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Abstract

This paper studies the interplay between left-handedness and economic development, thereby contributing to our understanding of the relationship between evolutionary forces, human diversity and growth. We propose a novel theoretical framework in which economic development influences the prevalence of left-handedness through structural change and a genetic mechanism driven by differential fertility. In particular, the emergence of the industrial sector puts left-handers at a reproductive disadvantage, because of their lower manual ability and wages. This fertility differential changes sign as soon as the income-fertility relationship is reversed, and eventually fades away when the rise of human capital makes manual skills irrelevant. Our model thus explains the decline and subsequent recovery of left-handedness observed over the last few centuries in the Western world. We further explore the possibility that left-handedness in turn influences growth: despite their lower productivity in manual tasks, left-handers may enhance technological progress through cognitive skills that are conducive to innovation, and through their contribution to the diversity of the workforce. This implies that the link between handedness and economic performance varies across stages of development. We present empirical evidence that lends credence to the core differential-fertility mechanism of our model and suggests that left-handedness can positively contribute to growth, once the economy has reached a sufficiently high level of human capital.

JEL Classification Codes: O11; O14; O33; O40; J13; J24; Q57.

Keywords: Handedness; Economic growth; Evolution; Diversity; Unified Growth Theory.

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1 Introduction

In this research, we propose an economic theory of the historical evolution of left-handedness, based on the process of structural change and a genetic mechanism driven by differential fertility. In our theory, handedness – an inheritable human trait that determines differential economic outcomes – is subject to the pressure of natural selection through the effect of economic conditions on reproductive success. Since left-handers hold specific economic attributes and contribute to the diversity of the workforce, we also explore, theoretically and empirically, how the prevalence of left-handedness may in turn influence economic growth. Our work contributes to a more general understanding of how economic factors can shape evolutionary forces, and *vice versa*. In this respect, left-handedness represents an observable, non-controversial phenotypical trait that characterizes human diversity and may also have economic relevance *per se*.

Handedness is the preference for one hand in executing actions, such as throwing or writing. It is not specific to, but is particularly strong in humans, both individually and on the aggregate: in fact, most people have a clear handedness preference, and for most, the right hand is preferred.[1] In the West today, about 10-13% of the population is left-handed, the result of a secular process that saw the prevalence of left-handedness follow a U-shaped trajectory, with the lowest rates (in the 2–6% range) observed during or at the end of the 19th century, and a marked increasing trend thereafter (McManus 2009). As we shall explain in Section 2, this pattern reflects "natural" left-handedness, which is independent from coercive hand-switching practices.

In human beings, natural handedness is linked to brain lateralization, *i.e.* the dominance of one cerebral hemisphere over the other in activities related to cognition and language. Left-handedness, in particular, corresponds to right-hemisphere dominance: as reported by McManus (2009), only 5–6% of right-handed individuals show any right hemisphere language dominance, compared to 30–35% among left-handed people.[2] There is abundant evidence that genetic and epigenetic factors play a major role in the determination of brain lateralization and handedness, with heritability explaining up to 2/3 of phenotypic variance (McManus and Bryden 1992, Schmitz et al. 2017).[3] Genetic research currently regards handedness as a polygenic trait, characterized by partial pleiotropy with respect to brain patterning. In particular, a genome-wide association study by Wiberg et al. (2019) identifies four significant loci for human handedness, three of which are related to brain development and patterning.[4][5]

A key element of our analysis relates to the consequences of being left-handed. Our interpretation of handedness as a dimension of human diversity, as well as the possibility that it is linked to economic performance, hinges on intrinsic differences between right- and left-handers. The literature suggests that left-handers have, on average, worse outcomes than right-

[1] Great apes like chimpanzees and bonobos are only mildly lateralized, as observed by Hopkins et al. (2011) and Marchant and McGrew (2013), who claim that "human handedness seems to be unique among living hominoids".

[2] Moreover, the *corpus callosum*, which connects the two hemispheres and regulates the speed of interhemispheric processing, is on average 11% larger among left-handed individuals (Witelson 1985). Heilman (2005) argues that a larger *corpus callosum* may translate into higher levels of creativity.

[3] Environmental factors, such as fetal stress *in utero* or at birth and prenatal exposure to testosterone, may also shape the differential brain structure of right- and left-handers (Medland et al. 2009, Vuoksimaa et al. 2009).

[4] A locus is a specific position on a chromosome where a particular gene is located.

[5] A recent study by Hermans, Ahn, and Rousseau (2020) has also detected much higher levels of the highly heritable Lipoprotein(a) in left-handed persons.

handers. For instance, Johnston et al. (2009), Johnston et al. (2013) and Goodman (2014) find that left-handers fare worse in terms of cognitive scores, earnings and human capital. Denny and O'Sullivan (2007) and Ruebeck, Harrington, and Moffitt (2007), however, show that college-educated left-handers tend to have higher wages. There is also evidence that left-handers are over-represented at the top of the ability distribution (Benbow 1986, Halpern, Haviland, and Killian 1998, Faurie et al. 2008, Faurie et al. 2012), and possess specific traits and cognitive styles that may be conducive to innovation and economic growth, such as creativity and divergent thinking (Newland 1981, Coren 1995), competitiveness (Hoffman and Gneezy 2010), and leadership skills (Mukherjee 2017).[6] Finally, left-handers are observed to be less productive in manual activities (Hanna et al. 1997, Adusumilli et al. 2004) and have more work and machine-related accidents (Halpern and Coren 1991, Graham et al. 1993, Aggleton et al. 1994, Taras, Behrman, and Degnan 1995, Coren and Previc 1996). This might be attributed to some intrinsic disadvantage of left-handers (as proposed by Freitas, Vasconcelos, and Botelho (2014), for instance) or to the use of less adapted tools and machines, which are mostly built by and for right-handers (Adusumilli et al. 2004, Bhushan and Khan 2006).[7]

We argue that the non-monotonic trajectory of left-handedness in the West over the past two centuries can be traced back to the process of structural change undergone by the economy. We treat left-handedness as an inheritable trait, whose prevalence in the population is affected by economic development through a differential-fertility mechanism. The latter depends on the existence of sector-specific productivity differentials between left- and right-handers.

In the pre-industrial society, left-handedness has no detectable influence on individual productivity, so that left- and right-handers earn equal wages and enjoy the same reproductive success. The rate of left-handedness is thus stable. With the industrial take off, however, unskilled left-handed workers become less productive, as manufacturing has a higher concentration of workers in serial production and uses more complex tools and machines, typically designed for right-handers.[8] Left-handers become poorer on average, and possibly less valuable on the marriage market. In a Malthusian framework, this generates a fertility differential in favor of right-handers, who transmit their genes more successfully to the following generation. Hence, the prevalence of left-handedness declines.

As the process of development continues, agents can eventually afford investing in education. At first, only skilled individuals, regardless of handedness, start having fewer, more educated children. In time, however, the demographic transition unfolds and unskilled right-handers start investing in education as well. At this point, left-handers display higher fertility rates on average. This drives an increase in the left-handedness rate, which eventually comes to an end, when more and more people become educated and work using their intellectual, rather than their manual ability. The difference in manual ability between left- and right-handed work-

[6] In particular, Halpern, Haviland, and Killian (1998) find that left-handed students significantly outperform right-handed ones in MCAT tests, while Faurie et al. (2008) report that left-handers are over-represented among individuals holding managerial, high-level position in the French electricity and gas company EDF–GDF.

[7] Two archival studies conducted on British cricketers (Aggleton, Kentridge, and Neave 1993, Aggleton et al. 1994) find strong evidence that left-handed men were more likely to die prematurely in accidents or in action (during World War I), probably due to the use of equipment adapted to right-handers.

[8] Perhaps not coincidentally, the 18th century saw the invention of machines such as the circular saw and the power press, which still injure left-handers disproportionately today (Taras, Behrman, and Degnan 1995).

ers becomes progressively irrelevant. Absent other forms of heterogeneity related to handedness, the average income gap closes and the fertility differential between left- and right-handed people vanishes, so that the share of left-handers in the population stabilizes.

To embed this narrative in a formal model, we need four ingredients. First, we consider a two-sector economy in the spirit of Ashraf and Galor (2012) and Litina (2016) and relate the structural shift out of agriculture to an exogenous increase in industrial productivity. Second, we allow for sector-specific productivity differentials between left- and right-handed workers, by assuming that left-handers perform worse in manual tasks related to industrial production. Third, we model endogenous fertility and education choices, with a quality-quantity trade-off driving the demographic transition, along the lines of De la Croix (2013). Fourth, we plug a genetic mechanism into the economic model, so that differential fertility by handedness drives the evolution of the share of left-handers in the population. This genetic mechanism does not exclude, and may even interact with environmental and cultural determinants of left-handedness that our theory leaves aside for the sake of simplicity.

The benchmark version of the model does not consider the possibility that left-handedness affects growth. However, the distinctive features of left-handedness, as well as its contribution to the diversity of the workforce, make it reasonable to explore this direction of causality as well. We then extend the model to include a feedback effect of left-handedness on productivity growth, and show that the correlation between left-handedness and economic performance varies across stages of development.

In support of our theory, we develop an empirical analysis articulated in two parts. First, we exploit individual data to validate the differential-fertility mechanism that governs the evolution of handedness in our model. We find evidence of fertility differentials between left- and right-handed persons, which are consistent with the historical trajectory of left-handedness rates. Second, we exploit variation across U.S. states and over time to explore the possible effect of left-handedness on growth. Consistent with the idea that left-handedness is associated with traits that are conducive to innovation, we find that a higher aggregate prevalence of left-handedness may yield faster economic growth. This only happens, however, in advanced stages of development, when production relies to a large extent on intellectual (as opposed to manual) ability. These findings can be regarded as suggestive evidence, in line with the model's prediction that the relationship between left-handedness and growth changes along the development process.

Our research is related to three strands of economic literature.

First, we contribute to the research looking at economic performance and natural selection along the development process, pioneered by Galor and Moav (2002) and developed by Lagerlöf (2007), Galor (2011), Galor and Michalopoulos (2012) and Galor and Özak (2016), among others. We share with these papers the idea of a two-way interaction between economic factors and the distribution of genetic traits in the population.[9] The role of markets and economic exchange in preserving some "weaker" traits over the course of human evolution has also been studied by Horan, Bulte, and Shogren (2005) and Saint-Paul (2007). In this respect, our analysis highlights

[9]Our research is also linked to papers emphasizing the role of evolutionary mechanisms in defining human outcomes, behaviors or traits with some economic relevance: see for instance Robson (2001), Horan, Bulte, and Shogren (2008), Alger and Weibull (2010). Some other studies, such as Gören (2017), take the prevalence of genetically-determined traits as exogenous, but explore their implication for economic growth.

that the relationship between diversity and development is time-varying: while early industrialization reduces the prevalence of left-handedness, the subsequent rise of human capital allows the share of left-handers to increase again, thus preserving this trait in the population. We also show how transitory economic phenomena may have long-lasting consequences for the genetic structure of human populations.

Second, we contribute to the literature studying the effects of diversity on economic growth – see for instance Alesina and La Ferrara (2005), Ashraf and Galor (2012), Alesina, Harnoss, and Rapoport (2016), Desmet, Ortuño-Ortín, and Wacziarg (2017) and Docquier et al. (2020). In particular, like Ashraf and Galor (2012), we find that the growth effects of diversity may vary across different stages of development. Given the genetic origin of handedness, our research is also linked to papers that look more specifically at the consequences of genetic diversity, such as Ashraf and Galor (2013), Ager and Brueckner (2018) and Cook and Fletcher (2018).

Third, our paper is related to the literature on differential socio-economic outcomes between left- and right-handed individuals. For instance, Denny and O'Sullivan (2007), Ruebeck, Harrington, and Moffitt (2007), Goodman (2014) and Guber (2019) use longitudinal surveys to explore the effects of handedness on individual earnings, human capital and labor-market performance. While our research is more concerned with the causes and consequences of the aggregate prevalence of handedness in the long run, this literature provides a motivation for our analysis and an empirical justification for some of the key assumptions of our model.

The remainder of the paper is organized as follows. In Section 2, we review the main stylized facts related to the historical evolution of left-handedness. In Section 3, we describe our benchmark model, whose dynamic implications (with exogenous growth) are then analyzed in Section 4. Section 5 extends our theory by introducing an endogenous growth mechanism, based on a feedback effect of left-handedness on aggregate productivity. In Section 6 we develop an empirical analysis of the handedness-growth relationship, and provide evidence in support of the differential-fertility mechanism governing the evolution of handedness. Section 7 concludes.

2 Left-handedness over time

Although a majority of humans is believed to have been right-handed since the appearance of the genus *Homo* (McManus 2009), establishing accurately how left-handedness rates have evolved in the very-long run (*i.e.* over several centuries) is difficult due to the lack of data.[10]

More reliable data are available for the 19th and 20th centuries. In particular, the most complete source of evidence on left-handedness is provided by the "Smell Survey" carried out by the *National Geographic* in 1986 (NGSS henceforth, Gilbert and Wysocki 1992). Aimed at studying the correlation between brain lateralization and olfactory ability, this survey was conducted by sending out a questionnaire accompanied by a scratch-and-sniff card. More than 1.4 million responses were collected from readers born between 1887 and 1975, among whom 1,221,992

[10]Coren and Porac (1977) provide indirect estimates based on hand use in unimanual activities, as displayed in artworks. Osteoarcheological evidence speaks of left-handedness rates in the 10–19% range between the 9th and the 16th century (Steele and Mays 1995, Cuk, Leben-Seljak, and Stefancic 2001, Kujanová et al. 2008), but is in general built on small samples.

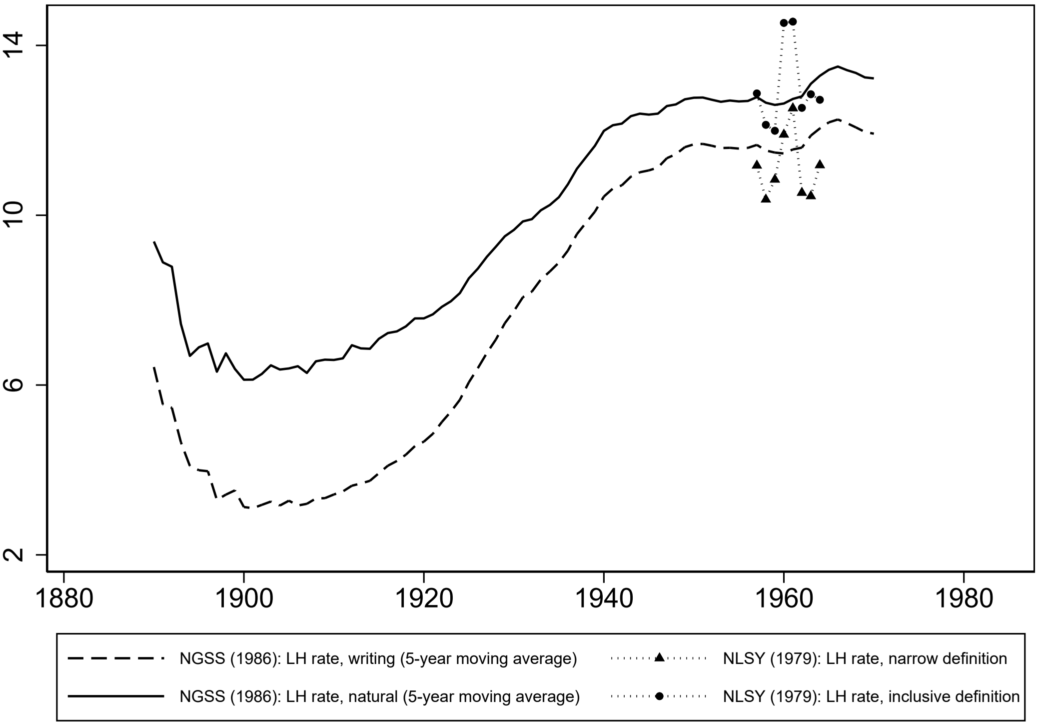

Figure 1: Left-handedness in the United States: 1887-1976.

resided in the United States. The NGSS also contained questions about left-handedness – a proxy measure for brain lateralization.

In Figure 1, we plot the share of left-handers among NGSS respondents in the U.S. against their year of birth. The dashed line depicts the percentage of respondents who say they use their left hand for writing, while the continuous line displays the percentage of respondents who either write with their left hand, throw with their left hand, or both. The two series follow a non-monotonic pattern over time: decreasing among people born between 1887 and 1905, increasing thereafter up to the 1950s cohorts, and eventually stabilizing.

The more comprehensive measure of left-handedness (based on the share of people who write, throw or perform both activities with their left hand) captures natural handedness, which – distinct from handedness in writing only – is less likely to be influenced by hand-switching practices related to the stigmatization of left-handers.[11] Hence, the relevant stylized fact from Figure 1 is the *U*-shaped trajectory of natural left-handedness over the past two centuries. Specifically, Figure 1 suggests that the share of naturally left-handed people in the U.S. population reached a minimum (around 6%) for cohorts born at the beginning of the 20th century, and then followed an increasing trajectory – until it stabilized (around 13%) for cohorts born from the end of the 1950s on. Hand-switching and forced dextrality cannot explain this pattern, as further

[11] There is evidence of hand-switching practices, with left-handed pupils being forced to write with their right hand (see for instance Kushner 2012 and Guber 2019). The vertical difference between the solid and the dashed lines in Figure 1, which measures the share of people who write with the right hand but throw with the left one, can be thought of as an approximation of the share of constrained left-handers. As it is bell-shaped, it suggests that coercion into right-handedness did participate in the *U*-shaped trajectory of left-writing. However, repression cannot account for the *U*-shaped pattern of the share of people who write and/or throw with their left hand, which is a better proxy for natural left-handedness.

shown by Ellis et al. (1998) for the U.K.[12]

As we measure left-handedness prevalence across cohorts based on data collected in 1986, one might suspect that the 20th-century increase is (at least partially) driven by a survivor bias, if left-handers have a shorter life expectancy. Empirical studies, however, strongly reject the hypothesis of mortality differentials between left- and right-handed people. In particular, Basso et al. (2000) find no evidence of higher survival rates among right-handers, focusing on a cohort of Danish twins born between 1900 and 1910.[13] Moreover, although left-handers may be subject to higher mortality in specific events, like wars (Aggleton et al. 1994), this is largely insufficient to explain the pattern in Figure 1.[14]

A positive aspect of the cohort-structure of our data is that it can attenuate the possible concern that left-handedness is misreported as a result of changing sociocultural attitudes. In the NGSS, persons of different ages were asked to declare their hand-preference in the same year (1986), thus mitigating the possible consequences of time-varying stigma for self-reporting bias. The propensity to misreport left-handedness is also limited by the fact that respondents did not fill their questionnaire in the presence of a surveyor, and that the NGSS was advertised as a study on olfaction and not on handedness *per se*.[15]

One may also worry about the representativeness of the NGSS sample, and the risk that self-selection biases our measure of left-handedness.[16] While we are not aware of any existing source of representative data for earlier cohorts, we can compare our NGSS estimates to those from representative surveys for more recent cohorts. To this end, in Figure 1 we report data from the National Longitudinal Survey of Youth 1979 (NLSY hereafter), from which we compute the percentage of left-handers in a representative sample of individuals born in the U.S. between 1957 and 1964. The left-handedness rates inferred from the NLSY are in line with the NGSS data. In particular, the narrow and inclusive definitions of left-handedness from the NLSY data match closely the NGSS writing and natural left-handedness rates.[17]

Finally, one may wonder whether the non-monotonic pattern of natural left-handedness is specific to the United States, or can also be found elsewhere. In Figure 2, we report the available evidence for other Western countries. The fact that left-handedness became more preva-

[12]In particular, Ellis et al. (1998) study forced dextrality on a sample of about 6,000 respondents in Lancashire, U.K. Consistent with the NGSS data, their results point to a much lower prevalence of left-handedness among older respondents (born at the end of the 1920s) than among younger respondents (born at the end of the 1970s). They find, however, that less than 20% of this difference can be explained by forced right-hand writing.

