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CHILDREN'S HEALTH, HUMAN CAPITAL ACCUMULATION, AND R&D-BASED ECONOMIC GROWTH

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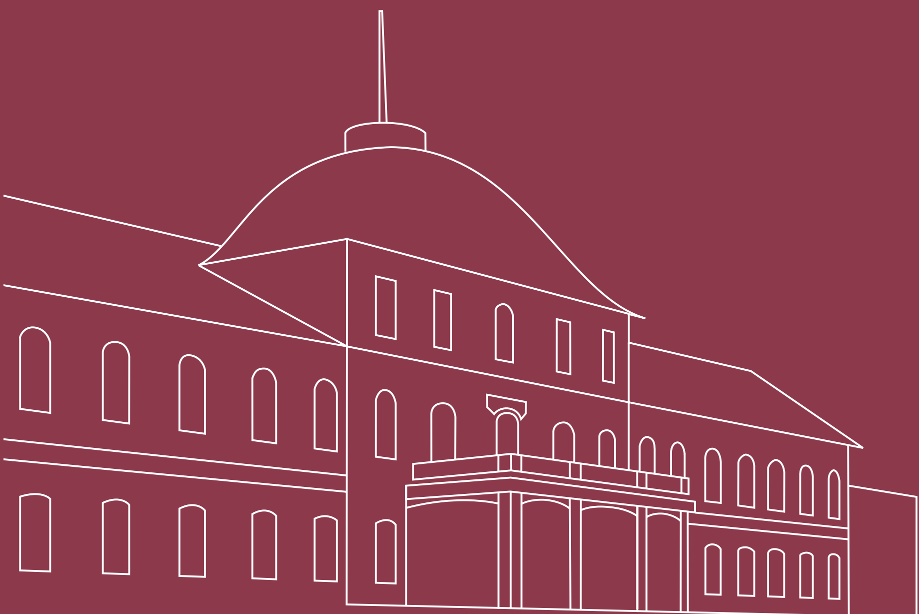

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Children's health, human capital accumulation, and R&D-based economic growth

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Abstract

We analyze the effects of children's health on human capital accumulation and on long-run economic growth. For this purpose we design an R&D-based growth model in which the stock of human capital of the next generation is determined by parental education and health investments. We show that i) there is a complementarity between education and health: if parents want to have better educated children, they also raise health investments and vice versa; ii) parental health investments exert an unambiguously positive effect on long-run economic growth, iii) faster population growth reduces long-run economic growth. These results are consistent with the empirical evidence for modern economies in the twentieth century.

JEL classification: I15, I25, J10, O30, O41.
Keywords: Children's Health, Education, Fertility, Economic Growth, Technological Progress, Long-run Economic Development.

1 Introduction

There has been a substantial improvement in childhood health within all industrialized countries over the last decades. According to the World Bank (2016)'s Health Nutrition and Population Statistics, the mortality rate of children under the age of 5 has decreased in the OECD from 63 deaths per 1000 children in 1960 to 7 deaths in 2015. This corresponds to a reduction of the child mortality rate of almost 90% within 2 generations. Furthermore, over the same time span, the prevalence of certain diseases, such as anemia, has decreased from 24% to around 15% among children. The substantial improvements in the health condition of children are therefore an important driver of the rise in the survival rate to the age of 65, which has increased between 1960 and 2015 from 64% to 83% for men and from 75% to 90% for women.

As far as the relationship between health and economic prosperity is concerned, there is a strong positive association between these two variables, as reflected in the famous "Preston Curve" (Preston, 1975). However, it is still an ongoing debate whether better health *causes* higher per capita income. While the positive effects of health on income are emphasized by Bloom et al. (1998), Cervellati and Sunde (2005), and Lorentzen et al. (2008),[1] some economists claim the opposite: lower mortality – as induced by a better health condition of the population – might trigger faster population growth and therefore a reduction in the growth rate of income per capita due to the well-known neoclassical capital dilution effect (cf. Solow, 1956; Diamond, 1965). In their influential work, Acemoglu and Johnson (2007) show that a 1% increase in life expectancy leads to a 1.7-2% increase in the population size but it raises aggregate GDP to a lesser extent. Consequently, according to their findings, a better health condition of the population *reduces* income per capita.

Aghion et al. (2011) and Bloom et al. (2014) in turn criticize the findings of Acemoglu and Johnson (2007). Their argument is that the negative effect of higher life expectancy on economic growth might come from the omission of a measure for the initial health condition from the regression specifications. Countries with a lower initial health condition of the population have a larger potential to improve health, but, at the same time, they have a lower economic growth potential. Including initial life expectancy as a proxy for initial health in the regressions, Bloom et al. (2014) show that there is a *causal positive* effect of better health on economic growth.

[1] See also Gallup et al. (1999), Bhargava et al. (2001), Ashraf et al. (2008), and Gehringer and Prettner (2014) for empirical findings and de la Croix and Licandro (1999), Kalemli-Ozcan et al. (2000), Boucekkine et al. (2002), Boucekkine et al. (2003), Lagerlöf (2003), and Bar and Leukhina (2010) for theoretical considerations.

