Center for
European,
Governance and
Economic Development Research

Discussion Papers

Number 393 – May 2020

TESTING UNIFIED GROWTH THEORY: TECHNOLOGICAL PROGRESS AND THE CHILD QUANTITY–QUALITY TRADE-OFF

Jakob Madsen
Holger Strulik

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

ISSN: 1439-2305

Testing Unified Growth Theory: Technological Progress and the Child Quantity–Quality Trade-off

Jakob Madsen*

Holger Strulik†

May 2020

Abstract. A core mechanism of unified growth theory is that accelerating technological progress induces mass education and, in interaction with child quantity-quality substitution, a decline in fertility. Using unique new data for 21 OECD countries over the period 1750-2000, we test, for the first time, the validity of this core mechanism of unified growth theory. We measure a country's technological progress as patents per capita, genetic-distance weighted foreign patents, and investment in machinery, equipment and intellectual property products. Controlling for other confounders like income, mortality, the gender wage gap, indicators for child labor, compulsory schooling, and time- and country-fixed effects, we establish a strong positive impact of technological progress on investments in education and a strongly negative one on fertility. Using two-stage regressions, we assess the child quantity-quality substitution that can be motivated by technological change. We estimate that a 10 percent increase of enrollment in primary and secondary school is associated with a decline of the general fertility rate by 3 to 4 percent.

Keywords: technological progress, fertility, education, quantity-quality trade-off, unified growth theory.

JEL: O40, O30, N30, J10, I25.

* University of Western Australia, Department of Economics, 35 Stirling Hwy, Perth, 6009 WA, Australia. email: jakob.madsen@uwa.edu.au

† University of Göttingen, Department of Economics, Platz der Göttinger Sieben 3, 37073 Göttingen, Germany; email: holger.strulik@wiwi.uni-goettingen.de.

1. Introduction

Unified growth theory (UGT) suggests that long-run economic development over the entire course of human history can be explained by one consistent model rather than by separate theories tailored for specific periods of development. The theory, developed by Galor and Weil (2000) and extended and refined by Galor and Moav (2000, 2002), conceptualizes human economic history as a phase transition through three regimes, the Malthusian Regime, the Post-Malthusian Regime, and the Modern Growth Regime (see Galor, 2005, 2011, for an extensive discussion). Technological progress, driven by population growth, eventually frees societies from the Malthusian Regime of stagnation at subsistence level and allows for both a gradual rise of income and increasing fertility rates during the Post-Malthusian Regime. The Modern Growth Regime is initiated when technological progress is sufficiently forceful to trigger an educational expansion and a fertility transition. During this phase, accelerating technological progress induces parents of later-born generations to invest more in education and to prefer a smaller number of offsprings. Declining population growth and increasing technological progress through a better-educated workforce accelerates economic growth such that economies that successfully initiate the fertility transition take off at unprecedented growth rates and eventually converge towards a steady state of high, human-capital-driven economic growth.

The central mechanism of UGT that initiates the transition to the Modern Growth Regime, has so far not been scrutinized empirically. This, perhaps, surprising fact can be explained by a lack of data for technological progress and education investment over the relevant time period for sufficiently many countries. The key UGT mechanism consists of two elements: (i) a child quantity-quality (QQ) substitution at the household level that motivates parents to enhance their investment in their offspring's education; and (ii) a positive effect of technological progress on the return to education.

Several studies have addressed the child QQ-trade-off (see below for a discussion of the literature). Evidence in favor of the QQ-trade-off, however, provides only necessary but not sufficient support for UGT. This is so because other theories of long-run development have been proposed that also employ the QQ-trade-off but not the technological progress mechanism. The perhaps most popular alternative theory is based on Becker's (1960) idea that rising income induces parents to opt for fewer children and spend more resources on their education (see Becker et al., 1990, and Moav, 2005, for a discussion in the context of long-run development). Based essentially on the QQ-trade-off, other theories of the fertility transition and take-off have been proposed, such as theories of child mortality (Kalemli-Ozcan, 2002, Lagerloef, 2003a); child labor (Hazan and Berdugo, 2002; Strulik, 2004); contraception (Bhattacharya and Chakraborty, 2017; Strulik, 2017); and adult life expectancy (Soares, 2005; Cervellati and Sunde, 2015). These theories, in the sense that they focus on long-run development from stagnation to modern growth, are also conceptualized as unified growth theories. Here, we confine the term to the canonical model of Galor and Weil (2000) and its refinements. The difference between these studies is the proposed mechanism that initiates and propels the QQ-trade-off. The unique feature of the canonical UGT (Galor and Weil, 2000) is that the driver of the QQ-trade-off is identified as accelerating technological progress, which induces more education and less demand for children.

A popular method used to identify the child QQ-trade-off is to use the exogenous variation in fertility due to twin births. Several studies using this approach and micro-data from modern societies have found little or mixed support for the QQ-trade-off (e.g. Black et al., 2005; Caceres-Delpiano, 2006; Rosenzweig and Zhang, 2009; Angrist et al., 2010). These studies, however, do not consider that, according to UGT, both education and fertility are endogenous. An unexpected variation in fertility violates the first order conditions of parental calculus from which the QQ-trade-off is derived. A true test of the QQ-trade-off would require an exogenous variation in the cost of children or the return to education (Galor, 2012).[1]

A couple of studies use long-run cross-country panel data to explore the determinants of the fertility transition and, indirectly, the QQ-trade-off. Lehr (2009) shows for the period 1960-1999 that fertility is negatively associated with secondary education and that it is positively associated with productivity increases at low stages of development and negatively at advanced stages. Murtin (2013) finds, for the period 1870-2000, that years of primary schooling (but neither income nor mortality) are a robust determinant of fertility. Herzer et al. (2012) show, for the period 1900-1999, that income growth causes fertility decline and Dalgaard and Strulik (2013) show that the timing of the fertility transition is a powerful predictor of contemporary income differences and that the correlation between the year of the onset of the fertility transition

[1] Klemp and Weisdorf (2018) found support for the QQ-trade-off during England's industrial revolution using the protogenesic interval (between marriage and first birth) as exogenous variation in fecundity. Bleakley and Lange (2009) provide evidence from hookworm eradication, conceptualized as a decline in the costs of education; Aaronson et al. (2014) provide evidence using improved access to education for African-American children in the U.S. south; and Bailey (2013) provides evidence using differences in access to oral contraceptives across US states in the 1960s and 1970s. Becker et al. (2010) demonstrate a QQ-trade-off in Prussia before the demographic transition with two-way causality between education and fertility. Fernihough (2017) shows for early 20th century Ireland that fertility is negatively associated with voluntary enrollment in secondary school.

and labor productivity is mediated by human capital accumulation. Chatterjee and Vogl (2018) match macro GDP data with micro fertility data and show that fertility declines with long-run growth. The finding of a negative association of fertility and growth supports UGT but does not constitute a strict test of its key mechanism. This is so because economic growth could be generated by various processes, such as opening to (transatlantic) trade, capital deepening, or the discovery of natural resources, i.e., processes that do not necessarily increase the return to education. The canonical UGT, however, hypothesizes that fertility declines due to technological progress and its impact on the return to education.

Here, we extend the literature in various directions. To test the model we collect annual data for 21 OECD countries over the period 1750–2010. We take the endogeneity of fertility and education into account and estimate how both are affected by technological progress, controlling for a variety of other potential confounders, such as the mortality rate, the gender wage gap, and the level and the growth rate of income. We measure technological progress by new patents per capita. Alternatively, we consider patents granted in foreign countries and weigh them by genetic distance to assess their local importance. Furthermore, we consider investment in machinery, equipment, and intellectual property products as a complementary measure of skill-biased technological change. We establish that technological progress is strongly positively associated with primary and secondary school enrolment ten year ahead and strongly negatively associated with the contemporary fertility rate. Furthermore, when technological progress is controlled for, income growth becomes insignificant (while the income level continues to exert a small negative impact on fertility). We then continue to estimate the QQ-trade-off that can be attributed to the UGT mechanism. For that purpose, we estimate the association of fertility with the part of education that is explained by technological progress. We find that a 10 percent increase of enrollment in primary and secondary school is associated with a decline of the general fertility rate by 3 to 4 percent.

The paper is organized as follows. In the next section we review the household side of Galor and Weil's (2000) UGT model and derive the key hypotheses. In Section 3 we introduce the empirical model and our handling of simultaneous endogeneity of the fertility and education decision; we present the data set and examine long-run regularities in graphical analyses. Section 4 provides the OLS and IV regression results, as well as robustness- and placebo tests. Section 5 concludes.