[13]Other studies discussing (and finding no evidence of) differential mortality by handedness include Harris (1993), Salive, Guralnik, and Glynn (1993), Persson and Allebeck (1994), Steenhuis, Østbye, and Walton (2001) and Martin and Freitas (2002).

[14]For instance, casualties in WWI and WWII – as reported by Chambers (2000) – amounted to 0.11% and 0.31% of the U.S. population measured in 1920 and 1940, respectively. This depends on U.S. soldiers having relatively low odds of death in war: 1.1% in WWI, 1.8% in WWII and 0.6% in the Korean War (Hobbes 2004).

[15]In addition, family studies – which do not suffer from time-varying reporting bias, as the handedness of parents and children is reported by the same person – point to a similar increasing pattern for left-handedness rates in the U.S. during the 20th century (see for instance Spiegler and Yeni-Komshian 1983 or Risch and Pringle 1985).

[16]An individual characteristic that could be correlated with both left-handedness and the propensity to be a reader of the *National Geographic* is gender, as men are more likely to be left-handed than women (McManus 2004). However, about 55% of the NGSS respondents were women, and computing gender-weighted left-handedness rates based on the sex ratio at birth yields U-shaped patterns that are very close to those of Figure 1.

[17]The NLSY questionnaire asks respondents whether they were born naturally left-handed, right-handed, or ambidextrous. Our narrow definition of left-handedness treats self-declared ambidextrous respondents as missing observations, while we pool them with left-handers in our inclusive definition.

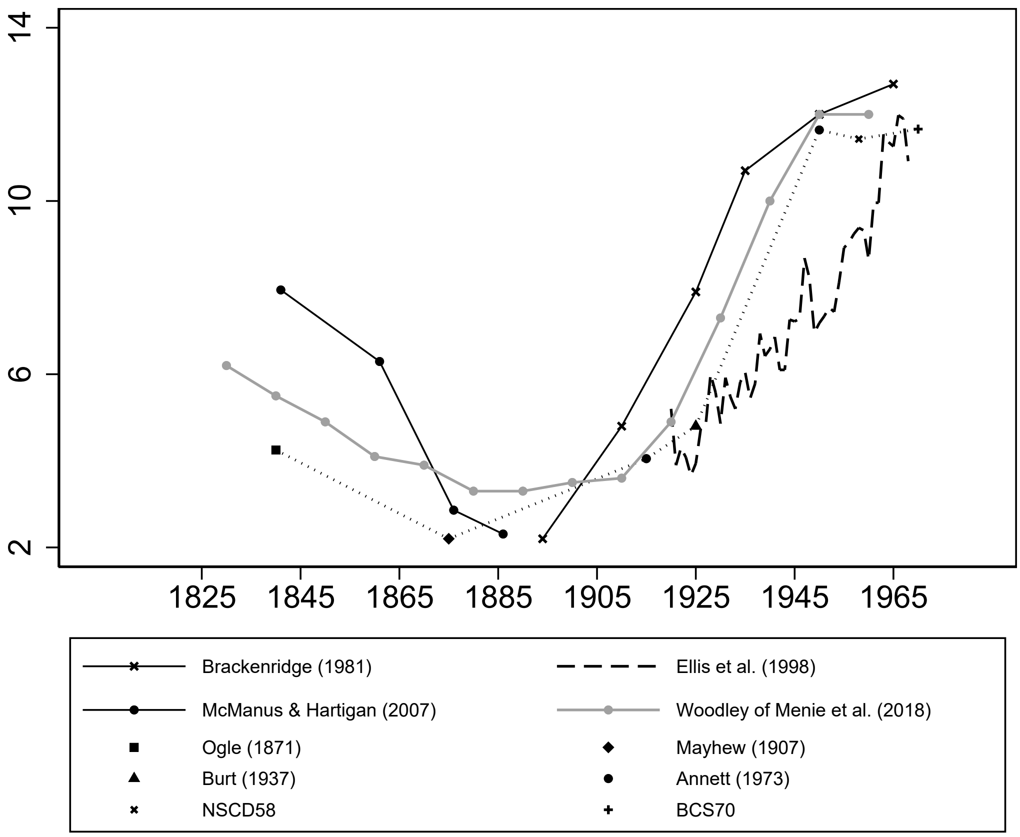

Figure 2: Left-handedness in the Western World: 1800-1970.

lent throughout the 20th century is confirmed by historical data on Australia and New Zealand (Brackenridge 1981), which show an increase from about 2% in 1894 to 13% in 1965, as well as by estimates for the U.K. (Ellis et al. 1998). A decline of left-handedness rates during the 19th century is documented by McManus and Hartigan (2007) for the U.K., and appears to be consistent with estimates from different sources – which also illustrate the subsequent recovery of left-handedness rates.[18] In addition, Woodley of Menie et al. (2018) reconstruct a U-shaped secular trend for left-handedness in the Western World, based on a meta-analysis of the literature on handedness. Taken together, the different measures of left-handedness used in Figure 2 point to a temporal pattern of left-handedness that is broadly consistent with that of Figure 1.

Figures 1 and 2 thus provide evidence that natural left-handedness in the Western World followed a non-monotonic trajectory over the last few centuries. After decreasing and reaching a nadir somewhere in the second half of the 19th century, the prevalence of left-handedness increased for most of the 20th century, and eventually stabilized. Our analysis of the interplay between left-handedness and economic development shall be consistent with this stylized fact.[19]

[18]Historical evidence for the U.K. is collected from Ogle (1871), Mayhew (1907) as cited by Crichton-Browne (1907), Annett (1973) and Burt (1937). We further rely on two recent longitudinal surveys: the National Child Development Study (NCDS58) and the British Cohort Study (BCS70), which track people born in Great Britain in March 1958 and April 1970, respectively.

[19]In Appendix A, we report additional evidence suggesting a non-monotonic cross-country relationship between left-handedness and development.

3 The model

We consider an overlapping-generations economy extending over infinite discrete time. The production block of the model (*i.e.* its supply side) is characterised by the state of technology (M_t), population (P_t), the proportion of left-handed agents (λ_t), and the shares of skilled individuals among right- and left-handers ($x_{R,t}$ and $x_{L,t}$, respectively). Together, these variables determine the incomes of skilled and unskilled left- and right-handed workers. Individual optimization (*i.e.* demand decisions) "transforms" those incomes into fertility and education choices which, by regulating the differential reproductive success of right- and left-handers, as well as human capital accumulation, determine the future values (at $t+1$) of population, left-handedness prevalence and the shares of skilled individuals.

In this Section, after describing the demographic structure of the model, we analyze optimal choices and production, as well as the simple genetic mechanism that drives the evolution of handedness. In Section 4 we will study the dynamic behavior of the benchmark model, assuming exogenous technological process. The latter assumption will then be removed in Section 5.

3.1 Population

In our model economy, individuals live for two periods: childhood and working-age. During the first period, agents are raised by their parents and do not make any decision. In the second period, they work and make utility-maximizing choices that will be analyzed in Section 3.2.

At time t, total working-age population is denoted by P_t. Agents are heterogeneous along two dimensions: handedness and skills. In particular, they can be left- or right-handed ($i = L, R$), unskilled or skilled ($j = U, S$). The (working-age) population of our economy is thus made up of $P_{L,t}$ left-handers and $P_{R,t}$ right-handers, with $P_{L,t} = \lambda_t P_t$ and $P_{R,t} = (1-\lambda_t)P_t$, where λ_t denotes the left-handedness rate. As far as skills are concerned, at time t the sub-populations of unskilled and skilled workers are denoted by $P_{U,t}$ and $P_{S,t}$, respectively.

Therefore, at any t we must have

$$P_t = P_{L,t} + P_{R,t} = P_{U,t} + P_{S,t}. \tag{1}$$

For later use, we define the share of skilled population by handedness as

$$x_{i,t} = \frac{P_{iS,t}}{P_{i,t}}. \tag{2}$$

where $i = L, R$.

Population dynamics is driven by fertility. After denoting by $n_{ij,t}$ the fertility of ij-type agents at time t, and by $\overline{n}_{L,t}$ and $\overline{n}_{R,t}$ the average fertility rates of left- and right-handers, we can write:

$$P_{t+1} = \sum_i \sum_j P_{ij,t} n_{ij,t} = (\lambda_t \overline{n}_{L,t} + (1-\lambda_t)\overline{n}_{R,t})P_t. \tag{3}$$

For ease of presentation, we assume reproduction to occur asexually, so that each individual has a single parent.

3.2 Optimization

At time t, an ij-type parent maximizes the utility function

$$u_{ij,t} = \ln c_{ij,t} + \gamma \ln n_{ij,t}\pi_{ij,t}, \tag{4}$$

where $c_{ij,t}$ denotes own consumption, $n_{ij,t}$ is the number of children, $\pi_{ij,t}$ is the probability that each child becomes skilled, and $\gamma > 0$ accounts for inter-generational, warm-glow altruism.

The parents' maximization problem is subject to technological and financial constraints. As far as technology is concerned, the probability of becoming skilled is a function of the education received by each child $e_{ij,t}$. In particular,

$$\pi_{ij,t} = \xi(\theta + e_{ij,t})^{\beta}, \tag{5}$$

where $\xi > 0$, $\theta > 0$ and $\beta \in (0, 1)$. The parameter ξ is a scale parameter, while the main role of θ is to prevent $\pi_{ij,t}$ from falling to zero when parents do not invest in education, so that there can always be some skilled agents in our economy. The parameter β measures the elasticity of the probability of becoming skilled to total education. Note that in our economy human capital accumulates at the extensive margin, *i.e.* through the increase in the number of skilled agents.

Similarly to Moav (2005), the budget constraint faced by the household is given by

$$(1 - \phi n_{ij,t})w_{ij,t} = c_{ij,t} + (e_{ij,t} + \tau)n_{ij,t}, \tag{6}$$

where $w_{ij,t}$ denotes the wage per unit of time of ij-type individuals, and will be determined within the production block of the model. The parameters $\tau > 0$ and $\phi \in (0, 1)$ account for the good- and time-cost of raising children, respectively. The labor supply of parents, who are endowed with one unit of time, depends entirely on fertility decisions.

The maximization problem solved by households is similar to De la Croix (2013), where parents are characterized by a form of joy-of-giving altruism, and face a quality-quantity trade-off regarding children.

Given the constraints specified in (5) and (6), parents choose $c_{ij,t}$, $n_{ij,t}$ and $e_{ij,t}$ so as to maximize (4). The resulting optimal choices are given by

$$e_{ij,t} = \begin{cases} 0 & \text{if } w_{ij,t} \leq \dfrac{\theta - \beta\tau}{\beta\phi} \\ \dfrac{\beta(\tau + \phi w_{ij,t}) - \theta}{1 - \beta} & \text{if } w_{ij,t} > \dfrac{\theta - \beta\tau}{\beta\phi} \end{cases}, \tag{7}$$

and

$$n_{ij,t} = \begin{cases} \dfrac{\gamma w_{ij,t}}{(1 + \gamma)(\tau + \phi w_{ij,t})} & \text{if } w_{ij,t} \leq \dfrac{\theta - \beta\tau}{\beta\phi} \\ \dfrac{\gamma(1 - \beta)w_{ij,t}}{(1 + \gamma)(\tau + \phi w_{ij,t} - \theta)} & \text{if } w_{ij,t} > \dfrac{\theta - \beta\tau}{\beta\phi} \end{cases}. \tag{8}$$

Parents invest in education as soon as their wage per unit of time exceeds $(\theta - \beta\tau)/\beta\phi$. Below this threshold, we have a corner solution for the optimal investment in education, *i.e.*

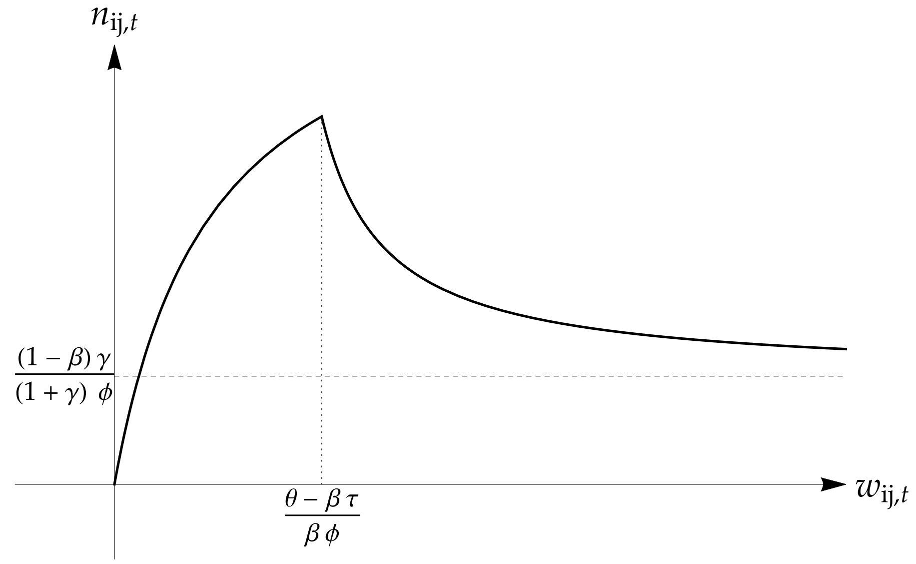

Figure 3: Endogenous fertility

$e_{ij,t} = 0$, and fertility is increasing in income, as $\partial n_{ij,t}/\partial w_{ij,t} > 0$. This defines a Malthusian fertility regime, in which children are a normal good. Above the threshold, parents' educational expenditure is given by an interior solution $e_{ij,t} > 0$, and it can be checked that $\partial n_{ij,t}/\partial w_{ij,t} < 0$ if $\theta > \tau$.[20] We assume this inequality to hold throughout the paper, thus warranting that in the modern regime fertility decreases with income. This happens because parents start substituting quantity with quality (of children), and the opportunity cost of having children is higher for richer parents. The resulting fertility function is depicted in Figure 3, where we also take into account that $\lim_{w_{ij,t}\to\infty} n_{ij,t} = (1-\beta)\gamma/((1+\gamma)\phi)$.

The endogenous fertility pattern described in Figure 3 implies that higher productivity translates into more reproductive success only as long as agents behave in a Malthusian fashion, with optimal choices corresponding to corner solutions. Therefore, our framework allows for reversals in fertility differentials along the process of economic development. As will become apparent in Section 4, the non-monotonicity of the fertility-income relationship plays a key role in our model, as it drives – in combination with technological progress – the decline and resurgence of the prevalence of left-handedness. However, our theory can also reproduce the U-shaped pattern of left-handedness described in Section 2 without relying on an increasing portion of the fertility-income relationship, *i.e.* in the absence of a Malthusian segment.[21] We demonstrate this in Appendix B, where we introduce the extensive margin of fertility, thereby implying that individuals with different incomes have a differential access to marriage and reproduction.

Before moving from the demand- to the supply-side of the model, let us stress that our characterization of household choices – based on asexual reproduction and single-parent families – can be suitably re-interpreted in terms of sexual reproduction, as discussed in Appendix C.

[20] In fact, we have that $\frac{\partial n_{ij,t}}{\partial w_{ij,t}} = -\frac{\gamma(1-\beta)(\theta-\tau)}{(1-\gamma)(\tau+\phi w_{ij,t}-\theta)^2}$.

[21] Whether or not a Malthusian segment characterized fertility in the U.S. at the end of the 19th century is still debated. See for instance Reher (2004), Jones and Tertilt (2006) and Baudin, de la Croix, and Gobbi (2015).

3.3 Technology and production

Our economy is made of two sectors producing a single homogenous good. In particular, we refer to a "traditional" sector (corresponding to agriculture or rural, low-tech production, and indexed by T) and a "modern" one (manufacturing, industry and services, indexed by M). Similar to Ashraf and Galor (2012) and Litina (2016), we will have decreasing returns to the number of workers in the traditional sector, and constant returns in the modern one. A distinctive assumption of our model is that, while all workers are equally productive in the traditional sector, handedness and skills are key determinants of individual productivity in the modern sector.

3.3.1 The traditional sector

In the traditional sector, all workers earn the same wage and, hence, have equal fertility regardless of their type: individual variables thus do not need to be indexed by ij. We assume that land is equally divided among workers, who spend a fraction $(1-\phi n_t)$ of their time on their plot of land. Each worker produces y_t^T according to the following production function:

$$y_t^T = T_t \left(\frac{X}{P_t^T}\right)^{\alpha} (1-\phi n_t), \tag{9}$$

where T_t is total factor productivity in the traditional sector, P_t^T is the size of the labor force working in the traditional sector, X is land, and $\alpha \in (0,1]$ allows for decreasing returns to land.

After normalizing total land to 1, Equation (9) becomes

$$y_t^T = T_t(1-\phi n_t)(P_t^T)^{-\alpha}, \tag{10}$$

and the wage per unit of time can be written as

$$w_t^T = T_t(P_t^T)^{-\alpha}. \tag{11}$$

Wages in the traditional sector are thus decreasing in the number of workers.[22]

3.3.2 The modern sector

In the modern sector, individual productivity depends on agents' type. Production takes place according to

$$Y_t^M = M_t \sum_i \sum_j \zeta_{ij} P_{ij,t}^M (1-\phi n_{ij,t}), \tag{12}$$

where $M_t > 0$ stands for total factor productivity, while $P_{ij,t}^M$ and $(1-\phi n_{ij,t})$ denote respectively the number and the working time of ij-type workers employed in manufacturing. The variable ζ_{ij} accounts for type-specific, and fully observable productivity, with

$$\zeta_{LU,t} = 1, \tag{13}$$

[22]In Appendix D, we develop an alternative version of the model, where the traditional sector is characterized by decreasing returns to both the number of workers and working time.

$$\zeta_{RU,t} = \rho, \quad (14)$$

and

$$\zeta_{iS,t} = h, \forall i = L, R. \quad (15)$$

We assume that $1 < \rho < h$, thus implying that handedness has no consequence for the productivity of the skilled workers, who are all equally productive, and always more productive than the unskilled. On the contrary, unskilled agents differ in terms of manual productivity, with left-handers being disadvantaged. As discussed in Section 1, this is consistent with the empirical evidence that left-handers are less effective – and even more likely to be injured – when working with tools and operating machines that are, in most cases, designed for right-handers.