Furthermore, using the same panel data for the period 1940-2000 as Acemoglu and Johnson (2007), Cervellati and Sunde (2011) find that the effect of life expectancy on economic growth might have been negative before the demographic transition when fertility rates stayed constant in the face of decreasing mortality, but that it is unambiguously positive after the onset of the demographic transition when higher life expectancy reduces the fertility rate such that population growth slows down. This implies a positive effect of health on income per capita in a neoclassical-type of growth model because the capital dilution effect is reduced. A complementary effect is that increases in life expectancy raise human capital investments, which also fosters economic growth as shown by Cervellati and Sunde (2005, 2013).

The aim of our paper is to contribute to this debate by showing another pathway by which health has the potential to impact on long-run economic growth, especially in modern knowledge-based economies that have already experienced the demographic transition in the past. Our argument is based on an endogenous growth mechanism where new ideas are created in a research sector by the human capital that a society devotes to R&D.[2] The aggregate human capital stock of a country is in turn a compound of the education level and the health condition of the population and there are feedback effects between these two variables (Schultz, 1961; Grossman, 2000; Becker, 2007). On the household side, health enters the utility function of parents who choose how much to invest in children's health and in children's education. We show that, if parents want to have better educated children, they also increase health investments in their children. This result is consistent with the empirical findings of Perri (1984), Behrman and Rosenzweig (2004) and Currie (2009), who document a negative effect of childhood ill-health on educational achievements.[3] In addition, healthier children perform better in school and will themselves have a higher health-related knowledge (Behrman, 2009). Overall, in our framework, human capital is used as an input in the production functions of the final goods sector, the R&D sector, the education sector, and the health sector. Given the positive role of health in the creation of human capital, there are more productive resources available for R&D in a healthier economy and this has the potential to lead to faster long-run economic growth (cf. Prettner et al., 2013; Kuhn and Prettner, 2016). Our model therefore characterizes an additional channel by which health could exert a

[2]For endogenous growth models, see Romer (1990), Grossman and Helpman (1991), Aghion and Howitt (1992), Jones (1995), Kortum (1997), Peretto (1998), Segerström (1998), Young (1998), Howitt (1999), and many others. For frameworks that explicitly model human capital as a result of schooling investments, see, for example, Funke and Strulik (2000), Strulik (2005), Grossmann (2007), Bucci (2008, 2013), Strulik et al. (2013), and Prettner (2014).

[3]See also Bleakley (2007), Bleakley and Lange (2009), Lucas (2010), and Oster et al. (2013) who document a positive effect of health on human capital.

positive effect on economic growth besides the neoclassical capital dilution effect (Cervellati and Sunde, 2011) and the Ben-Porath mechanism (Ben-Porath, 1967; Cervellati and Sunde, 2005, 2013).

The paper is organized as follows. We set up the model in Section 2, describe the consumption side, the production side, and the market clearing conditions. Section 3 contains the balanced growth path of the economy and the main analytical results. We then proceed to a numerical example to illustrate the transitional dynamics of the system. In Section 4 we conclude.

2 The model

Consider a knowledge-based economy a la Romer (1990) - Jones (1995) with five sectors: final goods production, intermediate goods production, R&D, education, and health. Physical capital and human capital are the two production factors. Physical capital is accumulated according to the savings and investment decisions of households and it is used to produce machines in the intermediate goods sector. Human capital is available in four different forms: as "workers" in the final goods sector for the production of the consumption aggregate, as "teachers" in the education sector for the production of the knowledge and skills of the next generation, as "healthcare personnel" for the improvement of the health condition of the next generation in the health sector (including also public health projects, for example, improvements in sanitation), and as "scientists" for the production of new blueprints for machines in the R&D sector.

The consumption side of the economy consists of overlapping generations of households who live for two time periods. Households consume, save, and choose the number of children on the one hand, and how much to invest in education and health of each child, on the other hand. The household's expenditures on education are used to hire the teachers to educate the young, while the household's expenditures on health are used to hire the healthcare personnel to improve the physical well-being of children.[4]

[4]There is a vast literature in which overlapping generation models are employed to endogenize life expectancy (Blackburn and Cipriani, 2002; Chakraborty, 2004; Cervellati and Sunde, 2005; Hashimoto and Tabata, 2005; Bhattacharya and Qiao, 2007; Castelló-Climent and Doménech, 2008; Osang and Sarkar, 2008; de la Croix and Licandro, 2013). Our work abstracts from the survival probability; instead we follow a short-cut formulation in which the health component is one of the determinants of the accumulation of human capital.

2.1 Households

We follow Strulik et al. (2013) and Prettner et al. (2013) in assuming that the utility function of households is given by

$$u_t = \log(c_{1,t}) + \beta \log(R_{t+1} s_t) + \xi \log(n_t) + \theta \log(e_t) + \zeta \log(f_t),$$

where $c_{1,t}$ is first period consumption of the generation born at time t, R_{t+1} is the capital rental rate, s_t denotes savings such that $c_{2,t} = R_{t+1} s_t$ refers to consumption in the second period of life, n_t is the fertility rate, e_t refers to education investments per child, f_t refers to health investments per child, β is the discount factor, ξ denotes the utility weight of children, θ refers to the utility weight of children's eduction, and ζ is the utility weight of children's health. For consistency, we employ the parameter restriction $\xi > \theta + \zeta$, which ensures that parents do not want to invest in children's education and health without having children in the first place. In addition, the restriction rules out immediate extinction (i.e., $n_t = 0$). The utility function without the health component of children is frequently used in the literature (cf. Strulik et al., 2013; Prettner et al., 2013; Bloom et al., 2015) because it operationalizes the "warm-glow motive of giving" as described by Andreoni (1989) and because it is the special case of logarithmic utility of the more general specification employed by Galor and Weil (2000) and Galor (2011).