2. The QQ-Trade-Off in Unified Growth Theory

Consider the following model, based on Galor and Weil (2000) and Galor (2005). Suppose households have the following preferences:

$$u_t = (1-\gamma)\log c_t + \gamma\left[\log n_t + \log h_{t+1}\right], \tag{1}$$

in which c_t is consumption in period t, n_t is fertility, h_{t+1} is human capital per child in period $t+1$, and γ is the utility weight of 'child services' $n_t h_{t+1}$. Human capital is produced by parents' investment in education per child, e_{t+1}. Parents are endowed with h_t units of human capital and receive a potential income, w_t, where w_t is the market wage per unit of human capital. Parents are endowed with one unit of time per period, which can be spent earning income or child rearing. Child rearing requires $\tau + e_{t+1}$ units of time, in which τ are essential time costs of child quantity and e_{t+1} are optional time costs of child quality. The implied budget constraint reads

$$c_t = \left[1 - (\tau + e_{t+1})n_t\right] w_t h_t. \tag{2}$$

The human capital of the next generation depends on parents' investment in education and on technological change (the growth rate of technology) g_{t+1}, such that $h_{t+1} = h(e_{t+1}, g_{t+1})$. The production function of human capital fulfils the following assumptions: (i) education increases human capital, $h_e \equiv \partial h_{t+1}/\partial e_{t+1} > 0$; (ii) technological progress reduces human capital (makes knowledge obsolete), $h_g \equiv \partial h_{t+1}/\partial g_{t+1} < 0$; and (iii) technological progress increases the return on education, $h_{eg} \equiv \partial^2 h_{t+1}/\partial e_{t+1}\partial g_{t+1} > 0$. Parents chose the levels of consumption and education that maximize utility (1) subject to the budget constraint (2) and the non-negativity constraints, $n_t \geq 0$, $e_{t+1} \geq 0$. Galor and Weil additionally impose a subsistence consumption constraint, which is important to differentiate between the Malthusian Regime (where the subsistence constraint binds) and the Post-Malthusian Regime'. These periods of human history share the feature that $e_{t+1} = 0$. Since here we focus on the transition to the Modern Growth Regime, where $e_{t+1} > 0$, and on the onset of the fertility transition, we ignore the corner solution for consumption and fertility and focus on the transition from the corner to the interior solution for education.

The first order condition with respect to child quantity, n_t, is obtained as:

$$n_t = \frac{\gamma}{\tau + e_{t+1}}. \tag{3}$$

The quantity (n_t)–quality (e_{t+1}) trade-off is clearly visible in (3). Observe that neither income nor technological progress has a direct impact on fertility. Galor (2011) argues forcefully, in a more general setup, that income should not have an impact on fertility once child- or infant mortality is controlled for. In the subsequent empirical literature there seems to be some confusion about the correct interpretation of the QQ-trade-off in (3). For a correct assessment, it should be noted that (3) is *not* the solution of the model. It is just one first-order condition. In particular, there is no causality going from education to fertility, nor from fertility to education. A central assumption of UGT is that the education and fertility decisions are taken simultaneously and are thus both endogenous. Exogenous variation in education, for example through compulsory schooling laws, or in fertility, for example through unplanned and thus sub-optimal twin births, are interesting mechanisms to scrutinize a quantity-quality trade-off but are of limited value for an empirical assessment of UGT (see Galor, 2012, for an extensive discussion).

Equation (3) becomes a solution of the model when it is considered together with the first order condition for education, which reads:

$$-\frac{(1-\gamma)n_t}{1-n_t(\tau+e_{t+1})}+\frac{\gamma}{h(e_{t+1},g_{t+1})}\cdot h_e(e_{t+1},g_{t+1})\leq 0, \tag{4}$$

The condition holds with equality when education is positive. Inserting (3) into (4) the first order condition for education becomes

$$G(e_{t+1},g_{t+1})=(\tau+e_{t+1})h_e(e_{t+1},g_{t+1})-h(e_{t+1},g_{t+1})\leq 0. \tag{5}$$

Equation (5) establishes the solution for education since fertility is eliminated from the equation. The equation contains education as the only endogenous variable, while all other parameters and variables are considered as exogenous from the household's perspective. Without further assumptions, the solution for education is not explicit. Its features, however, can be implicitly discussed. The key mechanism of UGT, namely that technological progress induces education is obtained from

$$\frac{\partial G}{\partial e_{t+1}}=(\tau+e_{t+1})h_{ee}<0, \qquad \frac{\partial G}{\partial g_{t+1}}=h_e(\tau+e_{t+1})-h_g>0.$$

When there is education, and thus $G=0$, the implicit function theorem provides

$$\frac{\mathrm{d}e_{t+1}}{\mathrm{d}g_{t+1}}=-\frac{\partial G/\partial g_{t+1}}{\partial G/\partial e_{t+1}}>0. \tag{6}$$

An additional and essential assumption of UGT is that the curvature of the education function ensures that $G(0, 0) < 0$. This assumption provides a corner solution for education and ensures that technological progress induces education only if its rate is high enough. To see why the assumption is essential, note that, in human history, there was always some technical change and the quantity-quality mechanism (3) was potentially always active.[2] The assumption $G(0, 0) < 0$ ensures that there exists a long period in history without mass education because technological progress was too low. Education and the fertility transition set in when the rate of technological progress is sufficiently high such that a positive solution for e_{t+1} exists that fulfills (6) with equality. Defining the threshold of technological progress where education turns positive as $\hat{g}$, the solution for education fulfils:

$$e_{t+1} \begin{cases} > 0 \text{ if } g_{t+1} > \hat{g} \\ = 0 \text{ otherwise.} \end{cases} \tag{7}$$

Inserting $e(g_{t+1})$ in (3), we obtain the solution for n_t, which contains fertility as the only endogenous variable, and technological progress and other parameters as exogenous determinants. Since fertility depends indirectly, through education and the QQ-trade-off, on technological progress, UGT concludes that increasing technological progress leads to declining fertility. Specifically we arrive at the following predictions of UGT:

(1) There exists a negative correlation between education and fertility (QQ-trade-off)

(2) Technological progress, if high enough, has a positive impact on education

(3) Technological progress, if high enough, has a negative impact on fertility

(4) Technological progress impacts on fertility through the education decision

(5) If technological progress becomes high enough, it triggers the fertility transition

(6) Income growth not driven by technological progress has no impact on education and fertility.

To the best of our knowledge, the predictions (2)–(6) have so far never been tested empirically. Most of the literature focuses on the correlation in (1), which constitutes an essential prerequisite of UGT but is insufficient to describe the core mechanism. The study that comes perhaps closest to our analysis is the one by Chatterjee and Vogl (2018) who find a negative impact of

[2] The child quantity-quality trade-off is not restricted to education as a measure of quality. Dalgaard and Strulik (2015, 2016) provide evidence for a trade-off between child quantity and nutrition and develop a theory on its foundation from first principles in energy consumption and ontogenetic growth.

long-run growth in income of the working age population on fertility in a panel of developing countries and interpret this as evidence for unified growth theory. Economic growth, however, is not the same as technological progress. Economic growth could increase, for example, by capital deepening, increasing labor force participation, increasing openness, discovery of natural resources, commodity price booms, or structural change that is independent of technological change. In this case, it would not trigger education and unified growth theory would predict that it should have no impact on education. Here, we focus on technological progress and therewith on the mechanism that is at the core of unified growth theory.

The preference and technology parameters of the model are likely to be country-specific and not necessarily time-invariant. Thus, we also include country fixed-effects and time fixed-effects in the regressions. We control for mortality, child labor, and female empowerment since these demographic variables have been suggested as being independent influences on fertility and education. Reverse causality is no issue since we measure technological progress at the same year as education and school children are unlikely to be responsible for innovations. However, we additionally instrument national technological progress with the technological progress of neighboring countries. The UGT model suggests that the level of income is not decisive for fertility and education. The unimportance of the level of income for the fertility transition in UGT is justified by the fact that Western countries that experienced the fertility transition at about the same time and, yet, displayed very different income levels, which makes income an unlikely driver of the fertility transition (Galor, 2005). However, since other theories disagree, we also control for the level of income (see Jones et al., 2010, for a review and a critical discussion).