In the modern sector, wages per unit of time are determined by marginal productivity according to

$$w^M_{ij,t} = M_t \zeta_{ij,t}, \quad (16)$$

and do not depend on the number of workers employed in this sector.[23]

3.3.3 Labor allocation and structural change

At every t, we must have

$$P_{ij,t} = P^T_{ij,t} + P^M_{ij,t}. \quad (17)$$

We assume perfect labor mobility between the two sectors, so that

$$w^M_{ij,t} = w^T_{ij,t} \quad (18)$$

whenever agents of the same type are employed in both sectors.

In this framework, industrialization is interpreted as the progressive inflow of unskilled workers to the modern sector.

We assume that in our economy both sectors are always operational. As will be formalized in Section 4, there is perfect segregation by skills at $t = 0$: the few existing skilled workers provide services in the (tiny) modern sector, while all the unskilled work in the T-sector.[24] This means that $P^T_{S,0} = 0$ and $P^M_{U,0} = 0$. Whether the M-sector eventually becomes attractive to unskilled workers, thus bringing about industrialization, depends on the relationship between w^T_t and $w^M_{iU,t}$. Intuitively, the modern sector can become viable to (some of) them because (i) population increases, thereby imposing decreasing returns onto traditional production, and/or (ii) productivity in the modern sector grows enough to attract unskilled labor.

To activate the latter mechanism, we introduce exogenous technological progress, so that

$$T_{t+1} = (1 + \mu) T_t, \quad (19)$$

[23]Individual productivity must be observable, for workers to receive their marginal product.

[24]The idea is that there are always a few intellectual, skilled workers, even in pre-industrial societies.

and

$$M_{t+1} = (1+\chi)M_t, \tag{20}$$

with $\mu \in (0,1)$ and $\chi \in (0,1)$. As in Hansen and Prescott (2002), we further assume $\chi > \mu$, which implies an increasing trend for M_t/T_t – thus paving the way to industrialization.

For the sake of analytical tractability, we normalize $T_t = 1$, $\forall t$ (*i.e.* $T_0 = 1$ and $\mu = 0$).

3.4 Genetics

We now introduce a genetic mechanism into our theory. To do so, we borrow from McManus (1985) a simple genetic model of handedness, which emphasizes the role of *additive* genetic effects (rather than dominance) in the determination of human handedness. Such model is consistent with the following features: (i) heritability of handedness, (ii) monozygotic discordance, and (iii) left-handedness being more subject to randomness.[25] Genetic research also suggests that handedness is a polygenic trait (see for instance McManus, Davison, and Armour 2013, Ocklenburg, Beste, and Güntürkün 2013, Somers et al. 2015, Wiberg et al. 2019). The single-locus model proposed by McManus (1985) has the merit of closely reproducing the results of more realistic but complicated multi-locus models.

For ease of exposition, we further simplify McManus (1985)'s model to make it compatible with the assumption of asexual reproduction made in Section 3.1. An alternative version of the genetic block of our model, allowing for sexual reproduction, will be considered in Appendix C. There, we show that the results of the more complex model, which is obviously better suited for diploid organisms (like humans), are essentially the same as those of our simplified framework.

Handedness is traced back to two different genotypes, denoted by D ("dexterity") and C ("chance"), respectively. We assume these genotypes to be fully inheritable, so that – in this simplified setting – we do not need to discuss the role of alleles, which are instead central to the more sophisticated genetic model in Appendix C.

To describe how genotypes translate into phenotypes (the visible expressions of the genotype), we denote by $p(i|k)$ (with $i = L, R$ and $k = C, D$) the probability of displaying phenotype i conditional on having the genotype k. We then assume that an individual with a D genotype is right-handed with certainty, *i.e.* $p(R|D) = 1$, while having a C genotype yields a positive probability of being right-handed, *i.e.* $p(R|C) = 1 - \omega$, with $\omega \in (0,1)$. Accordingly, the probability of being left-handed is zero for D-genotypes individuals and ω for C-genotypes individuals, so that $p(L|D) = 0$ and $p(L|C) = \omega$. Our model thus allows for both heterozygotic discordance and left-handedness being more subject to randomness.

We further denote by δ_t the frequency of D-genotypes at time t. Keeping in mind how genotypes can manifest themselves into phenotypes, the share of right-handers in the population at

[25] That handedness runs in families is a well-known fact, as explained in the Introduction. As far as monozygotic discordance is concerned, McManus and Bryden (1992) and Vuoksimaa et al. (2009), among others, have shown that 10 to 20% of monozygotic twins display different handedness. The higher degree of randomness associated with left-handedness is revealed, for instance, by the fact that only 5-6% of right-handers have right-hemisphere dominance for language, compared to 30–35% of left-handers (McManus 2009). In addition, Hepper, Wells, and Lynch (2005) have found that all right-hand thumb-sucking fetuses remain right-handers postnatally, while 34% of left-hand thumb-sucking fetuses become right-handers.

time t is then

$$1 - \lambda_t = p(R|D)\delta_t + p(R|C)(1 - \delta_t). \tag{21}$$

Using the expressions for $p(R|D)$ and $p(R|C)$, and solving for λ_t, we obtain the left-handedness rate

$$\lambda_t = \omega(1 - \delta_t). \tag{22}$$

At time $t+1$, genotype frequency depends on the reproductive success of left- and right-handed individuals at time t. Recalling that the average fertility of the right- and left-handers is denoted by $\bar{n}_{R,t}$ and $\bar{n}_{L,t}$, respectively, it can be shown that

$$\delta_{t+1} = \frac{\delta_t \bar{n}_{R,t}}{\bar{n}_{R,t} - \omega(1 - \delta_t)(\bar{n}_{R,t} - \bar{n}_{L,t})}. \tag{23}$$

We can therefore write

$$\Delta\delta_t = \frac{\omega(1 - \delta_t)\delta_t(\bar{n}_{R,t} - \bar{n}_{L,t})}{\bar{n}_{R,t} - \omega(1 - \delta_t)(\bar{n}_{R,t} - \bar{n}_{L,t})}, \tag{24}$$

and describe the implication of differential fertility for genotype frequency and the prevalence of left-handedness.

Lemma 1 *The frequency of genotype D increases (decreases), and the prevalence of left-handedness decreases (increases), when the average fertility of right-handers is higher (lower) than that of left-handers. In case right- and left-handers have the same reproductive success, genotype frequency stabilizes.*

Proof. Follows from Equations (24) and (22). In particular, $\delta_{t+1} = \delta_t$ if $\bar{n}_{R,t} = \bar{n}_{L,t}$. ■

To see the implications of our reduced-form genetic model in terms of inter-generational transmission of handedness, we can compute the probability of being left- or right-handed conditional on having a left- or right-handed parent. Unlike the probability of displaying a phenotype conditional on a given genotype, these "inter-generational" probabilities are time-dependent, as they depend on fertility choices, which are in turn shaped by economic conditions. Denoting by $p_t(R|R)$ the probability that an individual (who is adult at time t) has a right-handed child conditional on being right-handed herself, it can be shown that

$$p_t(R|R) = \frac{1 + \omega(\omega - 2)(1 - \delta_t)}{1 - \omega(1 - \delta_t)}. \tag{25}$$

Similarly,

$$p_t(L|R) = \frac{\omega(1 - \omega)(1 - \delta_t)}{1 - \omega(1 - \delta_t)}, \tag{26}$$

$$p_t(L|L) = \omega, \tag{27}$$

and

$$p_t(R|L) = 1 - \omega. \tag{28}$$

Note that $p_t(R|R)$, as defined above, is also the probability that an individual (who is adult at time $t+1$) is right-handed conditional on having a right-handed parent.

The probabilities defined in Equations (25)-(28) are consistent with the observation that handedness runs in families: in fact, it can be checked that $p_t(R|R) > p_t(R|L)$ and $p_t(L|L) > p_t(L|R)$.

4 Dynamics

Since there is a one-to-one relationship between δ and λ (Equation (22)), the process of development is fully determined by the sequence $\{M_t, P_t, \delta_t, x_{L,t}, x_{R,t}\}_{t=0}^{\infty}$.

In particular, the dynamic behavior of the model is summarized by the system

$$\begin{cases} M_{t+1} = M(M_t), \\ P_{t+1} = P(M_t, P_t, \delta_t, x_{L,t}, x_{R,t}), \\ \delta_{t+1} = \delta(M_t, P_t, \delta_t, x_{L,t}, x_{R,t}), \\ x_{L,t+1} = x_L(M_t, P_t, \delta_t, x_{L,t}, x_{R,t}), \\ x_{R,t+1} = x_R(M_t, P_t, \delta_t, x_{L,t}, x_{R,t}). \end{cases} \tag{29}$$

The first three difference equations (for M, P and δ) correspond to Equations (20), (3) and (23), respectively, where endogenous flow variables have been replaced with their optimal values.

The remaining two equations of the system describe the evolution of the share of skilled among left- and right-handers, x_L and x_R, depending on the genetic composition of the population (δ_t), the fertility of different types of agents ($n_{ij,t}$), their probabilities to have skilled children ($\pi_{ij,t}$), as well as the probability that children are left- or right-handed conditional on their parents' handedness ($p_t(L|L)$, etc.). Namely, we have that

$$x_{L,t+1} = \frac{(1-\delta_t)(x_{L,t}n_{LS,t}\pi_{LS,t}+(1-x_{L,t})n_{LU,t}\pi_{LU,t})p_t(L|L)+(1+\delta_t)(x_{R,t}n_{RS,t}\pi_{RS,t}+(1-x_{R,t})n_{RU,t}\pi_{RU,t})p_t(L|R)}{(1-\delta_t)(x_{L,t}n_{LS,t}+(1-x_{L,t})n_{LU,t})p_t(L|L)+(1+\delta_t)(x_{R,t}n_{RS,t}+(1-x_{R,t})n_{RU,t})p_t(L|R)}, \tag{30}$$

and

$$x_{R,t+1} = \frac{(1-\delta_t)(x_{L,t}n_{LS,t}\pi_{LS,t}+(1-x_{L,t})n_{LU,t}\pi_{LU,t})p_t(R|L)+(1+\delta_t)(x_{R,t}n_{RS,t}\pi_{RS,t}+(1-x_{R,t})n_{RU,t}\pi_{RU,t})p_t(R|R)}{(1-\delta_t)(x_{L,t}n_{LS,t}+(1-x_{L,t})n_{LU,t})p_t(R|L)+(1+\delta_t)(x_{R,t}n_{RS,t}+(1-x_{R,t})n_{RU,t})p_t(R|R)}, \tag{31}$$

where optimal choices and probabilities are given by Equations (5), (7)-(8) and (25)-(28).

We set initial conditions such that at $t = 0$ there is perfect segregation of labor, with sector M (T) employing only skilled (unskilled) workers. For this to be the case, we need

$$\frac{P_0^{-\alpha}}{h} < M_0 < \frac{P_{U,0}^{-\alpha}}{\rho}, \tag{32}$$

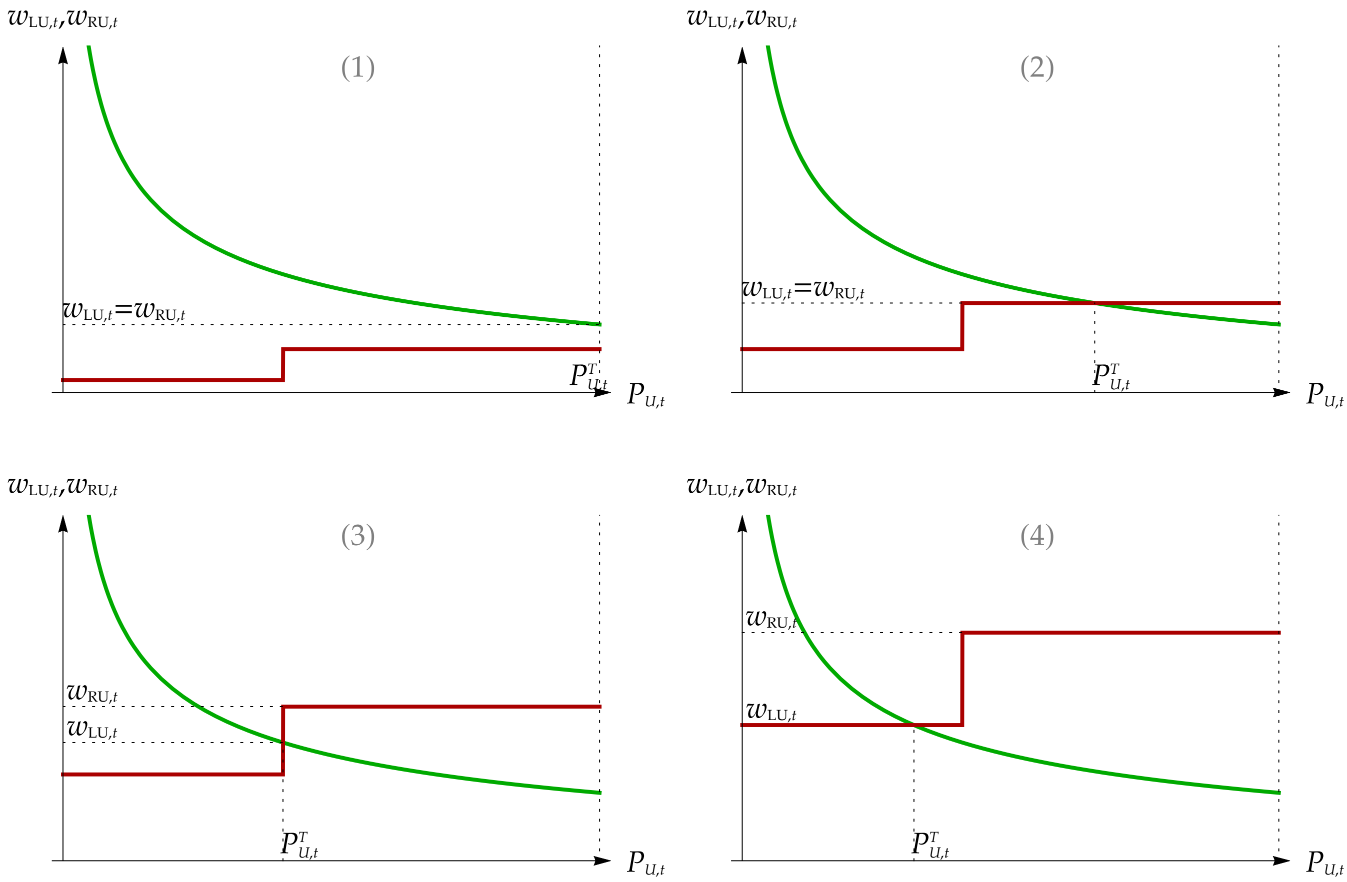

Figure 4: Structural change: traditional (green) *vs* modern (red) sector.

where

$$P_{U,0} = ((1 - x_{L,0})\lambda_0 + (1 - x_{R,0})(1 - \lambda_0))P_0.$$

4.1 Stages of development

To understand the dynamics of the model, it is useful to proceed stepwise. First, we characterize the process of structural change, by studying the effects of the increase in relative sectoral productivity on wages and sectoral employment. This allows us to define what we call the "stages of development". In a second step, we show how education, fertility, and eventually left-handedness evolve across the stages of development.

Since we assume that skilled workers work in the modern sector from the onset (Equation (32)), in our model the process of structural change has to be interpreted as the outflow of unskilled labor from the traditional to the modern sector. This can be visualized in Figure 4. In each panel, we plot the wages of the unskilled in the traditional (green) and modern (red) sectors, for both left- and right-handers ($w_{LU,t}$, $w_{RU,t}$) against the size of the overall unskilled population ($P_{U,t}$). The step in the red line reflects the different manual ability of left- and right-handed workers in the modern sector. The point of the horizontal axis corresponding to the step divides the total unskilled population ($P_{U,t}$) into left-handers ($P_{LU,t}$, to the left) and right-handers ($P_{RU,t}$, to the right). Each panel represents a stage of development, with the transition from one stage to another being driven by exogenous technological progress.

The economy starts in stage (1), with all unskilled workers employed in the traditional sector and earning the same wage. As time goes by, M increases until the modern sector becomes attractive to some unskilled workers, and the economy enters stage (2). In particular, some right-handers, who are relatively more productive than left-handers at modern tasks, find it profitable to work in the modern sector. This process goes on until stage (3), when all the unskilled right-handed workers are employed in the modern sector. A wage differential between left- and right-handers then emerges, in favor of the latter. The progressive relocation of left-handers to the modern sector characterizes the last phase of the process of structural change, stage (4), where the wage gap between unskilled left- and right-handers increases as productivity in the modern sector grows. This does not mean, however, that the *average* wage gap between left- and right-handers increases because, as we shall see later on, the relative weight of unskilled workers in the total population may substantially decrease over time.

The above reasoning finds its analytical expression in Proposition 1.

Proposition 1 (Stages of development) *Depending on the level of TFP in the modern sector, M, there are four possible stages of development for the model economy.*

(1) If $M_t < P_{U,t}^{-\alpha}/\rho$, the economy is characterized by

$$P_{LU,t}^{M} = P_{RU,t}^{M} = 0; \tag{33}$$

$$w_{LU,t} = w_{RU,t} = P_{U,t}^{-\alpha}. \tag{34}$$

All unskilled workers are employed in the T sector, and wages do not vary by handedness.

(2) If $P_{U,t}^{-\alpha}/\rho \leq M_t < P_{LU,t}^{-\alpha}/\rho$, the economy is characterized by

$$P_{LU,t}^{M} = 0, \tag{35}$$

$$0 < P_{RU,t}^{M} \leq P_{RU,t}; \tag{36}$$

$$w_{LU,t} = w_{RU,t} = \rho M_t. \tag{37}$$

Among unskilled workers, all left-handers are employed in the T sector, while some right-handers work in the M sector. In particular, $P_{RU,t}^{M} = P_{U,t} - (\rho M_t)^{-1/\alpha}$. Wages do not vary by handedness.

(3) If $P_{LU,t}^{-\alpha}/\rho \leq M_t < P_{LU,t}^{-\alpha}$, the economy is characterized by

$$P_{LU,t}^{M} = 0, \tag{38}$$

$$P_{RU,t}^{M} = P_{RU,t}; \tag{39}$$

$$w_{RU,t} = \rho M_t, \tag{40}$$

$$w_{LU,t} = P_{LU,t}^{-\alpha}. \tag{41}$$

Unskilled workers are segregated by handedness: all left-handers work in the T sector, all right-handers in the M sector. Right-handers earn higher wages.