The budget constraint of the household is given by

$$(1 - \psi n_t) h_t w_t = \eta e_t n_t + \kappa n_t f_t + c_{1,t} + s_t,$$

where ψ measures the unit cost of rearing each child, η measures the unit cost of the investment in education per child, κ measures the unit cost of the investment in health per child, h_t refers to the human capital level of an adult, which is tantamount to her productivity and is itself a compound determined by the education and health investments of her own parents, and w_t is the wage rate per unit of human capital.

The result of the optimization problem is given by optimal consumption, savings, fertility, education investments, and health investments as given by

$$c_{1,t} = \frac{h_t w_t}{1+\beta+\xi}, \tag{1}$$

$$s_t = \frac{\beta h_t w_t}{1+\beta+\xi}, \tag{2}$$

$$n_t = \frac{\xi-\zeta-\theta}{\psi\left(1+\beta+\xi\right)}, \tag{3}$$

$$e_t = \frac{\theta\psi h_t w_t}{\eta\left(\xi-\zeta-\theta\right)}, \tag{4}$$

$$f_t = \frac{\zeta\psi h_t w_t}{\kappa\left(\xi-\zeta-\theta\right)}. \tag{5}$$

At this stage we can state the following intermediate result that is consistent with the empirical findings discussed in the introduction.

Proposition 1.

i) If households want to have more children, the fertility rate is higher, while consumption, savings, and investments in children's health and education are lower;

ii) If households want to have better educated children, parental investments in both education and health are higher, while fertility is lower;

iii) If households want to have healthier children, parental investments in both education and health are higher, while fertility is lower.

Proof. Part i): By investigating Equations (1), (2), (4), and (5) it is straightforward that a higher level of ξ implies lower consumption, savings, children's health, and children's education. To see the effect on fertility, we compute the derivative of (3) with respect to ξ:

$$\frac{\partial n_t}{\partial \xi} = \frac{1+\beta+\zeta+\theta}{\left(1+\beta+\xi\right)^2\psi}$$

and observe that the derivative is unambiguously positive.

Part ii): By investigating Equations (3) and (5), fertility decreases and children's health increases with θ. To see the effect on children's education, we compute the derivative of (4) with respect to θ:

$$\frac{\partial e_t}{\partial \theta} = \frac{\left(\xi-\zeta\right)\psi h_t w_t}{\eta\left(\xi-\theta-\zeta\right)^2}.$$

Since we have that $\xi > \theta+\zeta$, the derivative is unambiguously positive.

Part iii): By investigating Equations (3) and (4), fertility decreases and children's education increases with ζ. To see the effect on children's education, we compute the derivative of (5) with respect to ζ:

$$\frac{\partial f_t}{\partial \zeta} = \frac{(\xi - \theta)\,\psi h_t w_t}{\kappa\,(\xi - \theta - \zeta)^2}.$$

Again, given $\xi > \theta + \zeta$, this derivative is unambiguously positive. □

Altogether, we observe that parents who invest more in their children's education also invest more in their children's health and vice versa. At the same time, higher investments in education and health imply that parents have fewer children. This is consistent with the evidence on the relation between health and education (cf. Perri, 1984; Behrman and Rosenzweig, 2004; Currie, 2009; Behrman, 2009; Case et al., 2005) and it is also consistent with the child quality-quantity trade-off as described by Becker and Lewis (1973).

Taking into account Equation (3), the evolution of the population size is governed by the difference equation

$$N_{t+1} = n_t N_t = \frac{\xi - \zeta - \theta}{\psi\,(1 + \beta + \xi)} N_t \tag{6}$$

and the labor force participation rate can be calculated as

$$lpr = 1 - \psi n_t = \frac{1 + \beta + \zeta + \theta}{1 + \beta + \xi}.$$

Naturally, the labor force participation rate is smaller than one because of the time parents spend on rearing children.

2.2 Production

The productions side of the economy consists of five sectors: final goods production, intermediate goods production, R&D, education, and health. The description of the first three sectors follows the standard R&D-based growth literature with the only difference being that human capital (as a compound of the number of people, their eduction level, and their health condition) is used instead of raw labor as a factor of production.

The final goods sector produces a consumption good Y_t with human capital

$H_t = h_t N_t$ and machines $x_{t,i}$ as inputs according to the production function

$$Y_t = H_{t,Y}^{1-\alpha} \int_0^A x_{t,i}^{\alpha} \, di, \tag{7}$$

where A is the technological frontier and $\alpha \in (0,1)$ denotes the elasticity of output with respect to machines of type i. Profit maximization implies

$$w_t = (1-\alpha) \frac{Y_t}{H_{t,Y}}, \qquad p_{t,i} = \alpha H_{t,Y}^{1-\alpha} x_{t,i}^{\alpha-1}, \tag{8}$$

where $p_{t,i}$ is the price of machines.