3. Empirical Method and Data

3.1. **Model Specification.** The following two models are estimated:

$$\begin{aligned}\log FER_{it} &= \lambda_0 + \lambda_1 \log GER^{PS}_{i,t+1} + \lambda_2 \log(Pat/Pop)_{it} + \lambda_3 \log(Y/Pop)_{it} + \lambda_4 \log CMR_{it} \\ &\quad + \lambda_5 \log W^{Gap}_{it} + CD + TD + \epsilon_{1,it} \qquad (8)\end{aligned}$$

$$\begin{aligned}\log GER^{PS}_{i,t+1} &= \gamma_0 + \gamma_1 \log FER_{it} + \gamma_2 \log(Pat/Pop)_{it} + \gamma_3 \log(Y/Pop)_{it} + \gamma_4 \log CMR_{it} \\ &\quad + \gamma_5 \log W^{Gap}_{it} + CD + TD + \epsilon_{2,it}, \qquad (9)\end{aligned}$$

where FER is the general fertility rate; GER^{PS} is gross enrollment rates (henceforth GERs) at primary and secondary levels; Pat is the number of new patents granted to residents in period t; Pop is population; Y is real GDP; CMR is the crude mortality rate, measured as the number of deaths per 1000 population; ϵ is a disturbance term; and $W^{Gap} = (W^M - W^F)/W^M$ is the gender wage gap, where W^M and W^F are hourly, weekly, or monthly wages of males and females; $GER^{PS}_{i,t+1}$ refers to GER^{PS}_{it}, forwarded 10 years. CD and TD are country- and time fixed effects. The model is estimated in non-overlapping 10-year intervals over the period 1750-2000. The sample period ends in the year 2000 to give room for the 10-year forwarded GER^{PS}. Data construction and data sources are relegated to the Data Appendix.

According to UGT and the child QQ trade-off, the fertility and education decision is taken simultaneously, implying that there is no causality going from education to fertility and vice versa. The right hand side variables GER^{PS} and FER thus control for confounding channels through which fertility may impact education and vice versa. The variables that potentially influence fertility and education according to the QQ model are technological progress, mortality, economic growth, and the gender wage gap. Since technological progress, proxied by patent intensity, is the key driver of the fertility transition in the UGT framework, we use various approaches to deal with potential endogeneity, as discussed in detail in the next sub-section (Section 3.2). The pooled seemingly unrelated regression estimator is used to account for cross-country residual correlation, the parameter estimates are corrected for cross-country heterogeneity and serial-correlation, and the model is estimated in non-overlapping 10-year intervals to filter out random and cyclical fluctuations and to allow for slow adjustment of the dependent variables to fluctuations in the independent variables within each observation interval. Each variable is measured as an annualized average within each 10-year interval except for the growth rate of per capita income, which is measured as the annualized geometric growth rate over each 10-year interval.

The models are estimated over the period 1750-2000, as well as for sub-periods, to capture the fertility transition in full and to allow for the effects of temporary fertility spurts. Estimates that are concentrated in the transitional period 1880-1980 may be overly influenced by medium-term time-trends; an effect that will be less pronounced over a longer time span. Furthermore, the efficiency gain from long historical data is crucial here because we estimate in 10-year intervals. It is important to stress that GERs are used here as opposed to the commonly used educational attainment. Educational attainment is a stock that is determined by past enrollment rates and the exit of older workers from the labor force into retirement and, as such, is determined in the past and is little influenced by contemporary decisions. Gross enrollment rates are the relevant outcome variable because they refer to education at the time at which the schooling decision is made.

The gender wage gap is included in the models as it affects the opportunity costs of having children relative to the income of the household (Galor and Weil, 1996). Galor (2005), for example, argues that the reduced gender wage gap starting during the Second Industrial Revolution, contributed to the fertility transition (see also Lagerloef, 2003b; Prettner and Strulik, 2017, and Strulik, 2019). Based on the identification strategy of Schultz (1985), Madsen et al. (2020) show that females gained a comparative advantage following the grain invasion from the new world starting in the second half of the 19th century. Crude mortality is included in the models since parents care about net fertility and because some strands of the demographics literature argue that the fertility transition was fueled by the mortality transition (see e.g. Guinnane, 2011). In standard economic frameworks, mortality plays no role in explaining net fertility or population growth. If child mortality is added in a standard fashion to the frameworks of Doepke (2005) and Galor (2011), it cancels out in the computation of the optimal net fertility rate. It is also worth stressing again that the same control variables are included in Eqs. (1) and (2) because the QQ model assumes that the fertility and educational decisions are jointly taken.

Technological progress is measured by patent-intensity, where the number of patents is normalized by population following second-generation Schumpeterian growth models (see, e.g., Ha and Howitt, 2007; Peretto, 1998; Madsen, 2008). If, on average, technological progress is skill biased, we would expect $\log GER^{PS}_{i,t+1}$ to be significantly positively related to $\log(Pat/Pop)_{it}$. Patents are excellent indicators of technological progress because they have been through screening, are not measured by errors, and are available far back in time. Furthermore, patents measure technological output as opposed to R&D expenditure in which all kind of research activities, many of which are unlikely to result in technological advances, are lumped together. Finally, patent-intensity is a stationary process with very low persistence (see Table 4 below and the surrounding discussion), which means that its significance in the regressions is not an outcome of a positive or negative time-trend it has in common with education and fertility. The downside of patents as technology indicators is that not all inventions are patented and that inventions are highly heterogeneous, which is not a problem if they are in large numbers; however, it is a problem for small numbers of patents. Since patent counts are new patent flows, patent-intensity measures technological progress and not the level of technology.

As a double check, we use the income share of net investment in machinery, equipment, and intellectual property products (IPP) as an alternative indicator of skill-biased technological progress as it is driven predominantly by new investment-specific technology. Krusell et al. (2000), for example, argue that demand for skills accelerates in response to increasing investment in machinery and equipment. In support of their theory, they find that the elasticity of substitution between capital equipment and unskilled labor is significantly higher than that of capital equipment and skilled labor. Similarly, Caselli (1999) develops a theory in which technological revolutions increase the demand for workers who are able to switch to sectors that benefit from new technologies. Caselli (1999) argues that skilled labor and capital investment were complementary during the First and the Second Industrial Revolutions. Overall, there is strong support in the literature for the idea that industrial revolutions are associated with increasing demand for skilled labor (see, for further references and discussion, Acemoglu, 2002; Galor, 2011).

It has been argued that technological progress could be unskilled-biased during the First Industrial Revolution such that technological advances during this period did not trigger a fertility transition (Galor, 2005). Here, we will show that even if technological progress during the First Industrial Revolution were skill-biased, it would not have been forceful enough to trigger a fertility transition. As shown in the data section 3.3 below, patent intensity was approximately 50 times larger during the Second Industrial Revolution than during the First Industrial Revolution. Furthermore, the real price of investment in machinery and equipment was flat before the 1870s, pointing towards insignificant investment-specific technological progress.

Per capita income growth and technological progress are both included in the models to make a clear distinction between growth driven by technological progress and growth driven by factors unrelated to technological progress, such as saving-induced capital deepening, land clearing, increasing labor force participation rates, Smithian growth (increasing division of labor), foreign trade, gold discoveries, commodity booms, terms of trade shocks etc. Essentially, per capita growth is included in the model to control for the impact of economic development on fertility and education.

Finally, one may question why we need to estimate both equations (8) and (9) since one is a mirror image of the other. There are two reasons why it is useful to estimate both models. First, since the ideal conditions are never met in an uncontrolled environment, the derived elasticities will differ across the two models. Following the classical errors-in-variables problem, for example, the correlation between the measurement error of the dependent variable and the residual is assumed to be zero, while this is not the case for the independent variables. The same reasoning applies to endogeneity due to the exclusion of unobserved control variables that differ between the two equations. Although we have included more control variables than almost all other long-run studies of the fertility transition, there are surely unobserved variables we have not controlled for, such as cultural and environmental factors, for example.

As explained in Section 2, equations (8) and (9) are derived from a standard UGT model following Galor and Weil (2000). According to this literature, the increasing rate of technological progress during industrialization increased the returns to human capital and, consequently, changed the incentives to trade quantity for quality in the fertility decision. It is worth stressing that it is technological progress and not the level of technology that is crucial for the fertility transition in the Galor-Weil (2000) model.

3.2. **Endogeneity and IV strategy.** Following unified theory, the focus variables are GERs, fertility and technological progress (Galor, 2005). As stated above, there is no causal effect from lagged fertility to education since the fertility and the educational decisions are taken simultaneously: lagged fertility is merely capturing the fertility effects of technological progress and other factors that influence the quantity-quality trade-off, such as compulsory schooling years, minimum working age, and the gender wage gap. Thus, the correct identification strategy is to use exogenous variables that shift the QQ-curve in the fertility-education dimension and *not* to instrument the movements along the QQ-schedule. To this end we estimate the following 2SLS regression:

First stage:

$$\log GER_{i,t+1}^{PS} = \alpha_0 + \alpha_1 \log(Pat/Pop)_{it}^{F} + \alpha_2 \log Sch_{it}^{Comp} + \alpha_3 \log Age_{it}^{Min} + CD + TD + \epsilon_{3,it} \quad (10)$$

Second stage:

$$\log FER_{it} = \beta_0 + \beta_1 \log GER_{i,t+1}^{PS} + CD + TD + \epsilon_{4,it} \quad (11)$$

where Sch^{Comp} is years of compulsory education; Age^{Min} is the minimum working age; and $(Pat/Pop)^F$ is the foreign patent-intensity weighted by the square root of genetic proximity as detailed in the data section below. We include one non-deterministic regressor at a time as well as all of them jointly in the first-stage regression to capture different dimensions of the QQ model.

