$

where $N_0^* > N_0$ (the case $N_0^* < N_0$ can be treated in the same way). We shall assume that the upward jump in the population at (economically active) age $s = 0$ is affecting only the low-skilled workers: $N_0^*(t) = L_0^*(t) + H_0^*(t)$, where

$$L_0^*(t) = \begin{cases} L_0 & \text{for } t \leq \bar{t}, \\ L_0^* & \text{for } t > \bar{t}, \end{cases}$$

with $L_0^* > L_0$ and $H_0^*(t) \equiv H_0 > 0$ for $t \in [0, T]$. Although the scenario N_0^* is different from the scenario with exponentially increasing population $N_0(t) = N_0 e^{\gamma(t-\bar{t})}$, $\gamma > 0$, considered in the numerical experiment, both scenarios have the same effect on the population change shortly after \bar{t} : in both cases the age distribution of the population shifts to lower ages in the time interval $[\bar{t}, \bar{t} + \omega)$. As we have already mentioned in Subsection 5.1, it is this shift that determines the policy change (before or after the demographic change) rather than the difference in the absolute size of the population, which plays no role.

Here we restrict the consideration to the case of imperfect substitutability between different qualifications ($\rho < 1$), with $\lambda_L = \lambda_H = 1$. The case of imperfect substitutability across ages is analytically more difficult and is enlightened only by the numerical results.

Denote by $u(t, s)$, $L(t, s)$, $H(t, s)$ the optimal path for the scenario with stationary demography, and by $u^*(t, s)$, $L^*(t, s)$, $H^*(t, s)$ the optimal path for the $N_0^*(t)$ scenario for the demography.

PROPOSITION 5. *Assume the following: (i) $\bar{t} > \omega$; (ii) there exist $s_0 \in (0, \omega)$ such that $u(t, s) > 0$ for $s \in [0, s_0]$ and $t < \bar{t}$. Then there exists a nonempty set $(t_1, t_2) \times (s_1, s_2)$ with $t_2 < \bar{t}$ such that $u^*(t, s) > u(t, s)$ on this set.*

We have thus established, theoretically and numerically, that a change of the learning rate takes place in the case of increasing/decreasing population even before the demographic change starts affecting the labor market. What is the economic reason for this effect?

- (A) Let us consider first the case of imperfect substitutability of high-skilled and low-skilled labor ($\rho < 1$), treated by Proposition 5. Because the additional labor that enters the labor market after the beginning of the demographic change at time \bar{t} is of low-skilled labor, the optimal balance between high-skilled and low-skilled labor will be violated by an excessive amount of low-skilled labor. Owing to imperfect substitutability across qualifications, in order to restore the optimal balance, the learning rate should be increased. Owing to the increasing marginal cost of learning, the cost per unit of learning rate would become higher than before the demographic change, if the learning rate for $t < \bar{t}$ were not increased. On the other hand, the young high-skilled labor at time t before and close to \bar{t} would remain high-skilled labor also after \bar{t} . Then at the optimum a part of the additional learning rate after the demographic change would be shifted to the years before the change, in order to take advantage of the lower learning cost. This is the positive anticipation effect.
- (B) In the case of imperfect substitutability of labor across ages ($\lambda_L < 1$, $\lambda_H < 1$, $\rho = 1$), the same intuitive reasoning applies, as we discussed in Subsection 5.1 for the

long-run behavior of the optimal learning rate. Then the anticipation effect (Figure 4 actually represents the anticipation phase) follows from the same reasoning as in part (A): shifting some of the educational efforts to times before \bar{t} (smoothing in this way the learning rate) decreases the costs of education.

In the case where λ_H and λ_L are both less than one and relatively close to each other, the same comment applies as at the end of Subsection 5.1.

The above analysis clearly exhibits the importance of the relation between the elasticity of substitution across ages for high-skilled and for low-skilled labor, which may lead to different (opposite) effects of the demographic changes on the optimal educational policy.

6. CONCLUSIONS

Skill and age heterogeneity have only rarely been integrated into formal macroeconomic models. However, such models constitute the framework for a normative analysis of the optimal age- and education-specific labor force. The aim of our paper is to provide a formal model of the optimal education policy at the macro level allowing for heterogeneity of the workforce with respect to its age and qualification skills. Within this framework, we study the optimal education rate in the context of changes in the labor demand (as represented by the elasticity of substitution across ages and qualification) and labor supply (as represented by the population growth rates).

We establish a number of numerical and analytical results on the optimal age-specific training rate. In the case of perfect substitutability of labor across age and qualification we show that the optimal age-specific training rate is independent of the labor supply. Once we allow for imperfect substitutability of workers across age and qualification, the optimal training rate depends on labor demand as well as labor supply factors. The analysis clearly exhibits the importance of the relation between the elasticities of substitution across ages of skilled and unskilled labor, which may lead to different (opposite) impacts of the demographic change on the optimal educational policy. As these results indicate, the relation between the elasticities of substitution of labor across ages plays a crucial role in the way the demographic changes affect (both in the short and in the long run) the optimal educational policy. A further interesting result that we obtained is the anticipation of future changes in labor supply. Already, several years in advance of the time when the actual change takes place, the optimal educational rate will change.