The intermediate goods sector is monopolistically competitive as in Dixit and Stiglitz (1977). Firms in the intermediate goods sector have access to the production technology $x_{t,i} = k_{t,i}$, where $k_{t,i}$ denotes physical capital employed by each firm. Operating profits of intermediate goods producers are then given by $\pi_{t,i} = p_{t,i} x_{t,i} - R_t k_{t,i} = \alpha H_{t,Y}^{1-\alpha} k_{t,i}^{\alpha} - R_t k_{t,i}$, such that profit maximization yields the optimal price of a machine as $p_{t,i} = R_t / \alpha$ for all i. In this context, $1/\alpha$ is the markup over marginal cost. Due to symmetry with respect to the pricing policy of individual firms, we know that the aggregate capital stock is $K_t = A_t k_t$ such that we can write the aggregate production function as

$$Y_t = (A H_{t,Y})^{1-\alpha} K_t^{\alpha}. \tag{9}$$

The R&D sector employs scientists $H_{t,A}$ to discover new blueprints A_t according to the production technology

$$A_{t+1} - A_t = \delta A_t^{\phi} H_{t,A}, \tag{10}$$

where δ refers to the productivity of scientists and $\phi < 1$ to the intertemporal spillover effects of technologies that raise the productivity of human capital employed in the research sector (cf. Jones, 1995). R&D firms maximize profits $\pi_{t,A} = p_{t,A} \delta A_t^{\phi} H_{t,A} - w_{t,A} H_{t,A}$, with $p_{t,A}$ being the price of a blueprint that they sell to the intermediate goods producers. From the first-order condition we get

$$w_{t,A} = p_{t,A} \delta A_t^{\phi}, \tag{11}$$

where $w_{t,A}$ refers to the wage rate per unit of human capital of scientists. The interpretation of this equation is straightforward: wages of scientists increase with their productivity as measured by δA_t^{ϕ} and with the price that a research firm can charge for the blueprints that it sells to the intermediate goods producers.

The education sector employs teachers with human capital $H_{t,E}$ to produce the knowledge and skills of the next generation.[5] Employment in the education sector is determined by the equilibrium condition that household expenditures for teachers are equal to the total wage bill of teachers, i.e.,

$$\eta e_t n_t N_t = H_{t,E} w_t \Leftrightarrow H_{t,E} = \frac{\theta H_t}{1+\beta+\xi}.$$

Similarly, the health sector employs healthcare personnel with human capital $H_{t,F}$ to improve the health condition of the next generation. Employment in the health sector is therefore determined by the equilibrium condition that household expenditures for health are equal to the total wage bill of healthcare personnel, i.e.,

$$\kappa f_t n_t N_t = H_{t,F} w_t \Leftrightarrow H_{t,F} = \frac{\zeta H_t}{1+\beta+\xi}.$$

Individual human capital is a Cobb-Douglas compound of the education level and the health condition such that

$$h_{t+1} = \left(\mu \frac{H_{t,E}}{N_{t+1}}\right)^{\nu} \left(\omega \frac{H_{t,F}}{N_{t+1}}\right)^{1-\nu} \tag{12}$$

where $H_{t,E}/N_{t+1}$ measures the education intensity per child, μ is the productivity in the schooling sector, $H_{t,F}/N_{t+1}$ measures the healthcare intensity, ω is the productivity in the healthcare sector, and ν denotes the elasticity of human capital with respect to education.

2.3 Market clearing

Labor markets are assumed to clear such that $L_t = L_{t,Y} + L_{t,A} + L_{t,E} + L_{t,F}$, where L_t is total employment and $L_{t,j}$ for $j = Y, A, E, F$ refers to employment in the four different sectors that use human capital. This implies that $H_t = H_{t,Y} + H_{t,A} + H_{t,E} + H_{t,F}$ because human capital is embodied. Since there is free movement of labor in the economy, wages in the final goods sector and in the R&D sector will be equal in equilibrium. Inserting (8) into (11) therefore yields the following equilibrium condition that equates the marginal value product of a worker in the final goods

[5] Berk and Weil (2015) underline the problem of older teachers in this context: with the phenomenon of population aging, workers will have older teachers, who might teach outdated knowledge. This observation is very interesting and it could be considered in an extension of our model that allows for this type of the "vintage effect".

sector and of a scientist in the R&D sector

$$p_{t,A}\delta A_t^{\phi} = (1-\alpha)\frac{Y_t}{H_{t,Y}}. \tag{13}$$

We follow Aghion and Howitt (2005) and assume that patent protection lasts for one generation, which is reasonably in line with the duration of patents in reality (cf. The German Patent and Trade Mark Office, 2016; The United States Patent and Trademark Office, 2016). After a patent expires, the right to sell the blueprint is handed over to the government that consumes the associated proceeds.[6] As a consequence, the patent price is given by the one-period profits of the intermediate goods sector, which can be written as

$$\pi_{t,i} = p_{t,A} = (1-\alpha)\alpha k_t^{\alpha} H_{t,Y}^{1-\alpha} = \left(\alpha - \alpha^2\right)\frac{Y_t}{A_t}.$$