Following Spolaore and Wacziarg (2009), we assume that technology spillovers are stronger among genetically closely related countries than genetically distant countries, because genetically close populations tend to have comparable habits, beliefs, customs, and values and these traits are transmitted from one generation to the next. Foreign patent intensity, $(Pat/Pop)^F$, is exogenous to the extent that foreign technological progress is driven by factors that are independent of domestic factors. This may not be true for the innovative powerhouses during the fertility transition such as Britain, Germany, France and the US. Excluding these countries from the regressions, however, does not affect the results.

Genetically weighted foreign patents may have affected technological progress because companies could, sometimes freely, adopt the technology created by their genetically proximate neighbors without any formal and informal R&D effort. Alternatively, patent-intensity could have been a concerted effort across the OECD countries. If this was the case, then we would have expected the same time-profile of research-intensity across the sample. However, this is not what we observe: Portugal, for example, has always had a comparatively low research intensity, Spain and Greece experienced an inverted U-shaped patent-intensity path during the 20th century, and the innovative activity was already increasing in the Scandinavian countries during the 19th century.

The minimum working age is included as a control variable because it affects the opportunity costs of education and, therefore, the trade-off between fertility and education. According to Galor and Moav (2006) and Doepke and Zilibotti (2008), the industrial class lobbied for a higher minimum working age during the 19th century as an incentive to increase investment in human capital and to reduce fertility. Doepke (2004) argues that child labor laws were influential for the demographic transition. Like the minimum working age, the number of compulsory school years positively affects the opportunity costs of having children and, additionally, reduces the cost of education to the extent that governments introduced free schooling to honor their commitment to compulsory education.

A key question is exogeneity of the instruments: the possibility that the instruments are outcomes of economic development. For example, one may argue that decisions on minimum working age and compulsory school years are determined by economic development. However, if this were the case, then we would expect Portugal and Spain to have schooling and minimum working age laws on par with Denmark, Finland, Norway and Sweden during the 19th century since all these countries had approximately the same average per capita income during the 19th century. However, this is not the case. The attitudes and policies towards education differed widely across these countries long before the fertility transition. Statutory laws introduced already in the 1730s in Denmark and Norway, were major forces behind the expansion of education starting more than 150 years before the start of the fertility transition in these two countries. For Spain in the mid-16th century, by contrast, the church authorities decided that the unrestricted production of books had to be stopped; essentially to prevent the expansion of Protestantism (Nalle, 1989). The decision resulted in a list of prohibited books in 1551 and door-to-door interviews by Inquisitors gradually increased in intensity after this year to prevent the spread of potentially dangerous ideas. This intervention broke the upward trend in literacy rates before 1551 and had long-lasting effects on education in Spain (Nalle, 1989). Furthermore, several scholarly articles argue that the Napoleonic Wars carried the seeds for the expansion of mass education in Europe during the 19th century (see, for a recent example, Aghion et al., 2019).

Summarizing, the evidence suggests that foreign patent intensity is unlikely to be endogenous.

3.3. **Data.** The models are estimated for the following 21 OECD countries: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, the UK and the US. The data are mostly obtained from national sources. As stated earlier, the data construction and sources are detailed in the Data Appendix.

For the gender wage gap, our approach is representativeness: to include the wages for as many sectors and professions as possible to ensure that the data is representative of the whole economy. The data indicate that the gender wage gap is not sensitive to payment intervals (hourly, weekly or monthly) and that it is similar in the manufacturing and service sector. However, the wage gap is generally lower for agriculture than for other sectors of the economy; a problem that is catered for in the estimates by ensuring a smooth transition from agriculture to manufacturing and by splicing the overlapping data. Most of the pre-WWI data are daily wages in the agricultural sector, after which manufacturing gradually takes over as the dominant non-service sector. The general fertility rate, FER, is calculated as the total number of live births per 1,000 females of reproductive age between 15 and 44 years in a population per year. This is a more precise measure of fertility than the crude birth rate (birth per 1000 population) because FER uses the female population aged 15 to 44 years in the denominator and, therefore, is not affected by the significantly changing age structure of the population during demographic transitions.

School enrollment rates, which are constructed by Madsen (2020), are estimated as school enrollment divided by the population of the relevant school age cohort. This has been a Hercules task as the data from standard sources used in the literature, such as Mitchell (2007), provides generally poor coverage during the 19th century and no data is available earlier than 1830. Mitchell (2007) obtains almost all his data from statistical yearbooks. However, the data in statistical yearbooks is generally inaccurate before and during the fertility transition because they often omit private education, education of ambulant schools, and home education. Furthermore, this data often shows implausible jumps or growth spurts (often triggered by changes in number of grades included at each level in the data), change the number of included districts, failure to make a clear distinction between vocational training and non-vocational education, and often show inconsistencies across censuses. Note that Mitchell (2007) explicitly warns about the quality of the school enrollment data.

Numerous sources are used to construct GERs and historical testimonies are used to understand the formal and informal school system that prevailed before the introduction of formal mass education in the 19th century. In Norway and in Denmark before compulsory education was introduced in the early 19th century, for example, no official school enrollment data is available (see the Data Appendix for a detailed discussion and references). This does not mean that education was non-existent during this period and earlier, as noted above. Reforms were introduced as early as 1736 and 1739 in Denmark and Norway. For example, the introduction of the confirmation reform in 1736 in Denmark, in which certain literacy standards were required for a child to be confirmed in the Protestant tradition, gave teenagers exceptionally strong incentives to learn reading skills from new-established schools, the clergy, and parents. Anybody who was not confirmed was prohibited from owning real estate, leasing land, and could not be married or become a soldier (Madsen, 2020). To give the children the opportunity to meet the required learning standard for confirmation, the 1739 school reform in Norway lead to the establishment of traveling schools to cater for isolated children in tiny settlements all over the country, in which teachers taught in each school district two months a year. Enrollment was close to 100%, suggesting a very effective coverage (Madsen, 2020). Without detailed country studies, the resort to routine retropolation of the GERs leads to large errors and misleading trajectories in a period that is essential to understand the educational expansion and the fertility transition.

Genetic distance-weighted research intensity spillovers are estimated from the following weighting scheme:

$$\left(\frac{Pat}{Pop}\right)_{it}^{Gen} = \sum_{j=1}^{31} \sqrt{\frac{1}{D_{ij}^{gen}}} \left(\frac{Pat}{Pop}\right)_{jt}^{d}, \quad j \neq i,$$

where D_{ij}^{Gen} is the genetic distance between countries i and j, and is measured as the distance between ethnic groups with the largest shares of the population in each country in a pair (denoted FST by Spolaore and Wacziarg, 2009), and is normalized by the average distance in the sample so that the weights sum to one. The weighting is assumed to be inversely related to the square root of distance to ensure that long distances get higher weights than in the case in which $1/D^{gen}$ is used as weights. Taking square roots implies that the genetic distance between Germany and China gets the weight of $1261^{-1/2} = 35.5$ and the genetic distance between Germany and Denmark gets the weight of $38^{-1/2} = 6.1$, which means that Denmark gets 6.1 times higher weight than China when $(D^{gen})^{-1/2}$ is used in the weighting scheme as opposed to 33.2 times more weight when $(D^{gen})^{-1}$ is used as weights.

Table 1. Summary Statistics

	Mean	Std Dev.		Mean	Std Dev.
$\log GER_{it}^{PS}$	3.373	1.204	$\log (Y/Pop)_{it}$	1.978	1.582
$\log FER_{it}$	4.716	0.398	$\log Sch_{it}^{Comp}$	1.101	1.054
$\log(Pat/Pop)_{it}$	-3.638	2.989	$\log Age_{it}^{Min}$	1.438	1.276
$\log CMR_{it}$	2.782	0.438	$\log(I^{M\&E}/Y)_{it}$	-3.431	1.966
$\log W_{it}^{Gap}$	-0.922	0.377	$\log(I^{B\&S}/Y)_{it}$	-2.511	1.400
$\Delta \log(Y/Pop)_{it}$	0.012	0.076			
$N = 5481$ Period: 1750-2000					

N is number of observations; GER^{PS} is gross enrollment rates at primary and secondary levels; FER is general fertility rate; Pat/Pop is patent intensity; CMR is crude mortality rate; W^{Gap} is gender wage gap; Y/Pop is per capita income; Sch^{Comp} is compulsory school years; Age^{Min}: minimum working age; $I^{M\&E}$ is real investment in machinery, equipment, and IPP; $I^{B\&S}$ is investment in non-residential building and structures.