(4) If $M_t \geq P_{LU,t}^{-\alpha}$, the economy is characterized by

$$0 < P_{LU,t}^{M} \leq P_{LU,t}; \tag{42}$$
$$P_{RU,t}^{M} = P_{RU,t}; \tag{43}$$
$$w_{RU,t} = \rho M_t, \tag{44}$$
$$w_{LU,t} = M_t. \tag{45}$$

Among unskilled workers, all right-handers are employed in the M sector, while some left-handers still work in the T sector. In particular, $P_{LU,t}^{M} = P_{LU,t} - M_t^{-1/\alpha}$. Right-handers earn higher wages.

Proof. See Appendix E. ■

4.2 Education, differential fertility, and the evolution of left-handedness

Proposition 1 describes how sectoral employment and wages evolve across the different stages of development. In particular, it gives us the conditions for the emergence of an income differential between unskilled left- and right-handers.

The next step to characterize the dynamics of our economy along the process of structural change is to study how wage differentials among sub-groups of the population translate into differential reproductive success. In fact, since handedness is a genetically transmitted trait, fertility differentials between left- and right-handers translate into dynamic variations in the prevalence of left-handedness. Furthermore, fertility and education decisions are intertwined in our model, so that we must characterize the outcome of household maximization, *i.e.* $e_{ij,t}$ and $n_{ij,t}$, depending on the state of the economy.

Before delving into the analytics of the question, three premises are in order. First, a key feature of our model is the existence of a Malthusian and a post-Malthusian fertility regime, as represented in Figure 3. The transition between the two regimes corresponds to an inversion of the income-fertility relationship, as described by Equation (8): more productive workers have a reproductive advantage throughout the Malthusian phase, while the opposite is true in the post-Malthusian regime. This switch can potentially occur within any specific stage of development, as soon as (some) agents invest in their offspring's education. As can be seen from Equation (7), an ij-type agent invests in education as soon as $w_{ij,t} > (\theta - \beta\tau)/\beta\phi$. Hence the demographic transition may start at different stages for different sub-groups of the population.[26]

Second, the difference in the average fertility of left- and right-handers ultimately depends on the fertility of the unskilled. In fact, while skilled individuals have the same productivity (and make the same optimal choices) regardless of their dominant hand, unskilled left-handers may earn lower wages than unskilled right-handers (because of lower productivity in manufacturing), thus displaying a different fertility behavior.[27]

[26] In our model, like in Moav (2005), heterogeneity among agents implies that in each period, different subgroups might be at different stages of the demographic transition, so that Malthusian behavior can subsist in the modern regime and *vice versa*.

[27] As long as there is no investment in education, we have the same share of left-handers among skilled and unskilled workers, so if unskilled left-handers are poorer, left-handers have a lower fertility rate on average. When people start investing in education and the income-fertility relationship is eventually reversed, left-handers – if poorer – are over-represented among the unskilled, who also have the highest fertility rate. Therefore, in the

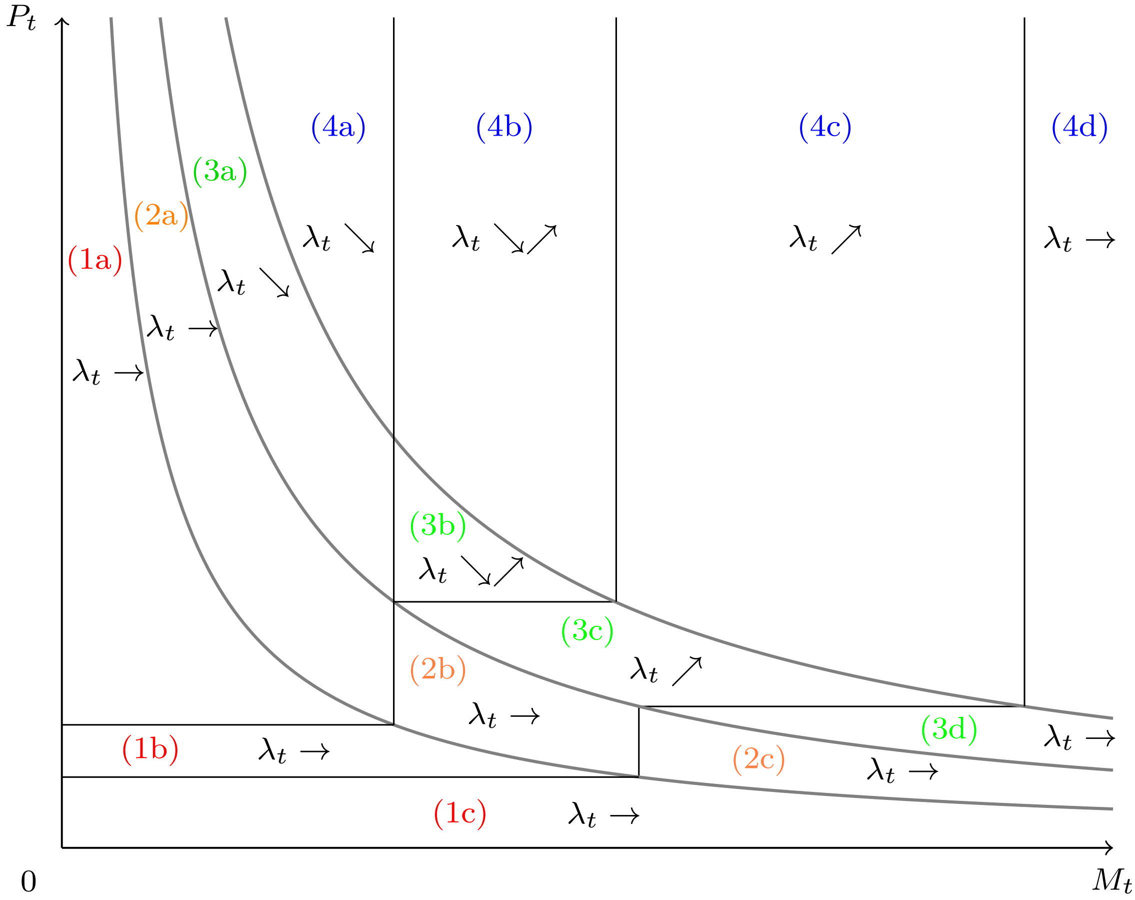

Figure 5: The dynamics of λ depending on technology and population

Third, the relevant dynamic equation to study the effect of differential fertility on the genetic transmission of handedness is Equation (23), which describes the evolution of δ, the proportion of D-genotypes. However, based on the one-to-one relationship between δ and the left-handedness rate λ established by Equation (22), we can determine the implications of differential fertility for λ, which is our main variable of interest.

To give a general illustration of the dynamic evolution of left-handedness, in Figure 5 we plot the conditions defining the stages of development from Proposition 1 in the (P_t, M_t) space – for a given prevalence of left-handedness, λ_t, and a given skill composition of the population, as defined by $x_{L,t}$ and $x_{R,t}$. In the figure, these conditions correspond to the downward-sloping curves that separate the four stages of development, which are denoted by the same numbers as in Proposition 1. Each stage is further partitioned into regions by horizontal and vertical segments representing the thresholds that correspond to a change in the fertility and/or education behavior of some sub-groups of the population, as will be specified analytically in Lemmas 2.1 to 2.4. Each region is then denoted by a letter following the number of the stage of development it belongs to (*e.g.* region (4b), within stage (4)).

Figure 5 can be thought of as an instantaneous picture of the model at time t, shedding light on the motion of λ from time t to time $t+1$. Drawn for given values of λ_t, $x_{L,t}$ and $x_{R,t}$, Figure 5

post-Malthusian regime left-handers have higher fertility on average, because (i) they are under-represented in the lowest-fertility group (the skilled), and (ii) unskilled left-handers have more children than unskilled right-handers, because they are less productive.

thus tells us how λ changes from t to $t+1$ for any possible combination of M_t and P_t. Note, however, that Figure 5 is not a phase diagram, for the boundaries between the different regions change over time and must be updated when the values of λ, x_L and x_R change from t to $t+1$.

Suppose for instance that the economy is in stage (4). We know from Proposition 1 that all the unskilled right-handers work in the modern sector. We also know that among the unskilled left-handers some work in the traditional, and some in the modern sector. This implies that there is a differential between left- and right-handers in terms of average wages, which translates into a differential reproductive success, so that $\Delta\lambda_t \neq 0$. But if we want to know the direction of the inequality, we need to characterize fertility and education choices throughout this stage, *i.e.* the threshold values of M_t and P_t defining the four different regions within stage (4). For each of these regions in stage (4), there is a corresponding different sign of $\Delta\lambda_t$.

With this in mind, we now turn to the characterization of optimal choices (*i.e.* fertility and education) across the four stages of development, in Lemmas 2.1 to 2.4.[28] We will then draw implications for the dynamics of λ in the subsequent Proposition 2.

Lemma 2.1 (Fertility and education, stage (1)) *Consider stage (1), as defined in Proposition 1. Within this stage of development, the following cases are possible.*

(1a) If $P_{U,t} > \left(\dfrac{\theta-\beta\tau}{\beta\phi}\right)^{-1/\alpha}$*, then* $e_{LU,t} = e_{RU,t} = 0$ *and* $n_{LU,t} = n_{RU,t}$.

(1b) If $\left(\dfrac{(1-\beta)\xi^{-1/\beta}+\beta(\theta-\tau)}{\beta\phi}\right)^{-1/\alpha} < P_{U,t} \leq \left(\dfrac{\theta-\beta\tau}{\beta\phi}\right)^{-1/\alpha}$*, then* $e_{LU,t} = e_{RU,t} > 0$ *and* $n_{LU,t} = n_{RU,t}$.

(1c) If $P_{U,t} \leq \left(\dfrac{(1-\beta)\xi^{-1/\beta}+\beta(\theta-\tau)}{\beta\phi}\right)^{-1/\alpha}$*, then* $e_{LU,t} = e_{RU,t}$ *is such that* $\pi_{LU,t} = \pi_{RU,t} = 1$*, and* $n_{LU,t} = n_{RU,t}$.

Proof. See Appendix E. ■

Lemma 2.2 (Fertility and education, stage (2)) *Within stage (2), as defined in Proposition 1, the following cases are possible.*

(2a) If $M_t < \dfrac{\theta-\beta\tau}{\beta\phi\rho}$*, then* $e_{LU,t} = e_{RU,t} = 0$ *and* $n_{LU,t} = n_{RU,t}$.

(2b) If $\dfrac{\theta-\beta\tau}{\beta\phi\rho} \leq M_t < \dfrac{(1-\beta)\xi^{-1/\beta}+\beta(\theta-\tau)}{\beta\phi\rho}$*, then* $e_{LU,t} = e_{RU,t} > 0$ *and* $n_{LU,t} = n_{RU,t}$.

[28] Notice that, for simplicity, the conditions defining regions within stage (1) and (3) are expressed in terms of P_U and P_{LU}. In the model however, there is a one-to-one mapping from these variables to P, which is the variable in the y axis in Figure 5, for given λ and x_i. It can indeed be proven that

$$P_t = \frac{P_{U,t}}{1 - x_{L,t}\lambda_t - x_{R,t}\,(1-\lambda_t)} = \frac{P_{LU,t}}{(1-x_{L,t})\,\lambda_t}.$$

(2c) If $M_t \geq \dfrac{(1-\beta)\xi^{-1/\beta}+\beta(\theta-\tau)}{\beta\phi\rho}$, *then* $e_{LU,t} = e_{RU,t}$ *is such that* $\pi_{LU,t} = \pi_{RU,t} = 1$, *and* $n_{LU,t} = n_{RU,t}$.

Proof. See Appendix E. ■

Throughout stages of development (1) and (2), right- and left-handed individuals have the same productivity, hence they make identical education and fertility choices. Notice, however, that while in regions (1a) and (2a) nobody among the unskilled invests in education, they all do in regions (1b) and (2b). Finally, in regions (1c) and (2c), the economy is in the limit case where the investment in education is large enough to ensure that all the members of the subsequent generation are skilled.[29] We characterize this limit case for the sake of completeness, even though it is of little empirical relevance.

Differences in fertility behavior among unskilled workers appear in stages (3) and (4), when a wage gap between left- and the right-handers emerges (see Figure 4).

Lemma 2.3 (Fertility and education, stage (3)) *Within stage (3), as defined in Proposition 1, the following cases are possible.*

(3a) If $M_t < \dfrac{\theta-\beta\tau}{\beta\phi\rho}$, *then* $e_{LU,t} = e_{RU,t} = 0$ *and* $n_{RU,t} > n_{LU,t}$.

(3b) If $M_t > \dfrac{\theta-\beta\tau}{\beta\phi\rho}$ *and* $P_{LU,t} > \left(\dfrac{\theta-\beta\tau}{\beta\phi}\right)^{-1/\alpha}$, *then* $e_{RU,t} > e_{LU,t} = 0$ *and* $n_{RU,t} \gtreqless n_{LU,t}$.

(3c) If $\left(\dfrac{(1-\beta)\xi^{-1/\beta}+\beta(\theta-\tau)}{\beta\phi}\right)^{-1/\alpha} < P_{LU,t} \leq \left(\dfrac{\theta-\beta\tau}{\beta\phi}\right)^{-1/\alpha}$, *then* $e_{RU,t} > e_{LU,t} > 0$ *and* $n_{RU,t} < n_{LU,t}$.

(3d) If $P_{LU,t} \leq \left(\dfrac{(1-\beta)\xi^{-1/\beta}+\beta(\theta-\tau)}{\beta\phi}\right)^{-1/\alpha}$, *then* $\pi_{LU,t} = \pi_{RU,t} = 1$, *and* $n_{LU,t} = n_{RU,t}$.

In particular, within region (3b) there exists a threshold value $\tilde{M}$, *such that* $n_{RU,t} > n_{LU,t}$ *if* $M_t < \tilde{M}$ *and* $n_{RU,t} < n_{LU,t}$ *otherwise.*

Proof. See Appendix E. ■

Lemma 2.4 (Fertility and education, stage (4)) *Within stage (4), as defined in Proposition 1, the following cases are possible.*

(4a) If $M_t < \dfrac{\theta-\beta\tau}{\beta\phi\rho}$, *then* $e_{LU,t} = e_{RU,t} = 0$ *and* $n_{RU,t} > n_{LU,t}$.

(4b) If $\dfrac{\theta-\beta\tau}{\beta\phi\rho} \leq M_t < \dfrac{\theta-\beta\tau}{\beta\phi}$, *then* $e_{RU,t} > e_{LU,t} = 0$ *and* $n_{RU,t} \gtreqless n_{LU,t}$.

[29] If all agents are skilled, some of them must end up in the traditional sector – as marginal productivity in that sector tends to infinity, when employment tends to zero.

(4c) *If* $\frac{\theta - \beta\tau}{\beta\phi} \leq M_t < \frac{(1-\beta)\xi^{-1/\beta} + \beta(\theta - \tau)}{\beta\phi}$, *then* $e_{RU,t} > e_{LU,t} > 0$ *and* $n_{RU,t} < n_{LU,t}$.

(4d) *If* $M_t \geq \frac{(1-\beta)\xi^{-1/\beta} + \beta(\theta - \tau)}{\beta\phi}$, *then* $\pi_{LU,t} = \pi_{RU,t} = 1$, *and* $n_{LU,t} = n_{RU,t}$.

In particular, within region (4b) there exists a threshold value $\hat{M}$, *such that* $n_{RU,t} > n_{LU,t}$ *if* $M_t < \hat{M}$ *and* $n_{RU,t} < n_{LU,t}$ *otherwise.*

Proof. See Appendix E. ■

Lemmas 2.3 and 2.4 illustrate how the emergence of human capital brings about the inversion of the income-fertility relationship, and shapes differential fertility by handedness. As soon as productivity differentials arise, such that $w_{RU,t} > w_{LU,t}$, a reproductive advantage for right-handers appears ($\bar{n}_{R,t} > \bar{n}_{L,t}$) when fertility is Malthusian (that is, as long as $e_{RU,t} = e_{LU,t} = 0$). On the contrary, once human capital becomes relevant (*i.e.* $e_{RU,t} \geq e_{LU,t} \geq 0$), $w_{RU,t} > w_{LU,t}$ implies that $\bar{n}_{R,t} < \bar{n}_{L,t}$. Note also that when both left- and right-handed unskilled workers invest in education, the progressive rise of human capital tends to reduce (reproductive) inequality, until everybody is skilled and the fertility differential vanishes.

Together with Lemma 1, Lemmas 2.1-2.4 allow us to establish how the frequency of the D-genotype (δ) and the prevalence of left-handedness (λ) evolve, conditional on the state of the economy. For ease of presentation, the following Proposition focuses on phenotypical dynamics, showing how λ moves within each phase of development. Given the one-to-one relationship between δ and λ in Equation (22), the underlying dynamics of δ follows an opposite pattern.

Proposition 2 (Evolution of left-handedness) *Consider the different stages of development defined in Proposition 1 and the regions defined in Lemmas 2.1-2.4. The prevalence of left-handedness*

- *is stationary in stages (1) and (2), and in regions (3d) and (4d);*
- *decreases in regions (3a) and (4a), in region (3b) for* $M_t < \tilde{M}$ *and in region (4b) for* $M_t < \hat{M}$*;*
- *increases in regions (3c) and (4c), in region (3b) for* $M_t > \tilde{M}$ *and in region (4b) for* $M_t > \hat{M}$*.*

Proof. The Proof follows directly from Lemma 1, given the differential fertility pattern emerging from Lemmas 2.1 to 2.4. ■

We can now make complete sense of Figure 5. Suppose for instance that the values of M_t and P_t (given $x_{L,t}$, $x_{R,t}$ and δ_t) are such that we are in region (4c): we can then infer from Lemma 2.4 that $\bar{n}_{L,t} > \bar{n}_{R,t}$, so that $\Delta\lambda_t > 0$, as stated in Proposition 2.

4.3 The dynamics of left-handedness: an example

For the sake of completeness, Proposition 2 discusses the dynamics of λ for all the possible combinations of the state variables of our model, including those that are arguably not appropriate to describe actual historical patterns. In this Section, we impose two additional assumptions on initial conditions so as to limit the number of possible dynamic trajectories and allow the model to conform to historical facts.