Plugging this into (13) and solving for employment of human capital employed in the final goods sector yields $H_{t,Y} = A_t^{1-\phi}/(\alpha\delta)$. Now we can use the relation $H_{t,A} = H_t - H_{t,Y} - H_{t,E} - H_{t,F}$, which is implied by the labor market clearing condition and the fact that human capital is embodied, to solve for human capital employment in the R&D sector as

$$H_{t,A} = \frac{(1+\beta)h_t N_t}{1+\beta+\xi} - \frac{A_t^{1-\phi}}{\alpha\delta}. \tag{14}$$

Plugging the resulting employment level of human capital of scientists into the production function of the R&D sector [Equation (10)], yields the following law of motion for blueprints

$$A_{t+1} = \frac{(1+\beta)\delta h_t N_t A_t^{\phi}}{1+\beta+\xi} - \frac{(1-\alpha)A_t}{\alpha}. \tag{15}$$

We immediately see that, *ceteris paribus*, a higher productivity of scientists (δ), a higher employment level of human capital in the R&D sector [$H_{t,A}$ as defined in Equation (14)], and stronger intertemporal knowledge spillovers (ϕ) all lead to a faster accumulation of patents between time t and $t+1$.

Capital market clearing requires that the stock of physical capital at time $t+1$ is equal to aggregate savings net of savings invested in the shares of intermediate

[6] For the long-run balanced growth rate of the economy it would make no difference if the government were allowed to invest part of (or even the total) of these proceeds.

goods producers such that

$$K_{t+1} = s_t N_t - p_{t,A}\left(A_{t+1} - A_t\right) = Y_t - c_{1,t}N_t - c_{2,t-1}\frac{N_t}{n_{t-1}} - G_t, \tag{16}$$

where G_t are governmental expenditures financed by the proceeds of expired patents. Note that $c_{2,t-1}N_t/n_{t-1}$ refers to the total consumption of the generation born at time $t-1$, which is in the second phase of its life cycle in year t and is of size N_t/n_{t-1}. Consequently, we have total output net of consumption expenditures, i.e., total investment in terms of physical capital, on the right-hand side of Equation (16). Solving the resulting equation for K_{t+1} as a function of K_t, H_t, and A_t yields

$$K_{t+1} = (1-\alpha)\,K_t^{\alpha}\left(\frac{A_t^{2-\phi}}{\alpha\delta}\right)^{1-\alpha} - \frac{(1-\alpha)\,A_t h_t N_t K_t^{\alpha}\left(\frac{A_t^{2-\phi}}{\alpha\delta}\right)^{-\alpha}}{1+\beta+\xi}. \tag{17}$$

Finally, we solve for the evolution of individual human capital as determined by parental investments in education and health. Plugging $H_{t,E}$ and $H_{t,F}$, which result from the household maximization problem into the production function of human capital [Equation (12)] yields

$$h_{t+1} = \frac{(\theta\mu)^{\nu}\,(\zeta\omega)^{1-\nu}\,\psi}{\xi-\zeta-\theta}h_t. \tag{18}$$

Note that, *ceteris paribus*, if parents want to have better educated children (higher θ) or if parents want to have healthier children (higher ζ), individual human capital accumulation increases. By contrast, if parents want to have more children (higher ξ), individual human capital accumulation decreases because of the quality-quantity trade-off. The main question that arises regarding aggregate human capital accumulation is whether the increase in individual human capital accumulation due to a stronger preference for children's health and education can overcompensate the associated reduction in the population growth rate.

3 Dynamics and long-run equilibrium

We summarize the model dynamics defined by (6), (15), (17), and (18) in the following four-dimensional system of difference equations:

$$A_{t+1} = \frac{(1+\beta)\delta h_t N_t A_t^{\phi}}{1+\beta+\xi} - \frac{(1-\alpha)A_t}{\alpha}, \tag{19}$$

$$K_{t+1} = (1-\alpha)K_t^{\alpha}\left(\frac{A_t^{2-\phi}}{\alpha\delta}\right)^{1-\alpha} - \frac{(1-\alpha)A_t h_t N_t K_t^{\alpha}\left(\frac{A_t^{2-\phi}}{\alpha\delta}\right)^{-\alpha}}{1+\beta+\xi}, \tag{20}$$

$$N_{t+1} = \frac{\xi-\zeta-\theta}{\psi(1+\beta+\xi)}N_t, \tag{21}$$

$$h_{t+1} = \frac{(\theta\mu)^{\nu}\psi(\zeta\omega)^{1-\nu}}{\xi-\zeta-\theta}h_t. \tag{22}$$

It follows that the variables A, N, and h grow at the following rates:

$$g_A = \frac{(1+\beta)\,\delta h_t N_t A_t^{\phi-1}}{1+\beta+\xi} - \frac{1}{\alpha}, \tag{23}$$

$$g_N = \frac{\xi-\zeta-\theta}{\psi\,(1+\beta+\xi)} - 1, \tag{24}$$

$$g_h = \frac{(\theta\mu)^{\nu}\,\psi\,(\zeta\omega)^{1-\nu}}{\xi-\zeta-\theta} - 1. \tag{25}$$

It is obvious from Equation (23) that a balanced growth path – along which the growth rate of technology stays constant – has to fulfill

$$\frac{h_t}{h_{t-1}}\frac{N_t}{N_{t-1}}\left(\frac{A_t}{A_{t-1}}\right)^{\phi-1} = 1.$$