3.4. **Graphical analysis.** Figures 1 and 2 display the average general fertility rate and the crude mortality rate for the OECD countries weighted by population. For the average country, the fertility transition took place over the approximate period 1880-1980; though interrupted by an increase in fertility from the depth of the Great Depression in 1932/33 to 1964. The fertility transition occurred roughly at the same time in all Western countries. France deviated somewhat from this pattern in that its fertility decline started already at the turn of the 19th century. However, the French fertility decline was initially slow and it accelerated from about 1880 such that the early decline can be understood as a gravitation towards the mean of the OECD countries and, as such, it does not constitute a fertility transition. More importantly, the French mortality rate was 38% higher than the OECD average over the period 1700-1800. Although gradually converging to the OECD average up until the 1870s, the mortality rate was 11% higher than the OECD average over the period 1800-1871. This mortality gap exemplifies the importance of allowing for mortality in the regressions.

Figure 1: General Fertility Rate

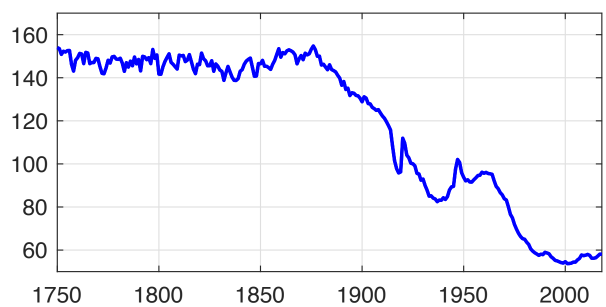
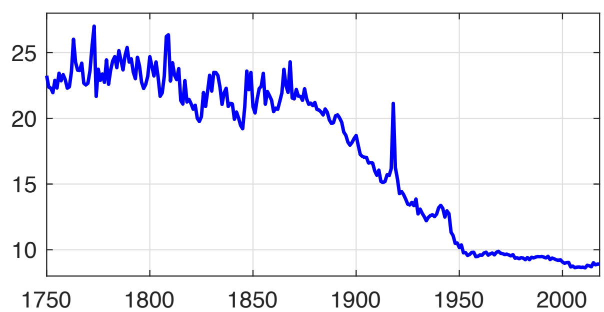


Figure 2: Crude Mortality Rate



Averages for OECD countries weighted by population. The general fertility rate, FER, is measured as the total number of live births per 1,000 females of reproductive age between 15 and 44 years in a population per year. The crude mortality rate is measured as the number of deaths per 1000 population.

Like FER, the crude mortality rate, CMR, starts a sharp downturn in 1880; however, the downturn is approximately completed in 1950, 30 years before the fertility transition is completed. If one accepts that FER reacts to CMR with a lag, then CMR is a potential candidate to explain the fertility transition as stressed by some strands of the demographic literature (Cleland, 2001; Guinnane, 2011; Kalemli-Ozcan, 2003). This conclusion may have been reached by comparing the data for France and Italy over the past three centuries, for which CMR and FER have moved in tandem for most of the time. However, the relationship between CMR and FER is mostly weak for the other OECD countries. Regressing FER on CMR and a time-trend for each individual country in our sample yields coefficients of CMRs that are statistically insignificant for Canada, the US, Belgium, Denmark, Norway, Sweden, Finland, the Netherlands and Switzerland. In the estimates below we find a significantly positive relationship between

FER and CMR; however, the declining CMR only accounts for approximately a quarter of the fertility transition.

Primary and secondary gross enrollment rates, GERs, display three growth regimes as seen from Figures 3 and 4: 1750-1820 (slow growth); 1820-1913 (moderate growth); and 1913-1980 (solid growth). The increase is driven predominantly by primary education before WWII and secondary education thereafter. However, as for fertility, the educational trajectories vary substantially across countries: They increase fast in countries with an early fertility transition (Canada, the US, Belgium, the Netherlands, Germany, Scandinavia, and Switzerland).

Figure 3: Primary and Secondary GER

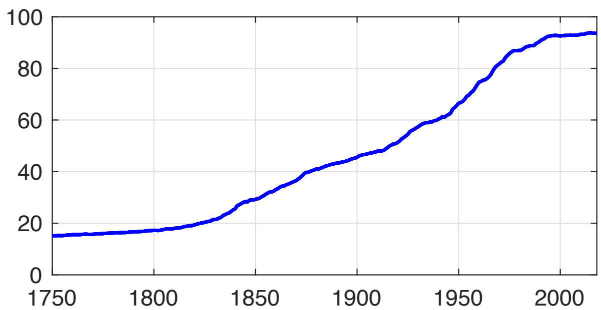
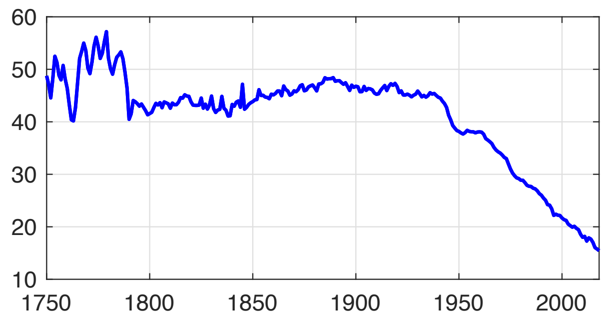


Figure 4: Gender Wage Gap



Averages for OECD countries weighted by population. GER measures the percentage of the population aged 6-17 that is enrolled in primary and secondary education. The gender wage gap is measured as $W^{Gap} = (W^M - W^F) \cdot 100/W^M$, where W^M and W^F are wages of males and females. Wage gap stated in percentages.

The gender wage gap, W^{Gap}, fluctuated around a relatively constant trend over the period 1800-1880, decreased slightly up to 1940 and has since decreased substantially. While the post-1940 decrease is consistent across all countries, Belgium, Italy, Spain, and Sweden experienced a slight decline during most of the 19th century. The decrease experienced by Italy and Spain in the 19th century, which was associated with a slight decrease in FER, may partly have been driven by convergence towards the OECD mean, noting that FER and W^{Gap} for these two countries were well above the OECD average at the turn of the 18th century.

Figure 5 displays patent intensity - a key variable in unified growth theory to the extent that it proxies skill-biased technological progress. Starting from a low level, the patent intensity increased markedly over the period 1850-1935 and, particularly, in the 1880s during which the fertility transition started in most of the sample countries. Since the 1880s, the average patent-intensity has fluctuated around a relatively constant level until the 1990s and then it increased further following the ICT revolution. Common for all countries in the sample is that

Figure 5: Patent-Population Ratio

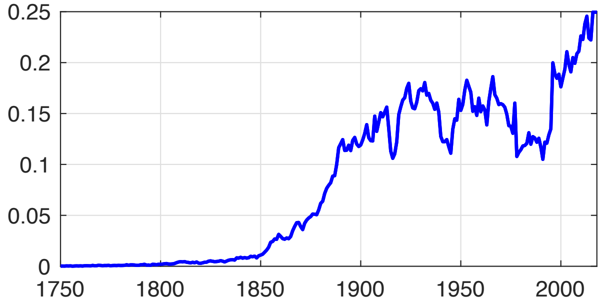
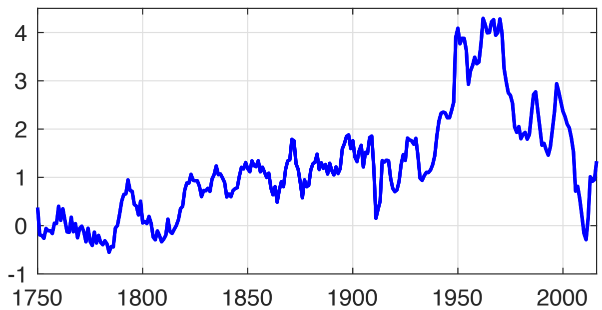


Figure 6: Per Capita Income Growth



Averages for OECD countries weighted by population. The patent-population ratio is measured as the number of patents granted per 1000 population. The annual per capita income growth rate is measured in 7-year centered averages, where the three-year endpoints are actual values; it is stated as a percentage.

technological progress was slow before 1850; thereafter, however, the path and the year of take-off differed across countries. Austria, Belgium, France, and the US, for example, experienced an early, but gradual, increase in patent intensity from 1850, whereas it occurred at a later stage in Finland and, particularly, in Greece, Ireland and Portugal.

Finally, Figure 6 shows that per capita income growth is, on average, close to zero up to the end of the Napoleonic Wars in 1815, increases to an approximate mean of 1% over the period 1816-1940, increases further to 3.5% during the Golden Period 1950-1973, and has since reverted back to the level that prevailed before the Golden Period. If the fertility transition was partly caused by economic development, we would expect shifts in per capita income growth to predate or coincide with shifts in the fertility rate. However, this is not what we observe: The fertility transition, on average, started 60 years after income growth jumped from zero to one percent after 1815; and the post-WWII baby boom coincided with the growth expansion during the Golden Period.