Various extensions of our analysis are promising. Our production technology depends only on labor. An obvious extension of our framework is to allow for physical capital in addition to human capital. So far we have assumed a relatively simple educational process, only implicitly taking into account the fact that people in education might not be active full-time in the labor market. These assumptions, as well as the assumption of full employment, could be relaxed in further extensions of our model. So far, we assume labor supply—as represented by the demographic

change—to be exogenous, but human capital composition will affect fertility, and mortality. The interdependence of education, fertility, and human capital [similar to that in Connelly and Gottschalk (1995)] could be studied. The assumption of the CES production function within each educational aggregate is restrictive as well. When workers from one age group are replaced by members of any other age group, the actual age difference does not matter. As was recently indicated in Prskawetz et al. (2008), the production function could be extended to allow a more flexible pattern of substitutability of workers across ages.

NOTES

1. Hence, although the social planner at the macro level takes into account changes in the supply of labor, an individual considers the demographic structure as constant. Moreover, when an individual invests into age specific education, he or she ignores that he or she thereby also influences the skill distribution in the macroeconomy at any instant of time. An obvious externality therefore arises, because the skill distribution together with the prevailing labor demand parameters will impinge on the returns to education for each individual.

2. Note that compared to our previous model at the firm level [Prskawetz and Veliov (2007)], the current model allows for a much more flexible and empirically relevant production function that includes imperfect substitutability across age and education. Although at the firm level the hiring and firing of workers constituted—in addition to the educational investment—a control variable, the educational rate is the only control variable in the social planner model because labor inflow is solely determined by demographic developments in the current model.

3. We stress that the problem is still nonlinear due to the bilinear dependence on (L, u) .

4. We can denote a change in the initial level of low-skilled and high-skilled labor as a demographic change because we abstract from endogenous modeling of the labor market and assume full employment.

5. The numerical solution is itself a challenging issue (this applies also to the previous sections). In our numerical analysis we use the general solver for age-structured optimal control problems developed by the third author, which is very briefly described in Feichtinger et al. (2004). A detailed description will be given in a forthcoming paper of the third author.

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APPENDIX A: DATA SPECIFICATIONS

In the numerical experiments we have used the following data:

- $\omega = 40$ —age of retirement minus initial working age $a^0 = 20$;
- $T = 140$ —end of the time interval;
- [45, 95]—the time interval used for the plots;
- $\delta(t, s) \equiv 0$ —there is no decay of the human capital;
- $e(s) \equiv 0$ —there is no learning by doing;
- $l(t, s) \equiv 0.1386$ —constant in age and time efficiency of learning;
- $\theta_L(t) \equiv 0.3, \theta_H(t) \equiv 0.7$;
- $p(s, u) \equiv p(u) = \frac{9}{520}u + \frac{3}{260}u^2$ —the cost of educating one low-skilled worker if the educational effort is at level u ;
- $\rho = 1$ —the aggregate low- and aggregate high-skilled labor are perfect substitutes;
- λ_L —the different values are specified in the respective sections and figure captions;
- λ_H —the different values are specified in the respective sections and figure captions;
- $r = 0.03$ —discount rate;
- $\bar{\pi}_L(s) = c_L \exp(\frac{q_1^2}{(s-m_L)^2 - q_2^2}), \bar{\pi}_H(s) = c_H \exp(\frac{q_1^2}{(s-m_H)^2 - q_2^2})$ —age-specific productivities of low-skilled and high-skilled workers [the functional form is taken from Prskawetz and Veliov (2007), where the parameters are identified using data from France for 1998];
- $\pi_L(s) = \bar{\pi}_L(s) / \int_0^\omega \bar{\pi}_L(\sigma) d\sigma, \pi_H(s) = \bar{\pi}_H(s) / \int_0^\omega \bar{\pi}_H(\sigma) d\sigma$ —age-specific relative efficiency parameters in the CES functions for the low- and high-skilled aggregate labor;
- $c_L = 500, c_H = 1000$ —scaling factors,
- $m_L = 13, m_H = 20$ —age of maximal productivity,
- $q_1 = 100, q_2 = 60$ —parameters identified from data;
- $L_0(t) \equiv 1000, H_0(t) \equiv 10^{-6}$ —the inflow of low and- high-skilled workers at the initial working age in the constant population scenario;
- $L_0(t) = 1000 \exp(0.0072(t - 45)), H_0(t) = 10^{-6} \exp(0.0072(t - 45))$ —the inflow of low- and high-skilled workers at the initial working age in the increasing population scenario;
- $L_0(t) = 1000 \exp(-0.0072(t - 45)), H_0(t) = 10^{-6} \exp(-0.0072(t - 45))$ —the inflow of low- and high-skilled workers at the initial working age in the decreasing population scenario.