From this we can infer the long-run growth rate of technology as

$$g_A^* = \left[(1+g_h)(1+g_N)\right]^{\frac{1}{1-\phi}} - 1 = \left[\frac{\zeta\,(\theta\mu)^{\nu}\,\omega\,(\zeta\omega)^{-\nu}}{1+\beta+\xi}\right]^{\frac{1}{1-\phi}} - 1.$$

From this result and Equation (9) we know that the long-run growth rate of per capita GDP that is associated with a constant capital-to-output ratio is given by

$$g_y^* = \left[(1+g_h)(1+g_A)\right] - 1 = \frac{(1+\beta+\xi)\,\psi\left[\frac{\zeta(\theta\mu)^{\nu}\omega(\zeta\omega)^{-\nu}}{1+\beta+\xi}\right]^{1+\frac{1}{1-\phi}}}{\xi-\zeta-\theta} - 1, \tag{26}$$

while the growth rates of aggregate GDP and aggregate physical capital are

$$g_Y^* = g_K^* = (1 + g_N)(1 + g_h)(1 + g_A) - 1 = \left[\frac{\zeta (\theta\mu)^\nu \omega (\zeta\omega)^{-\nu}}{1 + \beta + \xi}\right]^{1+\frac{1}{1-\phi}} - 1.$$

Next, we state our central results regarding the differential evolution of fertility, education, and health and their corresponding effects on long-run economic growth.

Proposition 2. *A reduction in the population growth rate is associated with an increase in the rate of long-run economic growth.*

Proof. The derivative of Equation (26) with respect to ξ is

$$\frac{\partial g_y^*}{\partial \xi} = \frac{\left[\zeta + \theta + \xi(\phi - 2) + \beta(\phi - 1) + \phi - 1\right]\psi \left[\frac{\zeta(\theta\mu)^\nu \omega(\zeta\omega)^{-\nu}}{1+\beta+\xi}\right]^{1+\frac{1}{1-\phi}}}{(\zeta + \theta - \xi)^2 (1 - \phi)}.$$

Recalling that the parameter restriction $\xi > \zeta + \theta$ has to hold to rule out immediate extinction and noting that the term $\phi - 2$ is smaller than -1 because $\phi < 1$, we see that the numerator of this expression is always negative. Since the denominator is always positive, the proof of the proposition is established.

□

The intuition for this finding is that parents who prefer to have fewer children, reduce fertility. This allows them – for a given income level – to spend more on education and health for each child. In addition, the reduction in fertility allows parents to supply more time on the labor market such that their disposable incomes raise. Part of this additional income is spent on education and health. While the reduction in fertility reduces the growth rate of the aggregate human capital stock, the increase in educational investments and health investments raises growth of aggregate human capital. Since the fall in fertility unleashes additional resources that can be spent on education and health, this effect is so strong that it overcompensates the negative effect of the reduction in fertility. Consequently, aggregate human capital accumulates faster and economic growth increases in case of lower fertility. This is a similar mechanism as in the partial equilibrium framework of Prettner et al. (2013). The implied negative association between fertility and long-run economic growth being consistent with the empirical evidence for modern economies (see, for example, Brander and Dowrick, 1994; Ahituv, 2001; Herzer et al., 2012).

Next, we obtain the following result.

Proposition 3. *Higher parental investments in education lead to an increase in the rate of long-run economic growth.*

Proof. Taking the derivative of Equation (26) with respect to θ provides

$$\frac{\partial g_y^*}{\partial \theta} = \frac{(\beta+\xi+1)\left\{\theta\left[\nu(\phi-2)-\phi+1\right]+\nu(\zeta-\xi)(\phi-2)\right\}\psi\left[\frac{\zeta(\theta\mu)^{\nu}\omega(\zeta\omega)^{-\nu}}{1+\beta+\xi}\right]^{1+\frac{1}{1-\phi}}}{\theta(\zeta+\theta-\xi)^2(1-\phi)}.$$

To see that this expression is positive, we note that the denominator is always positive. Furthermore, we inspect the following part of the numerator: $\theta[\nu(\phi-2)+1]+\nu(\zeta-\xi)(\phi-2)=\theta\nu(\phi-2)-\theta\phi+\theta+\nu(\zeta-\xi)(\phi-2)$. This is unambiguously positive because i) $\nu(\zeta-\xi)(\phi-2)$ is positive, ii) $\mid\theta\nu(\phi-2)\mid<\mid\nu(\zeta-\xi)(\phi-2)\mid$ since $\xi>\zeta+\theta$, and iii) $-\theta\phi+\theta$ is positive. □

The intuition behind this result is that parents who want to have better educated children do not only increase their educational investments but they also reduce fertility due to the quality-quantity substitution described in Becker and Lewis (1973). This implies in turn that they supply more of their time on the labor market and partly spend the additional income on education and health of their children. The additional investments in the quality of children are larger than the reductions in the investments in their quantity. Consequently, aggregate human capital growth increases, despite the fact that population growth decreases. Due to this increase in the rate of aggregate human capital accumulation, technological progress and economic growth gain momentum.

Finally, we obtain the following result.