4. Regression Results

4.1. **OLS Regressions.** The results of estimating the fertility and GERs regressions, equations (8) and (9), are presented in Table 2. Consider first the fertility regressions in the first five columns. The result in column (1) establishes a highly significantly negative bivariate relationship between FER_t and GER^{PS}_{t+1}, as predicted by UGT. In column (2), fertility is regressed on patent intensity as a simple bivariate relationship. The coefficient of $(Pat/Pop)_t$ is highly significantly negative as predicted by UGT. The coefficients of $(Pat/Pop)_t$ and GER^{PS}_{t+1} both remain highly significant when they are included in the same model (column (3)); however, as expected, the absolute magnitudes of their coefficients are below those of the first two columns because of their positive correlation, as discussed above, *viz* that education is mainly driven by technological progress in the QQ model and, therefore, that both regressors are affected by joint forces.

The coefficients of the focus variables, GER^{PS} and patent-intensity, remain statistically highly significant when all the variables in equation (8) are included in the regression in column (4). The absolute value of their coefficients are reduced compared to the baseline regression, a reduction that is driven almost entirely by the inclusion of CMR in the model as we should expect because it is, to a large extent, the net fertility rate that is explained by innovations after CMR is included in the regression. The gender wage gap is also statistically highly significantly positive and explains about 7% of the fertility decline over the period 1820-1980. As expected, the coefficient of the crude mortality rate is significantly positive, indicating that fertility responds positively to mortality as households seek, at least partially, to target the net reproduction rate. The decline in the crude mortality rate of approximately 55% over the period 1820-1980, is associated with a decline in the general fertility rate of 24%, thus explaining about 40% of the fertility decline over the same period.[3]

Per capita income is included in the regression in column (5). Per capita income is included as a control because, starting with Becker (1960), several theories argue in favor of a direct (and negative) influence of income on fertility. Although the coefficient of income is significantly negative, this finding should not be interpreted as a causal relationship since income is heavily endogenous. Nevertheless, the consideration of income in the regression does not affect the maintained UGT thesis of the QQ-trade-off: the coefficients of GER^{PS} and patent-intensity are quite resilient to the inclusion this confounder.

The results of estimating the GER^{PS} model given by equation (9) are presented in the last four columns of Table 2. The coefficient estimates are consistent with those of the estimates of the fertility model, noting that their absolute values are substantially larger in magnitude than their counterparts in the fertility regression, which, to a large extent, reflects that the standard

[3]Based on a back-of-the-envelope calculation, mortality reductions would contribute to slower population growth if the coefficient on $\Delta FER/\Delta CMR$ exceeds 1/2. The estimates thus suggest that the mortality decline mildly amplified population growth, which means that reductions in net fertility, at least to a large extent, cannot be attributed to the mortality decline and are instead explained by technological progress and the declining gender wage gap.

Table 2. Fertility and GER Regressions, OLS [Eqs. (1) and (2)]

	1	2	3	4	5	6	7	8	9
	$\log FER_t$	$\log FER_t$	$\log FER_t$	$\log FER_t$	$\log FER_t$	$\log GER^{PS}_{t+1}$	$\log GER^{PS}_{t+1}$	$\log GER^{PS}_{t+1}$	$\log GER^{PS}_{t+1}$
$\log GER^{PS}_{t+1}$	-0.176***		-0.128***	-0.075***	-0.053***				
	(0.000)		(0.000)	(0.000)	(0.000)				
$\log FER_t$						-0.860***		-0.654***	-0.391***
						(0.000)		(0.000)	(0.000)
$\log(Pat/Pop)_t$		-0.052***	-0.032***	-0.016***	-0.014***		0.095***	0.076***	0.067***
		(0.000)	(0.000)	(0.000)	(0.000)		(0.000)	(0.000)	(0.000)
$\log CMR_t$				0.452***	0.426***				-0.728***
				(0.000)	(0.000)				(0.000)
$\log W^{Gap}_t$				0.088***	0.079***				-0.167***
				(0.000)	(0.000)				(0.000)
$\Delta\log(Y/Pop)_t$				0.019					-0.030
				(0.628)					(0.576)
$\log(Y/Pop)_t$					-0.050***				
					(0.000)				
Frequency	10-Year	10-Year	10-Year	10-Year	10-Year	10-Year	10-Year	10-Year	10-Year
Est. Period	1750-2000	1750-2000	1750-2000	1750-2000	1750-2000	1750-2000	1750-2000	1750-2010	1750-2010
Obs.	546	546	546	546	546	546	546	546	546

p-values in parentheses. The data are measured in 10-year non-overlapping intervals. The SUR estimator is used and the parameter estimates are corrected for heteroscedasticity and serial correlation. Time and country dummies are included in all regressions. GER^{PS} is gross enrollment rates at primary and secondary levels; FER is general fertility rate; Pat/Pop is patent intensity; CMR is crude mortality rate; W^{Gap} is gender wage gap; Y/Pop is per capita income. *** = significant at 1%; ** = significant at 5%; * = significant at 10%.

deviation of GER^{PS} is 1.19 while it is 0.37 for the general fertility rate. The coefficients of fertility, patent-intensity, mortality and the gender wage gap are all highly significant and have the expected signs; thus giving further support for the core prediction of UGT.

4.2. **IV Estimation Results.** The first- and second-stage IV-regressions are presented in Table 3 and the instruments are included jointly as well as individually. First, we present estimates for benchmark comparison (column 1), noting that this regression should not be considered an IV regression in the traditional sense in which the instrument is exogenous. In the first stage, in column (1), we regress GER^{PS}_{t+1} on patent intensity and include the predicted value from this regression in the second stage regression to check the extent to which technological progress mediates the mapping between education and fertility. The high significance of the coefficient of GER^{PS}_{t+1} in the second-stage regression indicates that technological progress does indeed mediate the mapping between education and fertility.[4]

Turning to the IV-regressions, the coefficients of the instruments have the expected signs and the F-tests for exclusion restrictions are all in the region between 44 and 146, suggesting that the bias in the second-stage regression is likely to be low. The Hansen-Sargan test for

[4]The first-stage regression results are not identical to the regression in Table 2 because the first-stage regression in Table 3 is based on OLS.

Table 3. IV Regressions

	1	2	3	4	5
			Second Stage		
Dep. Var	$\log FER_t$	$\log FER_t$	$\log FER_t$	$\log FER_t$	$\log FER_t$
$\log GER^{PS}_{t+1}$	-0.266***	-0.386***	-0.395***	-0.335***	-0.388***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
			First Stage		
Dep. Var	$\log GER^{PS}_{t+1}$	$\log GER^{PS}_{t+1}$	$\log GER^{PS}_{t+1}$	$\log GER^{PS}_{t+1}$	$\log GER^{PS}_{t+1}$
$\log(Pat/Pop)_t$	0.195***				
	(0.000)				
$\log(Pat/Pop)^F_t$		0.270***	0.317***		
		(0.000)	(0.000)		
$\log Sch^{Comp}_t$		0.063		0.337***	
		(0.175)		(0.000)	
$\log Age^{Min}_t$		0.098*			0.310***
		(0.035)			(0.000)
F-value		51.0	146	43.8	48.6
J-test		3.39			
Frequency	10-Year	10-Year	10-Year	10-Year	10-Year
Est. Period	1750-2000	1750-2000	1750-2000	1750-2000	1750-2000
Obs.	546	546	546	546	546

p-values in parentheses. The OLS estimator is used in all first-stage regressions, while the SUR estimator is used in the second-stage equations, and the parameter estimates are corrected for heteroscedasticity and serial correlation. Time and country dummies are included in all regressions. J-test is the Hansen-Sargan χ^2 (3)-test for overidentifying restrictions. GER^{PS} is gross enrollment rates at primary and secondary levels; FER is general fertility rate; Pat/Pop is patent intensity; Pat/Pop^F is genetic-weighted; foreign patent intensity; Sch^{Comp} is years of compulsory education; Age^{min} is minimum working age. *** = significant at 1%; ** = significant at 5%; * = significant at 10%.

over-identifying restrictions is insignificant; thus giving no evidence against the instruments, that is, that not all instruments identify the same vector of parameters. The coefficients of the instruments are all significant at the 1% level when they are included individually; however, only $(Pat/Pop)^F_t$ is significant at the 1% level when all instruments are included jointly, presumably because of a high collinearity between the instruments. The coefficients of GER^{PS}_{t+1} in the second-stage regressions are all highly statistically significantly negative, suggesting that technological progress has been a potentially influential mediator for the education-fertility trade-off over the past 250 years, as implied by UGT.