APPENDIX B: THE MAXIMUM PRINCIPLE

In this appendix we explain how the optimality conditions described in Section 3 are obtained using the result in Feichtinger et al. (2003). This paper provides Pontryagin-type conditions for a class of problems of the form

$$\text{minimize } \int_0^T \int_0^\omega F(t, s, y(t, s), u(t, s), q(t)) ds dt, \tag{B.1}$$

subject to the equations

$$y_t(t, s) + y_a(t, s) = g(t, s, y(t, s), u(t, s)), \quad y(0, s) = y^0(s), \quad y(t, 0) = \varphi(t, q(t)), \tag{B.2}$$

$$q(t) = \int_0^\omega h(s, y(t, s), u(t, s)) ds, \tag{B.3}$$

and the control constraint

$$u(t, s) \in U. \tag{B.4}$$

Here t is the time, running in a given interval $[0, T]$, $s \in [0, \omega]$ is a scalar variable interpreted as age, $y(t, s) = (y_1(t, s), \dots, y_m(t, s)) \in \mathbf{R}^m$ and $q(t) = (q_1(t), \dots, q_r(t)) \in \mathbf{R}^r$ are the states of the system, $u(t, s) \in U$ is the control, U is a subset of \mathbf{R}^m , and F, g, h, y^0, φ are given functions.

We mention that models such as this often arise in population dynamics (as in the present paper), but also in other areas of economics, where s has the meaning of age of physical capital or technology [cf. Barucci and Gozzi (2001), Feichtinger et al. (2005, 2006)].

In our model $y = (L, H)$, but in order to pass to a model in the above form we need a slight modification of equations (4), (5). Namely, we set $q = (\bar{L}, \bar{H}, P)$, where \bar{L} and \bar{H} are new variables (replacing \tilde{L} and \tilde{H}) defined by

$$\bar{L}(t) = \int_0^\omega \pi_L(s)(L(t, s))^{\lambda_L} ds, \tag{B.5}$$

$$\bar{H}(t) = \int_0^\omega \pi_H(s)(H(t, s))^{\lambda_H} ds. \tag{B.6}$$

We have to modify the objective function (1) correspondingly:

$$\text{maximize } \int_0^T e^{-rt} \left[(\theta_L(t)(\bar{L}(t))^{\rho/\lambda_L} + \theta_H(t)(\bar{H}(t))^{\rho/\lambda_H})^{1/\rho} - P(t) \right] dt. \tag{B.7}$$

Obviously problem (B.7), (2), (3), (B.5), (B.6), (6), and (7) is equivalent to our original problem (1)–(7) and at the same time is in the form (B.1)–(B.4). Thus Theorem 1 in Feichtinger et al. (2003) readily gives the following: the optimal control $u(t, s)$ maximizes the function

$$(-\xi(t, s) + \eta(t, s))l(t, s)L(t, s)u - p(s, u)L(t, s), \tag{B.8}$$

where the adjoint variables ξ and η corresponding to L and H , respectively, satisfy the equations

$$\begin{aligned} \xi_t + \xi_s &= r\xi + (\xi - \eta)(e(s) + l(t, s)u(t, s)) \\ &\quad - (Y(t))^{1-\rho} \theta_L(t) \pi_L(s) (\bar{L}(t))^{\rho-\lambda_L} (L(t, s))^{\lambda_L-1} + p(s, u(t, s)), \end{aligned}$$

$$\xi(t, \omega) = 0, \quad \xi(T, s) = 0,$$

$$\begin{aligned} \eta_t + \eta_s &= r\eta + (-\xi + \eta)\delta(t, s) \\ &\quad - (Y(t))^{1-\rho} \theta_H(t) \pi_H(s) (\bar{H}(t))^{\rho-\lambda_H} (H(t, s))^{\lambda_H-1}, \end{aligned}$$

$$\eta(t, \omega) = 0, \quad \eta(T, s) = 0.$$

Setting $\Delta(t, s) = \eta(t, s) - \xi(t, s)$ and subtracting the first equation from the second, we obtain equation (8). Having in mind that $L(t, s)$ is positive, we obtain the claim of Proposition 1 from (B.8).

In the analysis of the optimal solution we implicitly assume also that the solution to our optimal control problem is unique, and that the necessary optimality condition (maximum principle) presented in Section 3 is also a sufficient condition. This assumption is automatically fulfilled if the mapping “control $u \rightarrow$ objective value” is strongly convex, for which there is strong evidence. However, these purely mathematical issues go beyond the scope of the present paper.