Proposition 4. *Higher parental investments in children's health lead to an increase in the rate of long-run economic growth.*

Proof. The derivative of Equation (26) with respect to ζ is given by

$$\frac{\partial g_y^*}{\partial \zeta} = \frac{(\beta+\xi+1)\left\{\zeta\left[\nu(\phi-2)+1\right]+(\nu-1)(\theta-\xi)(\phi-2)\right\}\psi\left[\frac{\zeta(\theta\mu)^{\nu}\omega(\zeta\omega)^{-\nu}}{1+\beta+\xi}\right]^{1+\frac{1}{1-\phi}}}{\zeta(\zeta+\theta-\xi)^2(\phi-1)}.$$

To see that this expression is positive, first note that the denominator is negative. Next, we inspect the following part of the numerator: $\zeta[\nu(\phi-2)+1]+(\nu-1)(\theta-\xi)(\phi-2)=\zeta+\zeta\nu(\phi-2)+(\nu-1)(\theta-\xi)(\phi-2)$. This expression is negative because $\xi>\zeta+\theta$, which implies that the derivative is positive. □

The intuition behind this result is similar to that of Proposition 3 and it is again rooted in the quality-quantity substitution. Parents who want to have healthier children do not only increase their health investments but they also reduce fertility. Again, this allows them to work more and spend part of the additional income on education and health of their children. Analogous to the intuition behind the previous result, this leads to faster human capital accumulation, technological progress, and economic growth.

3.1 Numerical illustration

Table 1: Parameter values for simulation

Parameter	Value	Parameter	Value
β	0.6	δ	7
ϕ	0.7	α	0.33
ξ	0.85	ζ	0.3
θ	0.4	ψ	0.05
μ	8.68	ω	8.65
ν	0.5		

We illustrate the transitional dynamics of the model and the long-run solution by solving the four-dimensional system of difference equations (19)-(22) for the parameter values displayed in Table 1. The discount factor β is computed based on a discount rate ρ that is equal to 2% and considering that each period lasts for 25 years in our OLG structure. The elasticity of output with respect to physical capital, α, and the knowledge spillover, ϕ, attain the values of 0.33 and 0.7, respectively (Acemoglu, 2009; Jones, 1995; Jones and Williams, 2000; Mankiw et al., 1992). The other parameters are chosen such that we obtain values of the growth rate of per capita GDP and the growth rate of the population along the balanced growth path that are consistent with the US experience averaged over the years 2006-2015 according to the World Bank (2016) data.[7] Figure 1 displays the convergence of the economic growth rate from above to its steady-state level. The dashed line (Country A) represents the baseline case. We observe that the long-run growth rate of per capita GDP almost reaches the intergenerational growth rate of per capita GDP of the US, which is 14.59%. The growth rate of the population is constant [see Equation (24)] and in our simulations we obtain a value of 22.45% which is a reasonable approximation of the US intergenerational population growth rate of 23.26%.

After the fifth period in the simulations, we increase the value of the weight of children's health in the parental utility function (ζ) by 1% in an alternative scenario

[7] We consider the growth rates of the population and of GDP per capita from 2006 to 2015 for which we compute the geometric mean. Afterwards we convert the yearly growth rates into their intergenerational counterparts.

(Country B). We observe that, after the increase in the parameter ζ, country B shows a higher growth rate as compared to country A. This is exactly what we stated in Proposition 3. The same result can be observed in Figure 2, where we plot the levels of technology. After the increase in the utility weight of children's health, country B overtakes country A in terms of the technology level. Altogether, these results are consistent with our theoretical findings as described in Proposition 4.

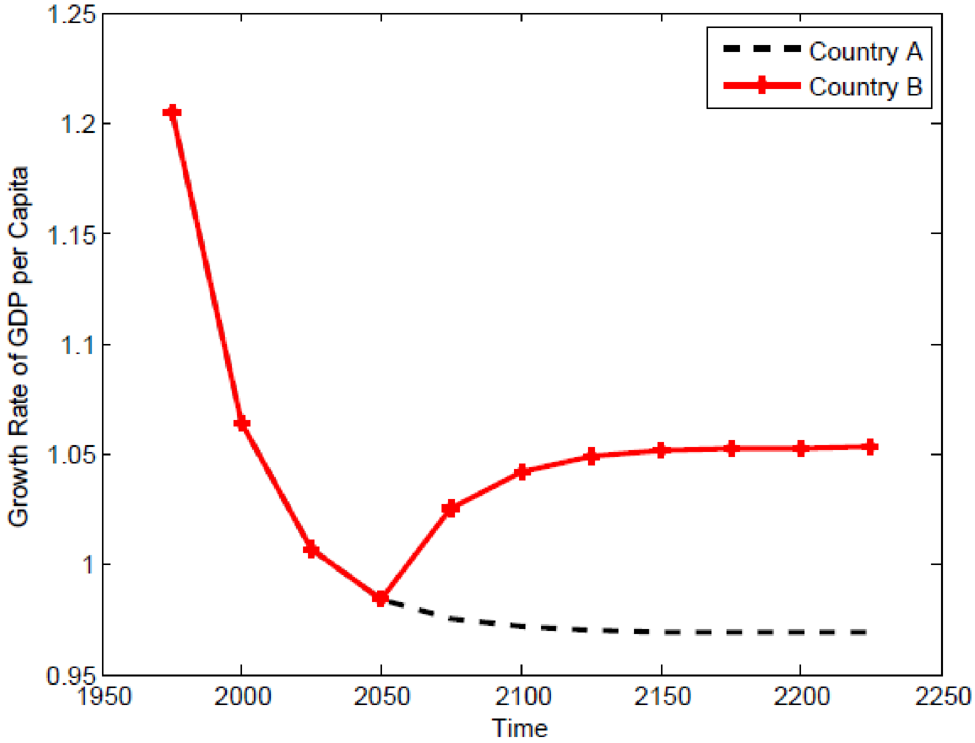

Figure 1: Growth rates of countries A and B over 15 periods. Note that, after the fifth period in the simulations, the weight of health in parental utility (ζ) increases by 1% in country B.