Table 1: Left-handedness along the stages of development: an example

(1a), (2a)	(3a)	(4a)	(4b)	(4c)	(4d)
$w_{LU,t}=w_{RU,t}$	$w_{LU,t}<w_{RU,t}$	$w_{LU,t}<w_{RU,t}$	$w_{LU,t}<w_{RU,t}$	$w_{LU,t}<w_{RU,t}$	$w_{L,t}=w_{R,t}$
$e_{LU,t}=e_{RU,t}=0$	$e_{LU,t}=e_{RU,t}=0$	$e_{LU,t}=e_{RU,t}=0$	$e_{RU,t}>e_{LU,t}=0$	$e_{RU,t}>e_{LU,t}>0$	$e_{R,t}=e_{L,t}>0$
$\bar{n}_{L,t}=\bar{n}_{R,t}$	$\bar{n}_{L,t}<\bar{n}_{R,t}$	$\bar{n}_{L,t}<\bar{n}_{R,t}$	$\bar{n}_{L,t}\lesseqgtr\bar{n}_{R,t}$	$\bar{n}_{L,t}>\bar{n}_{R,t}$	$n_{L,t}=n_{R,t}$
$\delta_t \rightarrow$	$\delta_t \nearrow$	$\delta_t \nearrow$	$\delta_t \nearrow\searrow$	$\delta_t \searrow$	$\delta_t \rightarrow$
$\lambda_t \rightarrow$	$\lambda_t \searrow$	$\lambda_t \searrow$	$\lambda_t \searrow\nearrow$	$\lambda_t \nearrow$	$\lambda_t \rightarrow$

First, we require population to be always non-decreasing. For this to be the case, we require that parameters and initial conditions satisfy

$$\frac{\gamma}{1+\gamma} \geq \max\left(\frac{\tau}{M_0}+\phi, \frac{\phi}{1-\beta}\right).^{30} \tag{46}$$

Second, we impose that the initial level of population is sufficiently high, so that no unskilled parent invests in education throughout stages (1), (2) and (3). The implied condition is

$$P_{LU,0} > \left(\frac{\theta-\beta\tau}{\beta\phi\rho}\right)^{-1/\alpha}. \tag{47}$$

This avoids a chronological mismatch between the demographic transition and the structural transformation of the economy. The idea is to have an industrial revolution in which unskilled workers switch from agriculture to manufacturing, while still being unskilled.

Besides being historically more accurate, this is a convenient simplification. Since P_t is non-decreasing and M_t is increasing, and the boundaries defining the stages of development in Proposition 1 can only shift towards the origin of the axes over time, the economy must undergo structural transformation. Moreover, the boundaries defining regions (4a) to (4d) are stable over time, since they depend on parameters only (see Lemma 2.4). Accordingly, under conditions (46) and (47), Figure 5 lends itself to a diachronic interpretation.

In Table 1, we illustrate the dynamics of our model economy under these hypotheses.

The economy starts off in region (1a), where unskilled wages do not depend on handedness, nobody invests in education, and the prevalence of left-handedness is constant (thus defining an initial steady-state of λ). At some point, the demographic dynamics and/or technological progress (*i.e.* increasing values of P and/or M) drive the economy towards region (2a), where wages are higher but still identical across handedness and insufficient to trigger investment in education. As a result, λ remains constant, before the economy enters region (3a). At that stage of development, a productivity gap emerges, conferring a reproductive advantage to right-handers, who earn higher wages throughout a phase characterized by Malthusian fertility and

[30] This (sufficient) condition is obtained by imposing that minimum fertility, in both the Malthusian and modern regimes, must not be lower than 1.

no investment in education. The proportion of left-handers λ thus starts to decrease. This decline continues within region (4a) and extends to region (4b), until the demographic transition begins and the income-fertility relationship is reversed, when unskilled right-handers become rich enough to invest in education. From then on, unskilled right-handers – who are still more productive – have fewer children than unskilled left-handers, thus implying a higher average fertility among left-handers. This drives the recovery of λ, which goes on throughout region (4c) where both left- and right-handed unskilled workers invest in education. The average-fertility differential, however, progressively shrinks, as more and more individuals become skilled, and the economy approaches region (4d). The rise in human capital thus erodes fertility differentials, until the prevalence of left-handedness stabilizes and λ reaches its final steady-state.

Overall, the dynamic behavior of λ is in line with the stylized facts emphasized in Section 2. Note also that, due to the discrete-time characterization of our model, the economy may or may not transit through some of the regions of Figure 5, such as (4a) or (4b) for instance, without changing qualitatively the dynamics of left-handedness.[31]

4.4 Simulations

Figure 5 allows us to understand the dynamic behavior of λ, our main variable of interest. The underlying evolution of δ is symmetric, as can be inferred from Equation (22). To visualize the dynamic pattern of the other variables of our model, however, we need to resort to numerical simulations, for the model is too complex to be solved analytically. In addition, numerical simulations enable us to establish whether the implications of the model are reasonably consistent with the historical evidence, in terms of both magnitude and timing.

Although too complex to be solved analytically, our model is too stylized to be properly calibrated. Therefore, we build our numerical exercise on a parametrization intended to yield plausible implications with respect to both the literature and the data.

Since ours is a two-period OLG model, we take one period in the model to correspond to twenty years in the data.

We deduce the value of χ from Pensieroso and Sommacal (2019), who calibrate the growth rate of sectoral productivity to match economic growth in the U.S. and in a sample of West-European countries. This gives $\chi = 0.444$. We further set $\alpha = 0.27$, which corresponds to the 1688 rent share in the English national accounts according to Doepke (2004).[32]

For what concerns the parameters regulating fertility behavior, we take $\phi = 0.075$ from De la Croix and Doepke (2003) and set $\tau = 0.3$. The latter implies that in terms of consumption, a child costs 30% of an adult, in line with evidence reported by Vogl (2015). We also set $\beta = 0.8$ and $\gamma = 0.6$ to impose a reasonable behavior onto the resulting trajectory of fertility.[33]

[31]One may also ask how the initially stationary rate of left-handedness is reached, before the perturbation brought about by industrialization, and why it is not equal to 50%. Although this goes beyond the scope of our model, a possible explanation – based on a frequency-dependent selection mechanism leading to stable polymorphism in the long-run – is provided in Appendix F (see also Billiard, Faurie, and Raymond 2005).

[32]In the literature, the parameter α is typically calibrated making reference to the rent share of output. In our model, as in Lagerlöf (2006), workers in the traditional sector earn the average product of labor, so that rents are, so to speak, redistributed to the workers.

[33]The values for β and γ are chosen to set a reasonable upper bound for Malthusian fertility, and the limit behavior of post-Malthusian fertility. In practice, we proceed as follows. We compute the $\lim_{w_{ij,t}\to\infty} n_{ij,t}$ for both

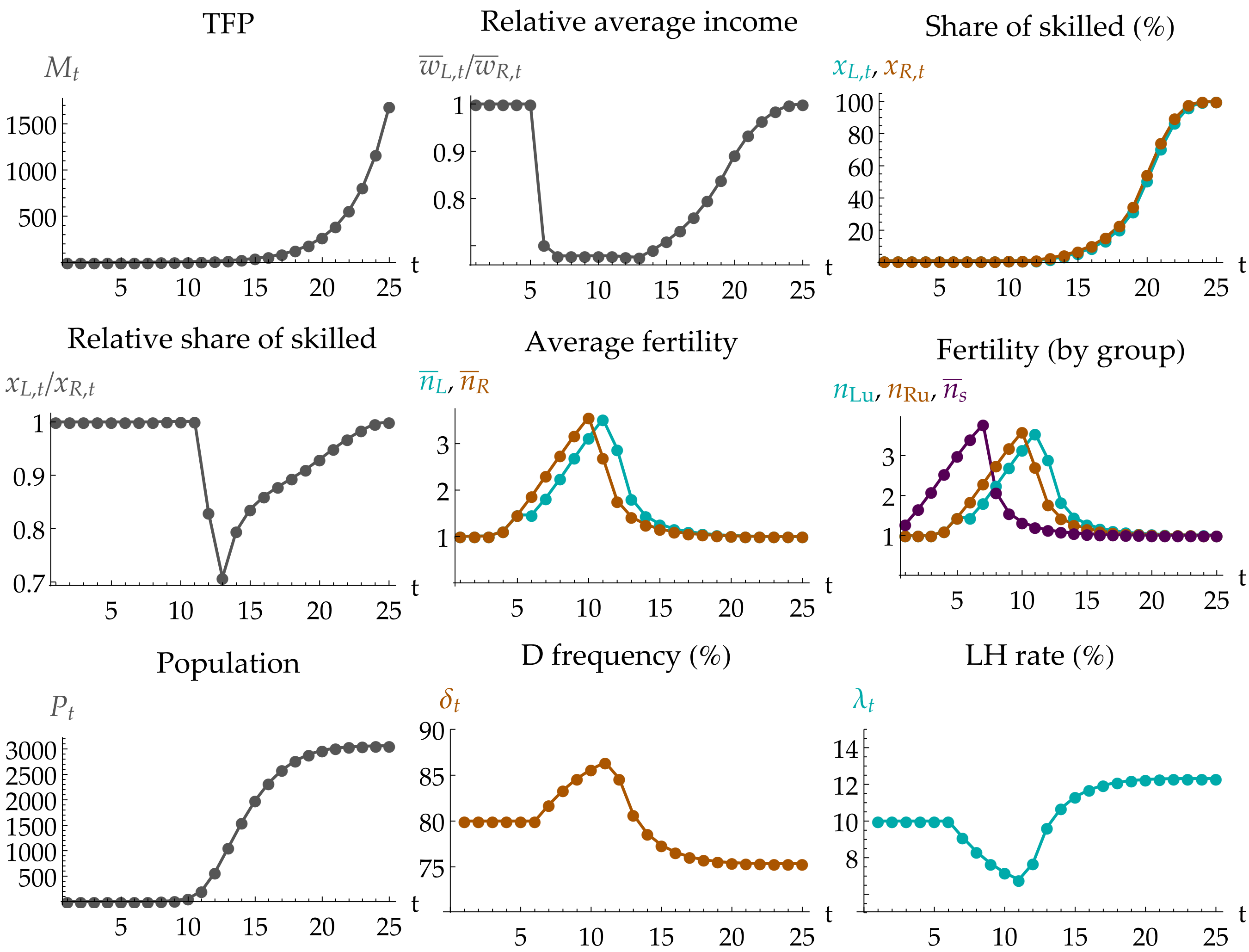

Figure 6: Simulations: the benchmark model

We further choose $\theta = 1$, $\xi = 0.01$, $\rho = 1.5$ and $h = 5.5$. Finally, following McManus (1985), we take $\omega = 0.5$.

As initial conditions, we set $M_0 = 0.25$ and $\delta_0 = 0.8$ (so that the initial prevalence of left-handedness is 10%). Initial population is normalized to 1, with $x_{L,0} = x_{R,0} = 0.01$. Note that parameters and initial conditions satisfy the condition expressed in Equation (32). Furthermore, they are compatible with Equations (46) and (47), thus warranting that our numerical simulations are consistent with the more general qualitative example described in Section 4.3.[34]

The simulated time paths of the key variables of our model are depicted in Figure 6.

the corner and interior solutions in Equation (8). We thus obtain $\overline{n} = \gamma/(\phi(1+\gamma))$ and $\underline{n} = (1-\beta)\gamma/((1+\gamma)\phi)$. $\overline{n}$ is a hypothetical upper bound to fertility under the Malthusian regime, should the demographic transition never occur. Relying on the literature, we estimate $\overline{n} = 5$, *i.e.* midway between Clark and Hamilton (2006) (according to whom the richest married testators in England between 1535 and 1628 left 4 to 5 surviving kids, so that $\overline{n} = 2.5$) and Pensieroso and Sommacal (2019) (who suggest $\overline{n} = 7.5$, by looking at children-ever-born for women aged more than 64 from the U.S. census data, 1900-1990). Given that $\phi = 0.075$, we thus obtain $\gamma = 0.6$. We set $\underline{n}$ equal to 1, so that population in the post-Malthusian regime is stationary in the long run. Given the chosen values of ϕ and γ, from $\underline{n} = 1$ we can residually determine $\beta = 0.8$, which lies in the range generally accepted by the literature.

[34]Our parametrization has an illustrative purpose and is not meant to gauge the quantitative importance of the genetic mechanism relative to alternative or complementary drivers of left-handedness.

We start by discussing production- and education-related variables. The first panel of Figure 6 reproduces the evolution of M, which grows at the exogenously constant rate χ. Technological progress induces structural transformation, which triggers the dynamics of the relative average income $\bar{w}_L/\bar{w}_R$, depicted in the second panel. At early stages of development (*i.e.* when the industrial sector is very small and employs only skilled workers) wages do not depend on handedness. A wage gap in favor of right-handers emerges as soon as unskilled workers enter the modern sector, in which the productivity of left-handers is lower. Eventually, the rise in human capital makes the average wage gap shrink because, although the productivity differential persists among unskilled workers, more and more individuals become skilled. The average income gap eventually vanishes when everybody is skilled. The third panel of Figure 6 shows the evolution of the proportion of skilled individuals in the population, which tends to one in the very long run. The fourth panel describes the dynamics of the relative share of skilled workers, x_L/x_R. It is constant and equal to one as long as nobody invests in education, becomes less than one as soon as right-handed (but not left-handed) unskilled workers start to invest in education, and finally increases and tends towards one thereafter. Overall, our simulation sees left-handers trail behind right-handers in terms of earnings and human capital, even in recent times. This is consistent with the empirical results of Goodman (2014). Our theoretical explanation, however, does not depend on an intrinsic cognitive disadvantage, but rather on the lower manual ability of left-handers, which makes them poorer, and thus less inclined to invest in education.

We now turn to fertility and population-related variables. Wage differentials translate into fertility differentials: $\bar{n}_L$ and $\bar{n}_R$ start equal, but follow different trajectories, as shown in the fifth panel of Figure 6 (the sixth panel further displays fertility by group). The advent of industry brings about a reproductive advantage in favor of more productive individuals, as long as the fertility behavior is Malthusian. With the demographic transition (that is, as soon as people start investing in education), the fertility differential is reversed (poorer people have more children), but subsequently declines and eventually disappears when everyone is skilled.

The pattern of differential fertility explains the trajectories of δ and λ represented in the last two panels of Figure 6. As discussed in Section 4.2, the behavior of λ is fully driven by fertility differentials among the unskilled. In particular, the rise of industry reveals the lower manual productivity of unskilled left-handers, thus causing a decline in the proportion of left-handed individuals in the population – until the demographic transition favors the recovery of left-handedness. The last panel shows how the simulated behavior of our model reproduces the historical trend of left-handedness documented by Figures 1 and 2: starting from 10%, it takes one hundred years for the left-handedness rate to reach its nadir, while forty years are sufficient to recover its previous level and forty more years to approach the new steady-state that, for the chosen parametrization, is around 12%. This suggests that our time-frame is appropriate, and wide enough for the genetic mechanism to drive the U-shaped evolution of left-handedness.[35]

Finally, the first panel of the third row of Figure 6 shows that our model is internally consistent, by depicting the S-shaped behavior of total population P implied by the demographic transition, which in our exercise requires two hundred years to be completed.

[35]In Galor and Michalopoulos (2012), the frequency of genetically determined traits can also significantly change over (relatively) short periods of time. In that paper, although the selection of entrepreneurial traits may have taken the whole Malthusian epoch, the recovery of risk-averse traits is a recent feature of mature economies.

5 Left-handedness and growth

So far, we have assumed that growth originates from exogenous innovations improving total factor productivity. We studied how economic development, through a genetic mechanism hinging on differential fertility, affects the evolution of left-handedness. One may argue, however, that the prevalence of left-handedness can in turn affect growth and economic development since, as discussed in Section 1, left-handed individuals seem to differ from right-handers along dimensions of economic relevance.

On the negative side, the literature suggests that left-handed people, on average, perform worse in cognitive tests (Johnston et al. 2009, Johnston et al. 2013), lag behind in terms of human capital and labor-market outcomes (Goodman 2014), and are disadvantaged in manual ability and tool use (Aggleton et al. 1994, Hanna et al. 1997, Adusumilli et al. 2004, Bhushan and Khan 2006). On the positive side, left-handers seem to be over-represented in the upper tail of the ability or earnings distribution (Benbow 1986, Halpern, Haviland, and Killian 1998, Ruebeck, Harrington, and Moffitt 2007, Faurie et al. 2008).[36] In particular, they have specific cognitive styles and personality traits that are conducive to innovation, such as divergent (creative) thinking (Newland 1981, Coren 1995), cognitive novelty-seeking (Goldberg et al. 1994), mental flexibility (Beratis et al. 2013), competitiveness (Hoffman and Gneezy 2010) and leadership skills (Faurie et al. 2008, Mukherjee 2017). This is not inconsistent with left-handers having lower scores in standard cognitive tests that, as pointed out by Denny and O'Sullivan (2007), are designed to measure convergent thinking. Finally, and because of their specific characteristics, left-handers contribute to the diversity of the workforce, which according to the literature, can play a key role in fostering economic growth (see for instance Ashraf and Galor (2013), Alesina, Harnoss, and Rapoport (2016), Ager and Brueckner (2018), Cook and Fletcher (2018), Docquier et al. (2020)).

Overall, there are reasons to believe that the effect of left-handedness on economic growth may be non-trivial and most likely non-monotonic, similar to the role of cultural diversity in Ashraf and Galor (2012), and to the prevalence of (genetically determined) entrepreneurial or novelty-seeking traits highlighted by Galor and Michalopoulos (2012) and Gören (2017).[37]

To account for this possibility in our model, we introduce a feedback effect of left-handedness on the growth rate of productivity in the modern sector:

$$\frac{\Delta M_{t+1}}{M_t} = a\lambda_t + \chi - b\left(1 - \frac{\bar{w}_{L,t}}{\bar{w}_{R,t}}\right)\lambda_t, \tag{48}$$

where $\Delta M_{t+1} \equiv M_{t+1} - M_t$, and $a \geq 0$, $b \geq 0$.

In this reduced-form description, the prevalence of left-handedness has a positive impact on productivity growth through the parameter a, due for instance to divergent thinking or the diversity effect, along with an *a priori* ambiguous effect through b, related to the wage differential between left- and right-handers. Since in our model $\bar{w}_{L,t}/\bar{w}_{R,t} \leq 1$, the latter effect is non-positive and can be explained by multiple factors that hamper the productivity of left-handers

[36] In Appendix G, we use the NLSY data to show that the distribution of wages for individuals with more than 16 years of education favors left-handers.

[37] A further similarity with Galor and Michalopoulos (2012) is that economic development implies a non-monotonic evolution of the trait under study over the course of human history.

(intrinsic disadvantage, use of tools designed for right-handers, etc.), and are reflected in the relative wage. The productivity loss imposed on the economy depends on both the share of left-handers (λ_t, extensive margin) and the severity of their disadvantage that we measure through the average wage gap ($1 - \bar{w}_{L,t}/\bar{w}_{R,t}$, intensive margin).[38] Note also that the accumulation of human capital can have an indirect effect on productivity growth, as average wages depend on the share of skilled individuals among left- and right-handers, *i.e.* x_L and x_R.