Quantitatively, technological progress, mediated through the channel of education, is influential for fertility. The coefficients of GER^{PS}_{t+1} are in the range between -0.34 and -0.39, and are, therefore, slightly higher than the OLS counterpart of -0.27 in the first column. A possible explanation for this under-attenuation bias in the OLS estimate, is that patent-intensity is highly volatile (see summary statistics, Table 1) and, thus, is a noisy indicator of technological progress. This stands in contrast to compulsory schooling, minimum working ages and foreign patent-intensity that have comparatively lower standard deviations and, therefore, better capture the effects of technological progress on the QQ-schedule.

4.3. **Alternative Technology Indicators, Placebo Tests, and Higher Frequency Data.** The estimates in this sub-section are based on post-1800 data because the data for investment ratios, which are used as alternative technology indicators, are only available for a few countries before 1800. Furthermore, we use one- or five-year non-overlapping data to test for the robustness of the results to high frequency data and to ensure that the number of observations per country is sufficiently large for the SUR estimator to be valid (T needs to exceed N for identification of the cross-country residual correlation).

The results are presented in Table 4. The parameters in the baseline regression in the first column are close to those of the estimates in 10-year intervals in Table 2 except that the coefficients of patent-intensity are significantly lower in the 5-year than the 10-year estimates due to the high volatility of patents and lagged responses. If the patent-intensity is measured in the 10-year averages and the model is still estimated in 5-year observation intervals, its coefficient becomes close to that of the regressions in 10-year observation intervals.

In the regressions in columns (2)-(4), skill-biased technological progress is measured by investment in machinery, equipment, and intellectual property products relative to real GDP, $I^{M\&E}/Y$. As argued by Krusell et al. (2000), the share of machinery and equipment in total GDP is a good proxy for skill-biased technological progress because it embodies new frontier technology that, at least in the short- to medium-run, needs to be operated by skilled workers. Consider first the regression in column (2) in which patent-intensity is replaced by $I^{M\&E}/Y$. The coefficient of $I^{M\&E}/Y$ is highly significantly negative, as we would expect. Economically, the approximately 250% increase in $I^{M\&E}/Y$ over the period 1880-1980 has resulted in an 11% decline of the fertility rate for the average OECD country. When patent intensity and $I^{M\&E}/Y$ are included in the same regression (column (3)), the technology effect is amplified since their coefficients are close to those in the regressions in which they are included individually (columns (1) and (2)). If patent-intensity is measured in 10-year averages, its coefficient is -0.020 and the coefficient of $I^{M\&E}/Y$ is -0.039. The strong complementarity between the two technology indicators suggests that they measure different dimensions of skill-biased technological progress and

Table 4. Robustness Checks

	1	2	3	4	5	6	7
	$\log FER_t$	$\log FER_t$	$\log FER_t$	$\log FER_t$	$\log FER_t$	$\log FER_t$	$\log FER_t$
$\log GER^P_{t+1}S$	-0.158***	-0.133***	-0.130***	-0.142***	-0.161***	-0.193***	-0.060***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$\log(Pat/Pop)_t$	-0.008***		-0.005***			-0.017***	-0.013***
	(0.000)		(0.033)			(0.000)	(0.000)
$\log CMR_t$	0.156***	0.130***	0.126***	0.132***	0.167***	0.258***	0.179***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$\log CMR_{t-4}$							0.362***
							(0.000)
$\log W^{Gap}_t$	0.221***	0.208***	0.207***	0.206***	0.22***	0.129***	0.102***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$\Delta \log(Y/Pop)_t$	0.014	-0.009	-0.006	-0.003	0.004	0.044	0.031
	(0.403)	(0.799)	(0.868)	(0.923)	(0.905)	(0.332)	(0.434)
$\log(I^{M\&E}/Y)_t$		-0.044***	-0.043***	-0.061***			
		(0.000)	(0.000)	(0.000)			
$\log(I^{B\&S}/Y)_t$				0.037***	-0.006		
				(0.000)	(0.790)		
Frequency	5-year	5-year	5-year	5-year	5-year	1-Year	10-year
Est. Period	1800-2005	1800-2005	1800-2005	1800-2005	1800-2005	1806-2006	1750-2000
Obs.	882	882	882	882	882	4242	546

p-values in parentheses. The SUR estimator is used, and the parameter estimates are corrected for heteroscedasticity and serial correlation. Time and country dummies are included in all regressions. The regressors are lagged 1-5 years in the one-year estimates in the last column, where the coefficients are the sum of all lags, and their associated significance are tests for the joint significance of all lags. GER^{PS} is gross enrollment rates at primary and secondary levels; FER is general fertility rate; Pat/Pop is patent intensity; CMR is crude mortality rate; W^{Gap} is gender wage gap; Y/Pop is per capita income; $I^{M\&E}/Y$ is real investment in machinery, equipment, and IPP as a share in total GDP; $I^{B\&S}/Y$ is real investment in non-residential building and structures as a share in total GDP. *** = significant at 1%; ** = significant at 5%; * = significant at 10%.

that the investment ratio reinforces the patent-induced fertility effect and further underscores the role played by technological progress during the fertility transition.

Now, it is possible that the coefficient of $I^{M\&E}/Y$ is affected by factors that are unrelated to skill-biased technological progress, such as saving behavior and economic development. To check for this possibility, we undertake a placebo test by including $I^{B\&S}/Y$ in the regressions in columns (3) and (4), with and without $I^{M\&E}/Y$ included. The coefficient of $I^{B\&S}/Y$ is either significantly positive (column (3)) or insignificant (column (4)). If the investment ratio captures economic development, then we would expect its coefficient to be negative and significant, neither of which are satisfied in the regressions. These results suggest technological progress had an effect on fertility quite independently of economic development and more thriftiness - a result that accords with the insignificance of the coefficients of per capita income growth.

To allow for a more precise timing between the variables, the fertility model is estimated using annual data in the regression in the column (6) in Table 4. All regressors are lagged 1-5 years to allow for a gradual adjustment towards equilibrium, noting that contemporary variables are not included as regressors to allow for the 9-month time-lag between conception and birth. The coefficients reported in the table are the sum of all lags and the associated p-values are their joint significance. The coefficients are all significant and of the expected signs, thus giving further support for UGT in the sense that the time-gap between fertility and education is consistent with the predictions of the model.

Finally, a four-decade lag of CMR is added to the baseline model in the last column in Table 4 to check for the possibility that the mortality decline that preceded the fertility decline during the 19th century may overrule the significance of the other covariates in the model. The model is estimated in 10-year intervals over the period 1750-2000 to make the estimates comparable to the baseline model in column (4) in Table 2. Lags of up to six decades were initially included in the model; however, except for the fourth lag, they were statistically insignificant at conventional levels and, consequently, omitted. The coefficients of patent-intensity, wage gap and education are comparable to the baseline regression results, suggesting that the principal results still stand. For mortality, the sum of the coefficients of CMR_t and CMR_{t-4} is 0.54, which is not much larger than that of 0.45 in the baseline regression.

Overall, the results in this subsection give the following insights: 1) the placebo tests suggests that the negative relationship between technological progress and fertility is not driven by a third factor that is affecting both, such as economic development; 2) the time-lag between fertility and education is consistent with the predictions of UGT; and 3) although mortality exerts a negative impact on fertility, its effect on fertility is not sufficiently powerful to influence the net fertility rate and has, therefore, not been a contributor to the decline of net fertility.

5. Conclusion

In this paper we have taken Galor–Weil (2000) seriously. To the best of our knowledge, we have provided the first empirical test of the core mechanism of the canonical unified growth theory according to which increasing technological progress initiated and propelled the fertility transition and the take-off of mass education. For this purpose we construct data for 21 OECD countries over the period 1750-2016, which enables us to capture the fertility transition in its entirety. Rather than using a measure of educational attainment of the population at large, we use enrollment rates in primary and secondary education ten years ahead in conjunction with contemporary fertility rates in order to closely match the UGT constructs of parental decisions on fertility and child education. We use two alternative measures of skill-biased technological progress: national patents per capita, and the income share of net investment in machinery, equipment, and intellectual property products.

The results show that technological progress has a strong positive impact on education and a strong negative effect on fertility - even after we control for other confounders such as mortality, the gender wage gap, and the level and growth rate of income. Assessing the quantitative power of the UGT mechanism, we find that a 10 percent increase in gross enrollment rates, instrumented by technological progress, is associated with a 3 to 4 percent decline in fertility. Since enrollment rates and technological progress more than doubled during the fertility transition, the UGT mechanism is sufficiently strong to provide a credible explanation of the transition from the post-Malthusian to the modern growth regime.

References

Aaronson, D., Lange, F. and Mazumder, B. (2014). Fertility transitions along the extensive and intensive margins. *American Economic Review* 104(11), 3701-24.