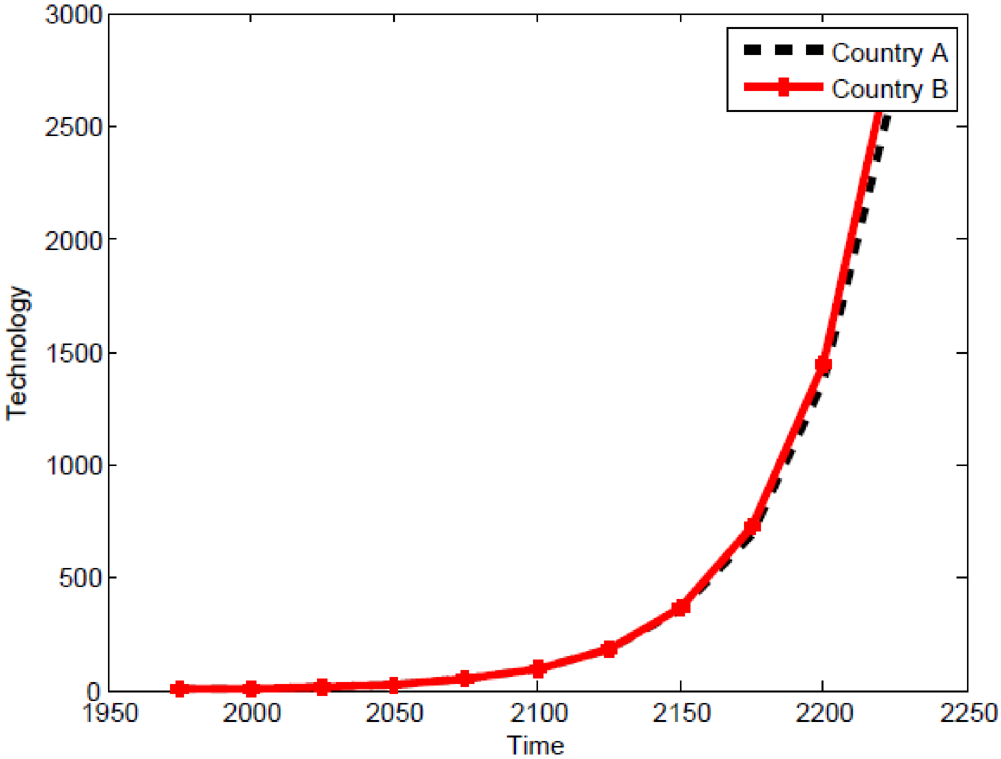

Figure 2: Technology levels of countries A and B over 15 periods. Note that, after the fifth period in the simulations, the weight of health in parental utility (ζ) increases by 1% in country B.

4 Conclusions

We set up a framework of R&D-based economic growth in which the stock of human capital is determined by parental education and health investments. Due to the quality-quantity tradeoff, an increase in fertility leads to a reduction in education and health investments to the extent that the growth rate of overall human capital slows down. The converse holds true for falling fertility. Altogether, this generates a pattern in which a lower population growth rate is associated with faster economic growth. This pattern is consistent with the empirical findings for modern economies in the second half of the twentieth century (Brander and Dowrick, 1994; Ahituv, 2001; Herzer et al., 2012). If parents prefer to have better educated children, they do not only increase educational investments but also health investments and if parents put more weight on their children's health they do not only raise health investments but also educational investments. This implies that there is a complementarity between health and education as emphasized in the literature.

We show that a better health condition of children raises the growth rate of human capital and therefore the growth rate of the central input in the R&D sector. As a consequence, technological progress increases, which in turn raises economic growth. This provides a mechanism based on R&D-based endogenous economic growth to explain the positive effect of health on growth that is found for modern economies (Cervellati and Sunde, 2011). This mechanism is likely to complement the ones that are based on the neoclassical capital dilution effect (Cervellati and Sunde, 2011) and on the Ben-Porath mechanism that a higher life expectancy implies a stronger incentive for education (Ben-Porath, 1967; Cervellati and Sunde, 2005, 2013).

To focus on the most important transmission channels of the effects of children's health on economic growth, we abstracted from some aspects that would be present in a more realistic setting but which would make the model more complicated such that analytical closed-form solutions for the long-run growth rates could not be obtained. For example, i) health might not only be represented by physical well-being but also by longevity, ii) the function by which health and education investments translate into human capital might have a more general form than the currently used Cobb-Douglas specification. While we do not find any reason to believe that generalizations along these lines would render our central results invalid, a consideration of these factors is surely a promising avenue for further research.

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