In this framework, the overall effect of left-handedness on technological progress depends on the stage of development – as $\partial(\Delta M_{t+1}/M_t)/\partial\lambda_t > 0$ if $\bar{w}_{L,t}/\bar{w}_{R,t} > 1 - a/b$. A possible interpretation is the following: at early stages of industrialization, the average wage gap is large, as left-handers are mostly unskilled and suffer from a productivity deficit in manufacturing. This is likely to translate into a negative net impact on growth, which may also be related to some disruptive effect of left-handers on production. Later on, as human capital increases, the average wage gap shrinks and the detrimental effect of left-handers on productivity (the "b" term in Equation (48)) is more than compensated by their beneficial effect (the "a" part). When this happens, left-handed workers may positively contribute to the TFP growth through creativity and divergent thinking – which are arguably more important when production is intensive in human capital. Our description of the impact of left-handedness on productivity growth is reminiscent of Ashraf and Galor (2012, 2013), according to whom diversity may hamper an economy's ability to exploit efficiently the existing technological frontier, but contributes to push the frontier further.[39]

Note that this extension of our model emphasizes that left-handedness influences economic development through its aggregate prevalence (as implied by Equation (48)), while in Section 3 development affects the left-handedness rate through individual differences in productivity.

We resort to simulations to compare the dynamics of the extended model with endogenous growth to that of the benchmark model, described in Section 4.4. To do so, we set the additional parameters $a = 0.5$ and $b = 5$, so that $1 - a/b = 0.9$. This means that the effect of left-handedness on productivity is positive if the wage of left-handers is at least 90% of that of the right-handers, and negative otherwise.

By comparison with Figure 6, Figure 7 shows that the extended model allowing for a feedback effect of left-handedness on growth has the same qualitative behavior as the benchmark model with fully exogenous growth. In particular, structural change triggers fertility differentials between left- and right-handers, which explain the trajectory of λ.

Handedness and growth, however, co-evolve along the development path in a non-trivial fashion. In particular, it appears that (i) a higher left-handedness rate may be instrumental in accelerating the industrial take-off, (ii) in intermediate stages of development, the productivity gap between right- and left-handers and/or the implied drop in the prevalence of left-handedness

[38]This formulation may also reflect the disruption or lack of coordination induced by the presence of left-handers in production, which can hamper the learning-by-doing process.

[39]By replacing $a\lambda_t$ with $a\lambda_t(1-\lambda_t)$ in Equation (48), we could bring our modelization even closer to Ashraf and Galor (2012, 2013), and identify a growth-maximizing left-handedness rate. By replacing $a\lambda_t$ with $ax_{L,t}\lambda_t$, one may instead introduce the realistic feature that only educated left-handers contribute positively to technological progress. None of these alternatives, however, would change the main implications of our analysis, namely that the correlation between left-handedness and growth changes across stages of development.

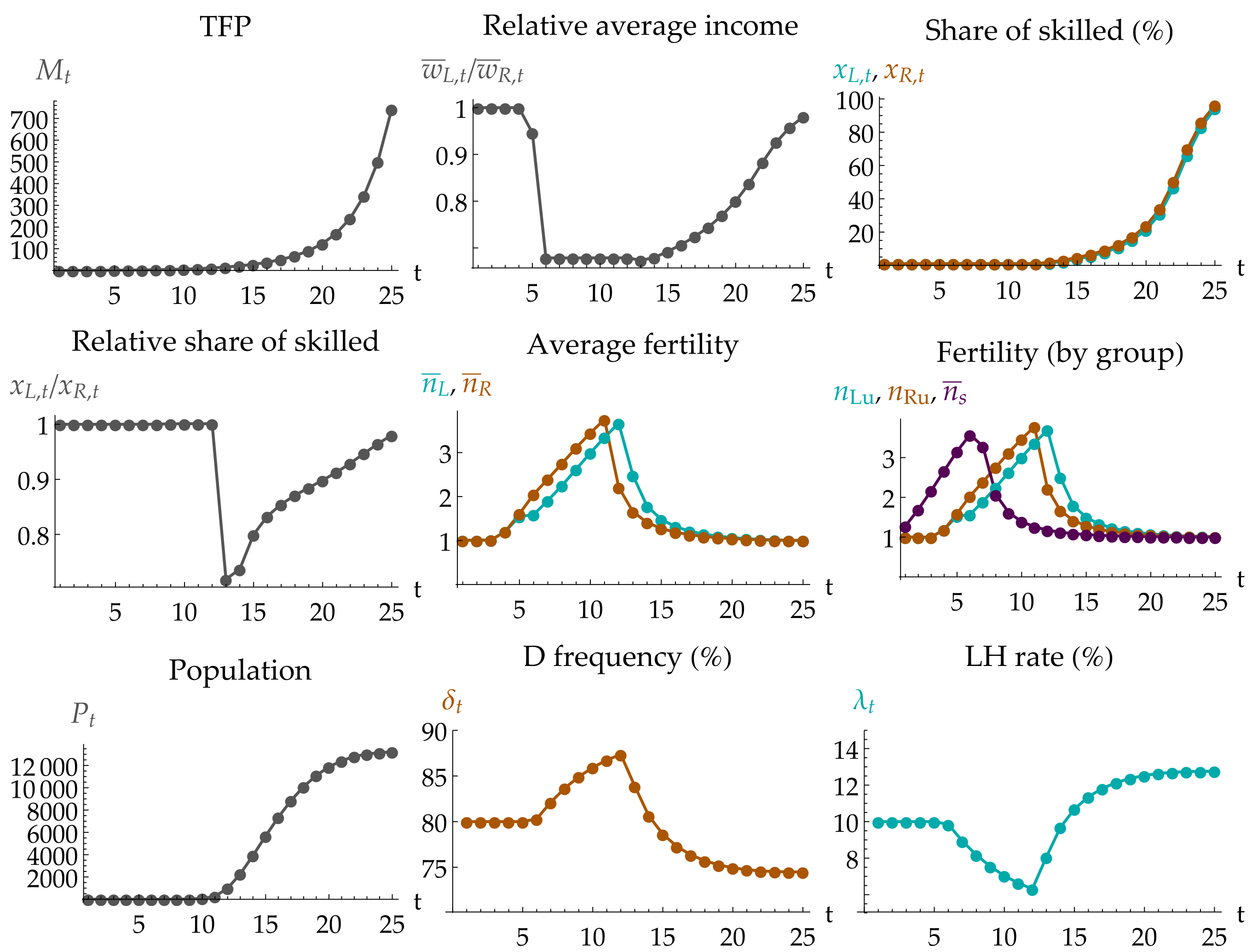

Figure 7: Simulations: endogenous growth

slow growth down, and (iii) the rise in human capital eventually restores a net positive contribution of left-handedness to growth.

This is visible from Figure 8, where we compare the evolution of selected variables in the two versions of our model. In the endogenous-growth model, the growth rate of GDP in the long-run is higher than in the exogenous-growth model, due to the positive diversity-effect of left-handedness – whose steady-state value is higher in the new version of the model. Growth is instead slower in the model with feedback effects during the industrial take-off, when the presence of left-handers is overall disruptive to production.[40] The feedback effect from left-handedness to growth also accentuates the dynamics of λ, which declines more substantially during the industrial take-off, but recovers faster and reaches a higher stationary value when

[40] More precisely, the growth rate of GDP per capita in both models increases substantially as structural change emerges. However, in early periods, the low productivity of left-handers in the modern sector hampers growth, and delays the accumulation of human capital, while the dynamics of the population under the Malthusian regime takes away some of the benefits of the additional growth. As soon as the demographic transition unfolds, the left-handedness rate stops decreasing, while the disruptive effect of left-handers on productivity becomes less and less important, since human capital accumulates and the average wage gap shrinks. The growth rate of GDP per capita increases in both models. When the share of skilled agents in the population is sufficiently high, the contribution of human capital accumulation to the growth rate of GDP becomes less and less important, and the latter converges asymptotically to its stationary value.

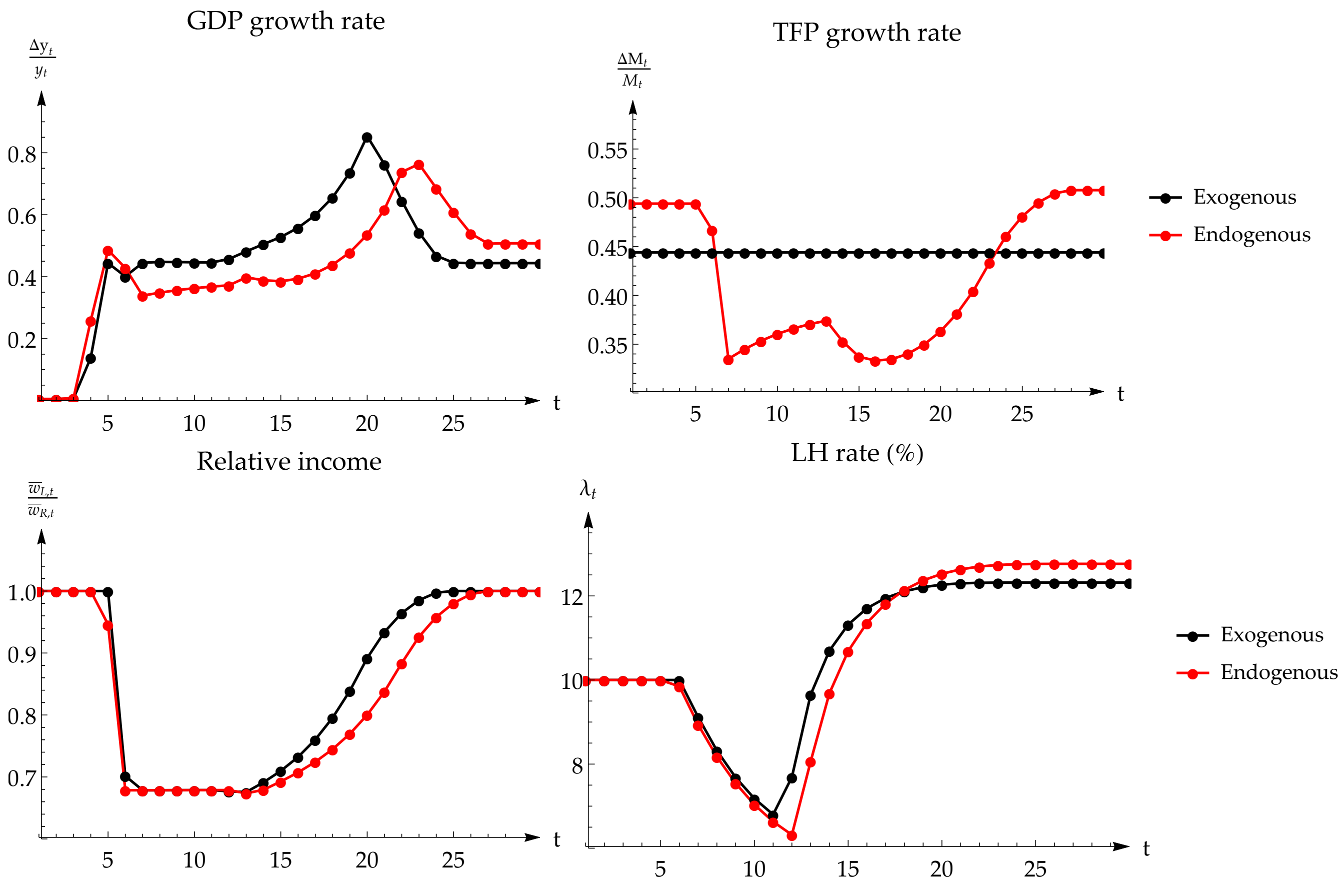

Figure 8: Endogenous *vs* exogenous growth

human capital becomes more important than manual ability.

As a further step in our theoretical appraisal of the handedness-growth relationship, in Figure 9 we plot the co-movement of the left-handedness rate and GDP per capita resulting from the simulations of the benchmark and extended models. For ease of presentation, Figure 9 only considers the simulated values of our variables of interest from $t = 12$, corresponding to the nadir of left-handedness. From that point on, the key endogenous variables evolve monotonically (thus simplifying the interpretation of the results), and the correlations obtained from our computational exercise become more immediately comparable with the trend observed in the NGSS data (which mostly cover the increasing part of the left-handedness trajectory).

Two features are noteworthy. First, both models imply a positive correlation between the prevalence of left-handedness and the *level* of GDP per capita. Such a correlation can also be found in the data: in Appendix G (Figure G.2) we plot the left-handedness rate, measured for each U.S. state and by decade (between 1910 and 1980), against real income, and observe an increasing pattern that matches the theoretical relationship displayed in Figure 9. Second, the two models exhibit different behaviors with respect to the correlation between the prevalence of left-handedness and the *growth rate* of GDP per capita. This correlation is positive in the exogenous growth setting, but non-monotonic when we consider a feedback effect of left-handedness on growth. The sign of the correlation between λ and the growth rate of GDP per capita may then change over time. The empirical investigation developed in Section 6.2 is consistent with such non-monotonic correlation, and provides evidence of a possible impact of left-handedness

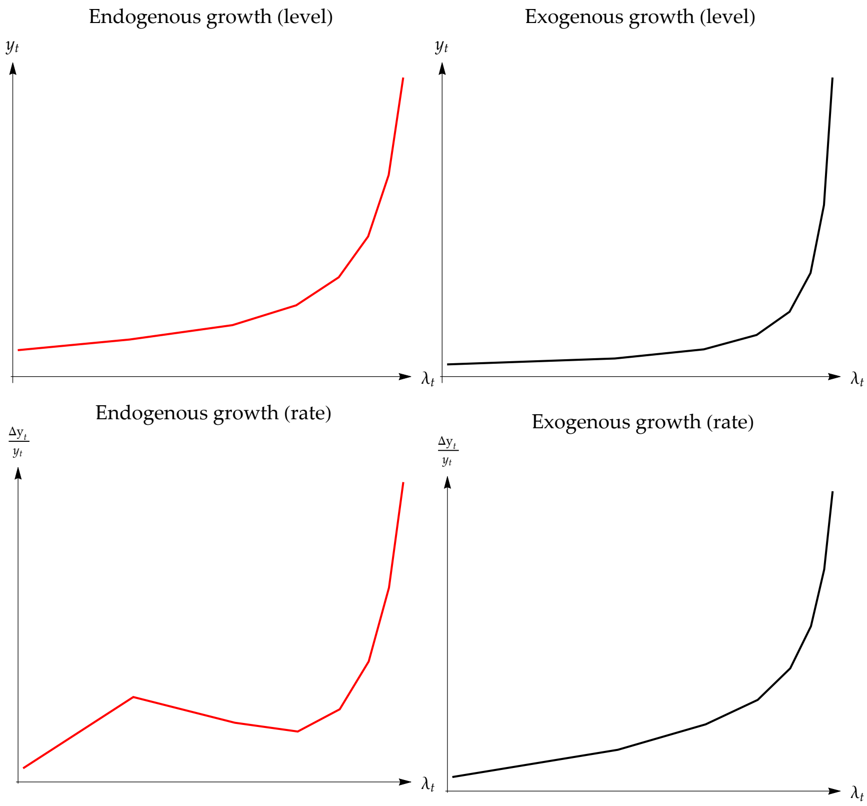

Figure 9: Co-movement of left-handedness and GDP per capita

on economic growth.

6 Empirical evidence

In this Section, we investigate whether empirical evidence lends support to our theoretical analysis, focusing on two distinct issues that can be explored based on available data. First, we discuss the empirical plausibility of the differential-fertility mechanism through which, in our model, economic development drives the evolution of handedness. Second, we investigate the possibility that the prevalence of left-handedness has a feedback effect on economic development, and that the sign of the effect varies across different stages of development – as suggested by the endogenous-growth extension of our model. By doing so, we both provide empirical evidence that is consistent with the implications of our theory, and contribute to the literature on the consequences of diversity for growth.

6.1 The differential-fertility mechanism

In our model, the evolution of left-handedness rates stems from a time-varying fertility differential. When the modern sector emerges, the average wage gap in favor of right-handers gives them a reproductive advantage, which drives the decline of left-handedness. This trend is reversed as soon as unskilled individuals start investing in human capital, and the lower income of left-handers translates into higher average fertility, which explains the recovery of left-handedness. Eventually, the erosion of the average wage gap drives the convergence of fertility between right- and left-handers, and the prevalence of left-handedness stabilizes.

To be consistent with the timing described in Section 2, we should observe in Western countries an average fertility gap in favor of right-handed people towards the beginning of the 20th century, that is for individuals born at the end of the 19th century, and conversely a fertility differential in favor of left-handed people for cohorts born at the beginning of the 20th century.

The data from SHARE (the Survey of Health, Ageing and Retirement in Europe) are useful to describe fertility patterns across handedness and over time. The first wave of this survey (Börsch-Supan 2019a) dates back to 2004 and targets a representative sample of the population aged over 50. It provides information on the dominant hand and the number of living children of surveyed individuals, while the third wave, SHARELife (Börsch-Supan 2019b), reports data on deceased children. Combining the first and third waves allows us to reconstruct total fertility. Overall, the sample for which we have information on both fertility and handedness consists of 18,868 individuals from 12 countries, born between 1904 and 1956.[41] Although they do not provide information on the fertility of cohorts born in the 19th century, the SHARE data are helpful to investigate whether left-handers born after 1900 have a higher average fertility than right-handers, which would be consistent with the recovery of left-handedness rate observed over the first half of the 20th century.

Panel (a) of Table 2 displays the results of the estimation, for five subsamples defined over successive birth cohorts, of the following equation:

$$TotalFertility_{i,c} = \alpha + \beta LH_{i,c} + \gamma X_{i,c} + \delta_c + \epsilon_{i,c}, \tag{49}$$

where i and c index individuals and countries, respectively. $TotalFertility_{i,c}$ is the total number of children ever born from individual i living in country c, $LH_{i,c}$ is the dummy for left-handedness, $X_{i,c}$ denotes the year of birth, and δ_c is a set of country fixed effects.

Compatible with the model, the results point to a fertility differential in favor of left-handed respondents for the cohort born before 1923, while younger cohorts do not exhibit any significant fertility differential by handedness.[42]

In panel (b), we additionally control for a *Couple* dummy taking the value one for individuals who have been in couple at one point in their life (and zero otherwise). The point estimate in column (1) suggests that left-handed respondents born before 1923 have on average nearly 0.7 children more than right-handed respondents of the same cohort, while there is still no detectable fertility differential for cohorts born from 1923 on.

Although purely descriptive, these results support the idea that left-handers were characterized by a higher average fertility, which translated into a growing left-handedness rate, approximately until the 1940s – which is consistent with the timing observed in Figures 1 and 2 – and that fertility rates subsequently converged. Note also that, although not statistically significant, the difference between the coefficients of interest of panels (a) and (b) in column (1) is compatible with the stigmatization of left-handers on the marriage market, as a larger fertility differential emerges once marital status is controlled for. This possibility that left-handedness also affects

[41] The countries in the sample are: Austria, Belgium, Denmark, France, Germany, Greece, Israel, Italy, the Netherlands, Spain, Sweden, and Switzerland.

[42] This pattern is robust to regressions without controls, and to alternative cutoff years. As shown in Appendix H, setting the cutoff to 1922 provides the most precise estimate.

Table 2: Completed fertility by cohort.