Acemoglu, D. (2002). Technical change, inequality, and the labor market. *Journal of Economic Literature* 40(1), 7-72.

Aghion, P., Jaravel, X., Persson, T. and Rouzet, D. (2019). Education and military rivalry. *Journal of The European Economic Association* 17(2), 376-412.

Angrist, J.D., Lavy, V. and Schlosser, A. (2010). Multiple experiments for the causal link between the quantity and quality of children. Journal of Labor Economics 28, 773-824.

Bailey, M.J. (2013). Fifty years of family planning: New evidence on the long-run effects of increasing access to contraception. *Brookings Papers on Economic Activity* Spring, 377-410.

Becker, G.S. (1960): An economic analysis of fertility. In: *Demographic and Economic Change in Developed Countries* (pp. 209–204), Columbia University Press.

Becker, G., Murphy, K. and Tamura, R. (1990). Economic growth, human capital and population growth. *Journal of Political Economy* 98(5), S12-S137.

Becker, S.O., Cinnirella, F. and Woessmann, L. (2010). The trade-off between fertility and education: Evidence from before the demographic transition. *Journal of Economic Growth* 15, 177-204

Bhattacharya, J. and Chakraborty, S. (2017). Contraception and the demographic transition. *Economic Journal* 127(606), 2263-2301.

Black, S.E., Devereux, P.J. and Salvanes, K. G. (2005). The more the merrier? The effect of family size and birth order on children's education. *Quarterly Journal of Economics* 120(2), 669-700.

Bleakley, H. and Lange, F. (2009). Chronic disease burden and the interaction of education, fertility, and growth. *Review of Economics and Statistics* 91(1), 52-65.

Caceres-Delpiano, J. (2006). The impacts of family size on investment in child quality. *Journal of Human Resources* 41(4), 738-754.

Caselli, F. (1999). Technological revolutions. *American Economic Review* 89(1), 78-102.

Cervellati, M. and Sunde, U. (2015). The economic and demographic transition, mortality, and comparative development. *American Economic Journal: Macroeconomics* 7(3), 189-225.

Chatterjee, S. and Vogl, T. (2018). Escaping Malthus: Economic growth and fertility change in the developing world. *American Economic Review* 108(6), 1440-67.

Cleland, J. (2001). The effects of improved survival on fertility: A reassessment. *Population and Development Review* 27(Supplement), 60-92.

Dalgaard, C.-J. and Strulik, H. (2013). The history augmented Solow model. *European Economic Review* 63, 134-149.

Dalgaard, C.J. and Strulik, H. (2015). The physiological foundations of the wealth of nations. *Journal of Economic Growth* 20(1), 37-73.

Dalgaard, C.J. and Strulik, H. (2016). Physiology and development: Why the West is taller than the rest. *Economic Journal* 126(598), 2292-2323.

Doepke M. (2004) Accounting for fertility decline during the transition to growth. *Journal of Economic Growth* 9(3), 347-383

Doepke, M. (2005). Child mortality and fertility decline: Does the Barro-Becker model fit the facts? *Journal of Population Economics* 18(2), 337-366.

Doepke, M. and Zilibotti, F. (2008). Occupational choice and the spirit of capitalism. *Quarterly Journal of Economics* 123(2), 747-793.

Fernihough, A. (2017). Human capital and the quantity–quality trade-off during the demographic transition. *Journal of Economic Growth* 22(1), 35-65.

Galor, O. (2005). From stagnation to growth: Unified growth theory. In: P. Aghion and S. Durlauf (eds.), *Handbook of Economic Growth* Vol 1A, (pp. 171-293) Amsterdam, North-Holland.

Galor, O. (2011). *Unified Growth Theory.* Princeton University Press.

Galor, O. (2012). The demographic transition: Causes and consequences. *Cliometrica* 6, 1-28.

Galor, O. and Moav, O. (2000). Ability-biased technological transition, wage inequality, and economic growth. *Quarterly Journal of Economics* 115(2), 469-497.

Galor, O. and Moav, O. (2002). Natural selection and the origin of economic growth. *Quarterly Journal of Economics* 117(4), 1133-1191.

Galor, O. and Moav, O. (2006). Das human-kapital: A theory of the demise of the class structure, *Review of Economic Studies* 73, 85-117.

Galor, O. and Weil, D. N. (1996). The gender gap, fertility, and growth. *American Economic Review* 86(3), 374-387.

Galor, O. and Weil, D.N. (2000). Population, technology, and growth: From Malthusian stagnation to the demographic transition and beyond. *American Economic Review* 90(4), 806-828.

Guinnane, T.W. (2011). The historical fertility transition: A guide for economists. *Journal of Economic Literature* 49(3), 589-614.

Ha, J. and Howitt, P. (2007). Accounting for Trends in Productivity and R&D: a Schumpeterian critique of semi-endogenous growth theory. *Journal of Money, Credit and Banking* 39(4), 733-774.

Hazan, M. and Berdugo, B. (2002). Child labour, fertility, and economic growth. *Economic Journal* 112(482), 810-828.

Herzer, D., Strulik, H. and Vollmer, S. (2012). The long-run determinants of fertility: One century of demographic change 1900–1999. *Journal of Economic Growth* 17(4), 357-385.

Jones, L.E., Schoonbroodt, A. and Tertilt, M. (2010). Fertility theories: Can they explain the negative fertility-income relationship? In: J.B. Shoven (ed.) *Demography and the Economy* (pp. 43-100), Chicago, IL: University of Chicago Press.

Kalemli-Ozcan, S. (2002). Does the mortality decline promote economic growth? *Journal of Economic Growth* 7(4), 411-439.

Kalemli-Ozcan, S. (2003). A stochastic model of mortality, fertility, and human capital investment. *Journal of Development Economics* 70, 103-18.

Klemp, M. and Weisdorf, J. (2018). Fecundity, fertility and the formation of human capital. *Economic Journal* 129(618), 925-960.

Krusell, P., Ohanian, L.E., Rios-Rull, J.V. and Violante, G.L. (2000). Capital-skill complementarity and inequality: A macroeconomic analysis. *Econometrica* 68(5), 1029-1053.

Lagerloef N.-P. (2003a). Gender equality and long-run growth. *Journal of Economic Growth* 8(4), 403-426.

Lagerloef, N.-P. (2003b). From Malthus to modern growth: Can epidemics explain the three regimes? *International Economic Review* 44(2), 755-777.

Lehr, C.S. (2009). Evidence on the demographic transition. *Review of Economics and Statistics* 91(4), 871-887.

Madsen, J.B. (2008). Semi-endogenous versus Schumpeterian growth models: Testing the knowledge production function using international data. *Journal of Economic Growth* 13(1), 1-26.

Madsen, J.B. (2020). The modernization hypothesis and the expansion in education since 1600. Economics Discussion Paper, Department of Economics, University of Western Australia.

Madsen, J. B., R. Islam and Tang, X. (2020). Was the Post-1870 Fertility Transition a Key Contributor to Growth in the 20th Century? Economics Discussion Paper, Department of Economics, University of Western Australia.

Mitchell, B.R. (2007). *International Historical Statistics*, 3 Volumes. New York: Palgrave Macmillan.

Moav, O. (2005). Cheap children and the persistence of poverty. *Economic Journal* 115(500), 88-110.

Murtin, F. (2013). Long-term determinants of the demographic transition, 1870–2000. *Review of Economics and Statistics* 95(2), 617-631.

Nalle, S.T. (1989). Literacy and culture in early modern Castile. *Past & Present* 125, 65-96.

Peretto, P.F. (1998). Technological change and population growth. *Journal of Economic Growth* 3(4), 283-311.

Prettner, K. and Strulik, H. (2016). Gender equity and the escape from poverty. *Oxford Economic Papers* 69(1), 55-74.

Rosenzweig, M.R. and Zhang, J. (2009). Do population control policies induce more human capital investment? Twins, birth weight and China's one-child policy. *Review of Economic Studies* 76(3), 1149-1174.

Schultz, T.P. (1985). Changing world prices, women's wages, and the fertility transition: Sweden, 1860-1910. *Journal of Political Economy* 93(6), 1126-1154.

Soares, R.R. (2005). Mortality reductions, educational attainment, and fertility choice. *American Economic Review* 95(3), 580-601.

Spolaore, E. and Wacziarg, R. (2009). The diffusion of development. *Quarterly Journal of Economics* 124, 469-529.

Strulik, H. (2004). Child mortality, child labour and economic development. *Economic Journal* 114(497), 547-568.

Strulik, H. (2017). Contraception and development: A unified growth theory. *International Economic Review* 58(2), 561-584.

Strulik, H. (2019). Desire and development. *Macroeconomic Dynamics* 23(7), 2717-2747.