	(1)	(2)	(3)	(4)	(5)
Birth year	*≤1922*	*1923 – 1932*	*1933 – 1942*	*1943 – 1952*	*≥1953*
			Panel (a)		
LH	0.488**	-0.153	-0.158	-0.152	-0.312
	(0.179)	(0.502)	(0.159)	(0.131)	(0.207)
Birth year	✓	✓	✓	✓	✓
Country dummies	✓	✓	✓	✓	✓
Observations	1,196	3,623	5,479	7,089	1,481
R-squared	0.033	0.015	0.030	0.031	0.043
			Panel (b)		
LH	0.698***	-0.0516	-0.180	-0.196	-0.163
	(0.151)	(0.421)	(0.155)	(0.144)	(0.202)
Couple (dummy)	3.576***	3.515***	3.201***	2.863***	2.672***
	(0.197)	(0.194)	(0.279)	(0.190)	(0.122)
Birth year	✓	✓	✓	✓	✓
Country dummies	✓	✓	✓	✓	✓
Observations	1,196	3,623	5,479	7,089	1,481
R-squared	0.148	0.108	0.146	0.171	0.163

OLS estimations using the SHARE survey weights. Dependent variable is total fertility. Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

the extensive margin of fertility is theoretically explored in Appendix B.2.

As stated above, we cannot rely on the SHARE dataset to study the fertility behavior of earlier cohorts. However, traces of a fertility differential in favor of right-handed people for these cohorts can be found in the previous literature.

A series of family studies, concerned with the transmission of left-handedness across generations, provide insights on fertility by handedness in the 19th century. In particular, five papers report data on the handedness of respondents and their parents, as well as on the respondents' number of siblings, which allow us to reconstruct the (completed) fertility of the respondents' parents. The results are summarized in Table 3, which displays the average fertility of couples (of parents) where both spouses are right-handed and where at least one spouse is left-handed (columns (2)-(3)). Consistent with our fertility-differential mechanism, the figures suggest that, for the earliest cohorts, fertility was higher among right-handers (in particular, in Chamberlain 1928 and Rife 1940). In line with the evolution of left-handedness rate over time displayed in Figures 1 and 2, as well as the results from the SHARE data presented in Table 2, the reproductive advantage of right-handers seems to shrink, and to eventually reverse, for cohorts born at the beginning of the 20th century.

Taken together, our results from the SHARE data and the evidence from family studies lend support to the fertility-differential mechanism of our model, according to which left-handers have been successively characterized by a fertility deficit (19th century) and surplus (first half of the 20th century), before converging to the same fertility as right-handers.

Table 3: Fertility by parental handedness in family studies.

	(1) Country, parents' birth cohort[a]	(2) Both RH	(3) At least one LH	(4) Nb of families
Chamberlain (1928)	U.S., 1875–85	3.56	3.32	2201
Rife (1940)	U.S., 1882–92	3.21	2.76	687
Annett (1973)	U.K., 1912–25	2.10	2.05	3644
Ashton (1982)	U.S., 1912–38	1.61	1.75	1806
Risch and Pringle (1985)	U.S., 1925–35	2.73	2.71	1564

[a]The papers used for this table typically do not specify the birth year of parents, but give more details about their children. We assign parents to a given birth cohort based on the age of their children, by assuming that parents are, on average, between 25 and 35 years older than their offspring. Although very crude, this range is consistent with available information on the age at marriage since 1890 in the U.S. (as the U.S. census data show, see `https://www.census.gov/data/tables/time-series/demo/families/marital.html`) and U.K. (as the Atlas of Victorian and Edwardian population data show, see `https://www.populationspast.org/about/`). It is also in line with Jones, Schoonbroodt, and Tertilt (2010), who assume the "average birth" to occur at age 27, given that – according to U.S. Census data for this period – the average age at first marriages for women ranges between 20 and 25.

6.2 The feedback effect of left-handedness on growth

As discussed in Section 5, there are reasons to believe that the prevalence of left-handedness matters for growth. In particular, there is evidence that left-handers are both less productive on average and over-represented in the upper-tail of the abilities distribution, and that they possess specific traits that may enhance innovation. Furthermore, they contribute to the diversity of the workforce, which the literature has shown to have a non-trivial effect on growth.

One implication of our theory is that, in the presence of a feedback effect of left-handers on productivity, we expect a non-monotonic relationship between the left-handedness rate and economic growth. In particular, when economic development drives the recovery and stabilization of left-handedness rates – a phase that roughly corresponds to the 20th century in the Western World – a positive correlation between left-handedness and growth should gradually emerge. As long as the share of left-handers is relatively low, the negative impact of left-handedness on growth should prevail, but for higher rates of left-handedness, the growth-enhancing effect of left-handers, amplified by the rise of human capital, should eventually restore a positive correlation. In accordance with our theory, a change in the sign of the empirical link between left-handedness and growth could thus be interpreted as evidence of a possible impact of left-handedness on productivity.

We empirically investigate the relationship between left-handedness and growth by estimating growth equations at the U.S.-state level. We exploit two main data sources to build a panel where each point is a state–decade pair. First, based on the 1.2 million U.S. residents from the NGSS (described in Section 2), we compute the prevalence of left-handedness among respondents aged 15 to 60 in each state in 1960, 1970, 1980 and 1990.[43] We thus rely on the age structure of the NGSS sample to infer the evolution of left-handedness rate over time. Second, we use data on state-level output per worker, provided by Turner et al. (2006), to compute the growth rate observed in each state–decade, over 1960–2000. In light of our theory, output per worker seems to be the most appropriate variable for measuring economic performance (rather than, for instance, income per capita, which is likely to be affected by other factors such as the returns on assets).[44]

Before moving on, let us briefly discuss two possible shortcomings related to the use of the NGSS dataset for our empirical exercise. First, as already stated in Section 2, respondents might be self-selected over specific characteristics, which could bias our measure of the cohort- and state-specific prevalence of left-handedness. Since the selection issue is particularly relevant for groups with a small number of observations, we focus on the cohorts of 1960, 1970, 1980 and 1990 (which respectively gather 603,790, 917,042, 1,002,554 and 910,252 respondents), and exclude data before 1960. Second, we observe the respondents' state of residence at the time of the survey, so that our estimates of state-level left-handedness rates are based on the implicit assumption that respondents were living in 1986 in the same state where they worked when aged 15 to 60. To mitigate the risk that migration biases our measurement of left-handedness, we start our analysis by focusing only on the latest cohort of our data, *i.e.* individuals born between 1930 and 1975, which we rely on to compute the prevalence of left-handedness in 1990.[45]

We thus start by estimating by OLS the following growth equation:

$$\ln y_{s,2000} - \ln y_{s,1990} = \gamma \ln y_{s,1990} + \alpha LH_{s,1990} + \beta \ln Pop_{s,1990} + \epsilon_s, \tag{50}$$

where s indexes states. The output per worker in state s at time t is thus denoted $y_{s,t}$, and the dependent variable measures growth between 1990 and 2000. On the right-hand side, we control for the initial output level (in logarithm), the prevalence of left-handedness, and the size of population (in logarithm), all measured in 1990.

We then exploit the time dimension of our data by also considering the earlier cohorts of 1960, 1970 and 1980. Specifically, we estimate

$$\ln y_{s,t} - \ln y_{s,t-10} = \gamma \ln y_{s,t-10} + \alpha LH_{s,t-10} + \beta \ln Pop_{s,t-10} + u_s + v_t + \epsilon_{s,t}, \tag{51}$$

where u_s and v_t respectively capture state fixed effects and period dummies, allowing us to control for state-level time-invariant unobserved characteristics and aggregate time trends.

The results of the estimations of Equations (50) and (51) are displayed in columns (1) and (2) of Table 4. In the cross-sectional setting – column (1) – the prevalence of left-handedness in 1990 appears to be positively related to growth from 1990 to 2000. In particular, a one point increase in the percentage of left-handers is associated, on average, with a 2.9% faster growth

[43]In Appendix I, we show that our results are robust to alternative definitions of the age group used to compute the prevalence of left-handedness.

[44]Output per worker is also used by other papers concerned, like ours, with the growth effects of specific factors – such as financial development and liberalization (Henry 2003, Jerzmanowski 2017) and health (Bloom, Canning, and Sevilla 2004).

[45]This concern is further assuaged when we consider shorter age brackets, as in Table I.1 of Appendix I.

Table 4: Left-handedness and output growth – I.

Dependent variable: Δln*(real output per worker)*	(1) OLS, 1990-2000	(2)	(3) FE	(4)
Initial real output per worker (ln)	-0.0703	-0.525***	-0.517***	-0.629***
	(0.101)	(0.0708)	(0.0716)	(0.0849)
LH (%)	0.0289***	-0.00400	-0.0103	-0.336**
	(0.0102)	(0.0305)	(0.0293)	(0.130)
LH (%) $\times$ Post-1980 (dummy)			0.0192**	
			(0.00832)	
LH (%) $\times$ Schooling (ln)				0.133**
				(0.0530)
Population (ln)	✓	✓	✓	✓
State fixed-effects		✓	✓	✓
Period dummies		✓	✓	✓
Post-1980 (dummy)			✓	
Schooling (ln)				✓
Observations	51	204	204	204
Number of states	51	51	51	51
R-squared	0.269	0.767	0.778	0.787

Robust standard errors clustered at the state level in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. *LH (%)* is the prevalence of left-handedness among the population aged 15 to 60, measured in the first year of each decade. *Population* (ln*)* and *Schooling* (ln*)* are also measured in the first year of the decade, the latter variable being equal to the average number of years of schooling among the 15-60.

(thus increasing the state-level average growth over the period from 17.4% to 17.9%). It also means that, on average, a one standard deviation increase in the 1990 left-handedness rate is associated with a 0.4 standard deviation increase in the 1990-2000 growth rate, a result which is somehow comparable to other findings from the literature on diversity and growth.[46] In the panel setting, where time trends and time-invariant heterogeneity across states are controlled for – column (2) – the correlation between left-handedness and growth becomes close to zero. This might be driven by the lower quality of the data for earlier cohorts. However, it may also reveal that left-handedness and growth are spuriously correlated in cross-section, because of confounding factors captured by the fixed effects in the panel setting. Or it may suggest that the correlation between handedness and growth evolves over time.

To investigate whether the latter interpretation, which is consistent with our endogenous-growth model, is empirically plausible, we interact the left-handedness rate with a dummy variable taking the value one for the two most recent periods (from 1980 to 2000) and zero for the two others (from 1960 to 1980). The results of this estimation, which still controls for state and period fixed effects, are displayed in column (3): they point to a significant positive relationship between left-handedness and growth from the 1980s, while no such relation emerges over the previous period. This is compatible with the theoretical prediction of a positive asso-

[46] Ager and Brueckner (2018) find that a one s.d. increase in immigrants' genetic diversity in 1870 translates into a 20% higher growth rate over the 1870-1920 period, which corresponds to around 0.2 s.d. and to +0.37% per annum. In our case, a one s.d. increase in the 1990 left-handedness rate is associated with a 2.6% higher growth rate over the following decade, which corresponds to around 0.4 s.d. and to +0.26% per annum.

ciation between left-handedness and economic growth emerging only in recent times, *i.e.* when the level of development is sufficiently high. To check that the handedness-growth link changes with the level of economic performance, in column (4) we replace the *Post-1980* dummy by a continuous proxy for development, namely the state-level average number of years of schooling among people aged 15 to 60, computed from the U.S. census data and measured at the beginning of each decade (Ruggles et al. 2021). Consistent with our theory, the relationship between left-handedness and growth appears to depend upon the level of development, as proxied by education. Specifically, while left-handedness seems to be negatively related to growth when education is low, the correlation between the share of left-handers and growth becomes positive once the average years of schooling exceeds, approximately, 11.5 years – a threshold that the U.S. on average, as well as most of the states, had reached by the end of the 1970s.[47]

These findings confirm the intuition that for the contribution of left-handed people to growth to materialize, the economy must reach a certain level of human capital and development. This is in turn consistent with the idea that the pro-growth effect of left-handers is related to their intellectual ability, while they are more likely to hinder growth in unskilled economies, where manual ability (and possibly conformism) are key determinants of economic success.

The benchmark results in Table 4 may suffer from an endogeneity bias due to the fact that – as explained in Sections 3 and 4 – structural change, itself related to economic growth, is expected to affect the prevalence of left-handedness. We then perform two further exercises. Without claiming that they allow us to fully circumvent the endogeneity problem inherent to the left-handedness-growth relationship, we argue that – taken together– they provide suggestive evidence in support of our theoretical predictions.

First, we re-estimate Equation (50) instrumenting the share of left-handers in the population aged 15 to 60 with the share of left-handers in the previous generation (aged more than 60).[48] By doing so, we essentially use the genetic determinant of lateralization as a source of variation in left-handedness. Since the prevalence of left-handedness in the previous generation (say, parents) not only influences left-handedness in the current generation (children), but is also correlated with contemporary and future economic performance, we additionally control for the lagged growth rate when implementing this IV strategy (thus mitigating the concern that the instrument violates the exclusion restriction). The second-stage results are displayed in column (1) of Table 5.[49] Consistent with the OLS estimation (column (1) of Table 4), they highlight a positive link between the prevalence of left-handedness in 1990 and economic growth over the 1990-2000 period. The point estimate suggests that a one percentage point increase in the share of left-handers is associated, on average, with a 3.8% faster growth.

An instrument like this cannot be used to exploit the time depth of the reconstructed panel, because of the lack of reliable information about the earliest cohorts. Therefore, we complement our analysis with a generalized method-of-moments specification, as a robustness check. The use of a GMM estimator to address endogeneity issues is frequent in the empirical growth lit-

[47]In 1980, 10 states still exhibited an average level of education lower than the threshold (Alabama, Arkansas, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, West Virginia).

[48]Using alternative age groups to measure left-handedness yields similar results.

[49]Left-handedness prevalence in the previous generation is a good predictor of left-handedness prevalence in the current one. Specifically, the first-stage coefficient of interest is equal to 0.767, with a p-value lower than 1% and, as shown in Table 5, the first-stage F-test is well above the rule-of-thumb critical value of 10.

Table 5: Left-handedness and output growth – II.

Dependent variable: Δln*(real output per worker)*	(1) 2SLS, 1990-2000	(2) 	(3) sGMM	(4)
Initial real output per worker (ln)	-0.0835	-0.115**	-0.227***	-0.185***
	(0.0816)	(0.0460)	(0.0464)	(0.0444)
LH (%)	0.0376***	0.0169**	0.00162	-0.0674**
	(0.00937)	(0.00754)	(0.00743)	(0.0268)
LH (%) $\times$ Post-1980 (dummy)			0.0267***	
			(0.00958)	
LH (%) $\times$ Schooling (ln)				0.0318***
				(0.00978)
Population (ln)	✓	✓	✓	✓
State fixed-effects		✓	✓	✓
Period dummies		✓	✓	✓
Lagged dependent	✓			
Post-1980 (dummy)			✓	
Schooling (ln)				✓
Observations	51	204	204	204
Number of states	51	51	51	51
R-squared	0.344			
First stage F-test	43.01			
Number of instruments		49	50	55
AR1 test (p-val)		0.001	0.000	0.001
AR2 test (p-val)		0.166	0.352	0.166
Hansen test of joint instrument validity (p-val)		0.261	0.317	0.430
Difference-in-Hansen test of instrument subsets (p-val):				
Instruments for levels		0.267	0.229	0.486
Instruments for initial output		0.731	0.703	0.959

Col (1): robust standard errors clustered at the state level in parentheses. Col (2)-(4): Windmeijer-corrected standard errors clustered at the state level in parentheses. *** p<0.01, ** p<0.05, * p<0.1.
LH (%) is the prevalence of left-handedness among the population aged 15 to 60, measured in the first year of each decade. *Population (*ln*)* and *Schooling (*ln*)* are also measured in the first year of the decade, the latter variable being equal to the average number of years of schooling among the 15-60.
In columns (2) and (3), we use the second to fifth lags (both in differences and in levels) as instruments. In column (4), we use the second to fourth lags.

erature, as can be seen from DeJong and Ripoll (2006), Hausmann, Hwang, and Rodrik (2007), Jerzmanowski (2017), Ager and Brueckner (2018), or Berg et al. (2018), among others.[50] In particular, we resort to the system GMM estimator derived by Blundell and Bond (1998), which estimates simultaneously one equation in differences (using appropriate lagged values of the right-hand side variables as instruments – see Arellano and Bond 1991), and one equation in levels (using lagged first differences as instruments). System GMM allows us to exploit both time-series and cross-sectional variation in the data, which is adequate in our case, given the high within-state persistence of left-handedness.

The results are shown in columns (2) to (4) of Table 5, the three specifications being symmetric to those in Table 4.[51] The findings are very much in line with the fixed-effects estimates. In

[50] All these papers take advantage of panel data to study the empirical relevance of possible growth-enhancing factors, and use growth regressions very similar to our Equation (51).

[51] In columns (2) and (3), we use the second to fifth lags (both in differences and in levels) as instruments. In column (4), we use the second to fourth lags. Using the second to fifth lags yields very similar results but generates 63

particular, a positive and significant link between left-handedness and growth emerges from the 1980s (column (3)), and if the average level of education is sufficiently high (column (4)).

Our empirical results are compatible with the existence of a non-monotonic correlation between left-handedness prevalence and economic growth. In Appendix J, we further investigate whether – as implied by our theory in Section 5 – left-handedness may relate to the pace of technological progress. As explained in the Appendix, our results suggest that left-handedness might indeed affect economic growth through the productivity channel, namely by pushing the technological frontier further.

While it does not provide full-fledged causal identification, the empirical exercise developed above lends credence to the results of our theory, by unveiling correlations that conform with those generated by the model. In particular, our regression results support the idea that the prevalence of left-handedness may concur to determine the pace of economic growth.

7 Conclusion

In this paper, we explore the relationship between economic development and human handedness, a trait that is governed by evolutionary forces and contributes to human diversity.

We provide an explanation for the non-monotonic evolution of left-handedness in the Western World over the last few centuries. The key mechanism, supported by empirical evidence, hinges on the differential impact of technological change on the productivity – and thereby the reproductive success – of left- *vs* right-handers. An interesting implication of our analysis is that market forces do not necessarily foster or preserve, but can also threaten diversity. In particular, during early stages of industrialization left-handers had a reproductive disadvantage and their prevalence decreased. But for the demographic transition, left-handedness would have been driven to extinction – a Darwinian tale of the "survival of the fittest". The emergence of human capital, instead, rescued left-handedness, and created a suitable environment for a positive contribution of left-handedness to productivity growth.

Consistent with the view that left-handers possess distinctive traits (divergent thinking, etc.) that enhance innovation, we also find empirically that the prevalence of left-handedness may be beneficial for economic growth. This positive effect emerges in recent times, characterized by a greater importance of human capital in production. This echoes the findings of the literature on diversity, which highlights how the relationship between diversity and economic performance changes across different stages of development.

Finally, one may wonder whether geographical differences in left-handedness may contribute to explain – along with other deep-rooted factors – the pattern of comparative development across countries. By providing a first assessment of the link between handedness and growth, our analysis sets the stage for future research on this topic.

instruments, which is relatively high given the standard rule of thumb that the number of instruments should not exceed the number of cross-sectional units (Roodman 2009). In all specifications, we apply the two-step procedure which corrects for a nontrivial covariance matrix, the small-sample adjustments, and the Windmeijer (2005) correction of downward-biased standard errors in finite samples. The usual GMM validity tests, such as the Hansen test for the joint validity of the instruments and the Arellano-Bond first- and second-order residual autocorrelation tests, are satisfactory. In addition, the difference-in-Hansen tests for the validity of instrument subsets confirm that the stationarity restrictions on initial conditions required for the validity of sGMM are satisfied (see Roodman 2009).

References

Adusumilli, Prasad S, Christian Kell, Jae-Hyung Chang, Scott Tuorto, and I Michael Leitman. 2004. "Left-handed surgeons: are they left out?" *Current Surgery* 61 (6): 587–591.

Ager, Philipp, and Markus Brueckner. 2018. "Immigrants' Genes: Genetic Diversity and Economic Development in the US." *Economic Inquiry* 56 (2): 1149–1164.

Aggleton, John P, J Martin Bland, Robert W Kentridge, and Nicholas J Neave. 1994. "Handedness and longevity: archival study of cricketers." *British Medical Journal* 309 (6970): 1681.

Aggleton, John P, Robert W Kentridge, and Nicholas J Neave. 1993. "Evidence for longevity differences between left handed and right handed men: an archival study of cricketers." *Journal of Epidemiology and Community Health* 47 (3): 206–209.

Alesina, Alberto, Johann Harnoss, and Hillel Rapoport. 2016. "Birthplace diversity and economic prosperity." *Journal of Economic Growth* 21 (2): 101–138.

Alesina, Alberto, and Eliana La Ferrara. 2005. "Ethnic diversity and economic performance." *Journal of Economic Literature* 43 (3): 762–800.

Alger, Ingela, and Jörgen W Weibull. 2010. "Kinship, incentives, and evolution." *American Economic Review* 100 (4): 1725–1758.

Annett, Marian. 1973. "Handedness in families." *Annals of Human Genetics* 37 (1): 93–105.

Arellano, Manuel, and Stephen Bond. 1991. "Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations." *Review of Economic Studies* 58 (2): 277–297.

Ashraf, Quamrul, and Oded Galor. 2012. "Cultural Diversity, Geographical Isolation, and the Origin of the Wealth of Nations." *IZA Discussion Paper*, no. 6319.

———. 2013. "The "Out of Africa" Hypothesis, Human Genetic Diversity, and Comparative Economic Development." *American Economic Review* 103 (1): 1–46.

Ashton, Geoffrey C. 1982. "Handedness: An alternative hypothesis." *Behavior Genetics* 12 (2): 125–147.

Basso, Olga, Jørn Olsen, Niels V Holm, Axel Skytthe, James W Vaupel, and Kaare Christensen. 2000. "Handedness and mortality: A follow-up study of Danish twins born between 1900 and 1910." *Epidemiology*, pp. 576–580.

Baudin, Thomas, David de la Croix, and Paula E Gobbi. 2015. "Fertility and childlessness in the United States." *American Economic Review* 105 (6): 1852–1882.

Benbow, Camilla P. 1986. "Physiological Correlates of Extreme Intellectual Precocity." *Neuropsychologia* 24:719–725.

Beratis, Ion N, Andreas D Rabavilas, Miltiadis Kyprianou, George N Papadimitriou, and Charalabos Papageorgiou. 2013. "Investigation of the link between higher order cognitive functions and handedness." *Journal of Clinical and Experimental Neuropsychology* 35 (4): 393–403.

Berg, Andrew, Jonathan D Ostry, Charalambos G Tsangarides, and Yorbol Yakhshilikov. 2018. "Redistribution, inequality, and growth: new evidence." *Journal of Economic Growth* 23 (3): 259–305.

Bhushan, Braj, and Shah Mohd Khan. 2006. "Laterality and accident proneness: a study of locomotive drivers." *Laterality: Asymmetries of Body, Brain and Cognition* 11 (5): 395–404.

Billiard, Sylvain, Charlotte Faurie, and Michel Raymond. 2005. "Maintenance of handedness polymorphism in humans: a frequency-dependent selection model." *Journal of Theoretical Biology* 235 (1): 85 – 93.

Bloom, David E, David Canning, and Jaypee Sevilla. 2004. "The effect of health on economic growth: a production function approach." *World Development* 32 (1): 1–13.

Blundell, Richard, and Stephen Bond. 1998. "Initial conditions and moment restrictions in dynamic panel data models." *Journal of Econometrics* 87 (1): 115–143.

Börsch-Supan, Axel. 2019a. Survey of health, ageing and retirement in Europe (SHARE) Wave 1. Release version: 7.0.0. SHARE-ERIC Data set.

———. 2019b. Survey of health, ageing and retirement in Europe (SHARE) Wave 1 – SHARE-LIFE. Release version: 7.0.0. SHARE-ERIC Data set.

Brackenridge, CJ. 1981. "Secular variation in handedness over ninety years." *Neuropsychologia* 19 (3): 459–462.

Burt, C. 1937. *The Backward Child*. London, UK: London University Press.

Chamberlain, Herbert D. 1928. "The inheritance of left-handedness." *Journal of Heredity*, pp. 557–559.

Chambers, John. 2000. *The Oxford Companion to American Military History*. Oxford, UK: Oxford University Press.

Clark, Gregory, and Gillian Hamilton. 2006. "Survival of the richest: the Malthusian mechanism in pre-industrial England." *Journal of Economic History* 66 (3): 707–736.

Cook, C Justin, and Jason M Fletcher. 2018. "High-school genetic diversity and later-life student outcomes: micro-level evidence from the Wisconsin Longitudinal Study." *Journal of Economic Growth* 23 (3): 307–339.

Coren, Stanley. 1995. "Differences in divergent thinking as a function of handedness and sex." *American Journal of Psychology*, pp. 311–325.

Coren, Stanley, and Clare Porac. 1977. "Fifty Centuries of Right-Handedness: The Historical Record." *Science* 198 (4317): 631–632.

Coren, Stanley, and Fred Previc. 1996. "Handedness as a predictor of increased risk of knee, elbow, or shoulder injury, fractures and broken bones." *Laterality: Asymmetries of Body, Brain and Cognition* 1 (2): 139–152.

Crichton-Browne, James. 1907. "Dexterity and the bend sinister." *Proceedings of the Royal Institution of Great Britain*, no. 18:623–652.

Cuk, Tonka, Petra Leben-Seljak, and Marija Stefancic. 2001. "Lateral asymmetry of human long bones." *Variability and Evolution* 9 (1): 79–23.

DeJong, David N, and Marla Ripoll. 2006. "Tariffs and growth: an empirical exploration of contingent relationships." *Review of Economics and Statistics* 88 (4): 625–640.

De la Croix, David. 2013. *Fertility, education, growth, and sustainability.* Cambridge University Press.

De la Croix, David, and Matthias Doepke. 2003. "Inequality and growth: why differential fertility matters." *American Economic Review* 93 (4): 1091–1113.

Denny, Kevin, and Vincent O'Sullivan. 2007. "The Economic Consequences of Being Left-Handed Some Sinister Results." *Journal of Human Resources* 42 (2): 353–374.

Desmet, Klaus, Ignacio Ortuño-Ortín, and Romain Wacziarg. 2017. "Culture, ethnicity, and diversity." *American Economic Review* 107 (9): 2479–2513.

Docquier, Frédéric, Riccardo Turati, Jérôme Valette, and Chrysovalantis Vasilakis. 2020. "Birthplace diversity and economic growth: Evidence from the US states in the Post-World War II period." *Journal of Economic Geography* 20 (2): 321–354.

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

Ellis, Simon J, PJ Ellis, Eileen Marshall, Christine Windridge, and Steven Jones. 1998. "Is forced dextrality an explanation for the fall in the prevalence of sinistrality with age? A study in northern England." *Journal of Epidemiology & Community Health* 52 (1): 41–44.

Faurie, Charlotte, Sébastien Bonenfant, Marcel Goldberg, Serge Hercberg, Marie Zins, and Michel Raymond. 2008. "Socio-economic status and handedness in two large cohorts of French adults." *British Journal of Psychology* 99 (4): 533–554.

Faurie, Charlotte, Violaine Llaurens, Tatyana Hegay, and Michel Raymond. 2012. "Handedness and socioeconomic status in an urban population in Uzbekistan." *Evolution and Human Behavior* 33 (1): 35–41.

Freitas, Cidália, Maria Olga Vasconcelos, and Manuel Botelho. 2014. "Handedness and developmental coordination disorder in Portuguese children: Study with the M-ABC test." *Laterality: Asymmetries of Body, Brain and Cognition* 19 (6): 655–676.

Galor, Oded. 2011. *Unified Growth Theory.* Princeton RI: Princeton University Press.

Galor, Oded, and Stelios Michalopoulos. 2012. "Evolution and the growth process: Natural selection of entrepreneurial traits." *Journal of Economic Theory* 147 (2): 759–780.

Galor, Oded, and Omer Moav. 2002. "Natural selection and the origin of economic growth." *Quarterly Journal of Economics* 117 (4): 1133–1191.

Galor, Oded, and Ömer Özak. 2016. "The agricultural origins of time preference." *American Economic Review* 106 (10): 3064–3103.

Gilbert, Avery N, and Charles J Wysocki. 1992. "Hand preference and age in the United States." *Neuropsychologia* 30 (7): 601–608.

Goldberg, Elkhonon, Richard Harner, Mark Lovell, Kenneth Podell, and Silvma Riggio. 1994. "Cognitive bias, functional cortical geometry, and the frontal lobes: laterality, sex, and handedness." *Journal of Cognitive Neuroscience* 6 (3): 276–296.

Goodman, Joshua. 2014. "The wages of sinistrality: Handedness, brain structure, and human capital accumulation." *Journal of Economic Perspectives* 28 (4): 193–212.

Gören, Erkan. 2017. "The persistent effects of novelty-seeking traits on comparative economic development." *Journal of Development Economics* 126:112–126.

Graham, Charles J, Rhonda Dick, Vaughn I Rickert, and Robert Glenn. 1993. "Left-handedness as a risk factor for unintentional injury in children." *Pediatrics* 92 (6): 823–826.

Guber, Raphael. 2019. "Making it right? Social norms, handwriting and human capital." *Labour Economics* 56:44–57.

Halpern, Diane F, and Stanley Coren. 1991. "Handedness and life span." *New England Journal of Medicine* 324 (14): 998.

Halpern, Diane F, Mark G Haviland, and Charles D Killian. 1998. "Handedness and Sex Differences in Intelligence: Evidence from the Medical College Admission Test." *Brain and Cognition* 38:87–101.

Hanna, George B, Tim Drew, Peter Clinch, Sami Shimi, Peta Dunkley, Cathryn Hau, and Alfred Cuschieri. 1997. "Psychomotor skills for endoscopic manipulations: differing abilities between right and left-handed individuals." *Annals of Surgery* 225 (3): 333.

Hansen, Gary D, and Edward C Prescott. 2002. "Malthus to Solow." *American Economic Review* 92 (4): 1205–1217.

Harris, Lauren J. 1993. "Do left-handers die sooner than right-handers? Commentary on Coren and Halpern's (1991)" Left-handedness: A marker for decreased survival fitness."." *Psychological Bullettin* 114 (2): 203–234.

Hausmann, Ricardo, Jason Hwang, and Dani Rodrik. 2007. "What you export matters." *Journal of Economic Growth* 12 (1): 1–25.

Heilman, Kenneth M. 2005. *Creativity and the Brain*. Psychology Press.

Henry, Peter Blair. 2003. "Capital-account liberalization, the cost of capital, and economic growth." *American Economic Review* 93 (2): 91–96.

Hepper, Peter G, Deborah L Wells, and Catherine Lynch. 2005. "Prenatal thumb sucking is related to postnatal handedness." *Neuropsychologia* 43 (3): 313–315.

Hermans, Michel P, Sylvie A Ahn, and Michael F Rousseau. 2020. "Lipoprotein (a) levels are doubled in left-handed patients with diabetes." *Diabetes & Metabolism* 46 (2): 169–172.

Hobbes, Nicholas. 2004. *Essential Militaria: Facts, Legends, and Curiosities about Warfare Through the Ages*. McArthur.

Hoffman, Moshe, and Uri Gneezy. 2010. "Left Handed Women are More Competitive than Right Handed Men: On the Biological Basis of Gender Differences in Competitiveness." Mimeo.

Hopkins, William D, Kimberley A Phillips, Amanda Bania, Sarah E Calcutt, Molly Gardner, Jamie Russell, Jennifer Schaeffer, Elizabeth V Lonsdorf, Stephen R Ross, and Steven J Schapiro. 2011. "Hand preferences for coordinated bimanual actions in 777 great apes: implications for the evolution of handedness in hominins." *Journal of Human Evolution* 60 (5): 605–611.

Horan, Richard D, Erwin Bulte, and Jason F Shogren. 2005. "How trade saved humanity from biological exclusion: An economic theory of Neanderthal extinction." *Journal of Economic Behavior & Organization* 58 (1): 1–29.

Horan, Richard D, Erwin H Bulte, and Jason F Shogren. 2008. "Coevolution of human speech and trade." *Journal of Economic Growth* 13 (4): 293–313.

Jerzmanowski, Michał. 2017. "Finance and sources of growth: evidence from the US states." *Journal of Economic Growth* 22 (1): 97–122.

Johnston, David W, Michael ER Nicholls, Manisha Shah, and Michael A Shields. 2009. "Nature's experiment? Handedness and early childhood development." *Demography* 46 (2): 281–301.

———. 2013. "Handedness, health and cognitive development: evidence from children in the National Longitudinal Survey of Youth." *Journal of the Royal Statistical Society: Series A (Statistics in Society)* 176 (4): 841–860.

Jones, Larry E., and Michele Tertilt. 2006. "An Economic History of Fertility in the U.S.: 1826-1960." *NBER Working Paper*, no. 12796.

Jones, Larry E, Alice Schoonbroodt, and Michèle Tertilt. 2010. "Fertility Theories: Can They Explain the Negative Fertility-Income Relationship?" Chapter 2 of *Demography and the Economy*, edited by John B. Shoven, 43–100. University of Chicago Press.

Kujanová, M, L Bigoni, J Velemínská, and P Velemínskỳ. 2008. "Limb bones asymmetry and stress in medieval and recent populations of Central Europe." *International Journal of Osteoarchaeology* 18 (5): 476–491.

Kushner, Howard I. 2012. "Retraining left-handers and the aetiology of stuttering: the rise and fall of an intriguing theory." *Laterality: Asymmetries of Body, Brain and Cognition* 17 (6): 673–693.

Lagerlöf, Nils-Petter. 2006. "The Galor–Weil model revisited: A quantitative exercise." *Review of Economic Dynamics* 9 (1): 116–142.

———. 2007. "Long-run trends in human body mass." *Macroeconomic Dynamics* 11 (03): 367–387.

Litina, Anastasia. 2016. "Natural land productivity, cooperation and comparative development." *Journal of Economic Growth* 21 (4): 351–408.

Marchant, Linda F, and William C McGrew. 2013. "Handedness is more than laterality: lessons from chimpanzees." *Annals of the New York Academy of Sciences* 1288 (1): 1–8.

Martin, William Lee Berdel, and Monique Barbosa Freitas. 2002. "Mean mortality among Brazilian left-and right-handers: Modification or selective elimination?" *Laterality: Asymmetries of Body, Brain and Cognition* 7 (1): 31–44.

McManus, Ian Christopher. 1985. "Handedness, language dominance and aphasia: A genetic model." *Psychological Medicine*. 8:3–40.

———. 2004. *Right hand, left hand: The origins of asymmetry in brains, bodies, atoms and cultures*. Harvard University Press.

———. 2009. "The history and geography of human handedness." Chapter 3 of *Language lateralization and psychosis*, edited by Iris E. C. Sommer and René S. Kahn, 37–57. Cambridge University Press.

McManus, Ian Christopher, and M. Philip Bryden. 1992. "The genetics of handedness, cerebral dominance, and lateralization." *Handbook of Neuropsychology* 6:115–115.

McManus, Ian Christopher, Angus Davison, and John AL Armour. 2013. "Multilocus genetic models of handedness closely resemble single-locus models in explaining family data and are compatible with genome-wide association studies." *Annals of the New York Academy of Sciences* 1288 (1): 48–58.

McManus, Ian Christopher, and Alex Hartigan. 2007. "Declining left-handedness in Victorian England seen in the films of Mitchell and Kenyon." *Current Biology* 17 (18): R793–R794.

Medland, Sarah E, David L Duffy, Margaret J Wright, Gina M Geffen, David A Hay, Florence Levy, Catherina EM Van-Beijsterveldt, Gonneke Willemsen, Grant C Townsend, Vicki White, et al. 2009. "Genetic influences on handedness: data from 25,732 Australian and Dutch twin families." *Neuropsychologia* 47 (2): 330–337.

Moav, Omer. 2005. "Cheap Children and the Persistence of Poverty." *Economic Journal* 115:88–110.

Mukherjee, Satyam. 2017. "Individual performance and leader's laterality in interactive contests." *Laterality: Asymmetries of Body, Brain and Cognition* 22:362–376.

Newland, G Anthony. 1981. "Differences between left-and right-handers on a measure of creativity." *Perceptual and Motor Skills* 53 (3): 787–792.

Ocklenburg, Sebastian, Christian Beste, and Onur Güntürkün. 2013. "Handedness: a neurogenetic shift of perspective." *Neuroscience & Biobehavioral Reviews* 37 (10): 2788–2793.

Ogle, William. 1871. "On dextral pre-eminence." *Medico-Chirurgical Transactions* 54:279–301.

Pensieroso, Luca, and Alessandro Sommacal. 2019. "Agriculture to Industry: the End of Intergenerational Coresidence." *Review of Economic Dynamics* 34:87–102.

Persson, Per-Gunnar, and Peter Allebeck. 1994. "Do left-handers have increased mortality?" *Epidemiology*, pp. 337–340.

Reher, David S. 2004. "The demographic transition revisited as a global process." *Population, Space and Place* 10 (1): 19–41.

Rife, DC. 1940. "Handedness, with special reference to twins." *Genetics* 25 (2): 178.

Risch, N, and G Pringle. 1985. "Segregation analysis of human hand preference." *Behavior Genetics* 15 (4): 385–400.

Robson, Arthur J. 2001. "The biological basis of economic behavior." *Journal of Economic Literature* 39 (1): 11–33.

Roodman, David. 2009. "How to do xtabond2: An introduction to difference and system GMM in Stata." *The Stata Journal* 9 (1): 86–136.

Ruebeck, Christopher S, Joseph E Harrington, and Robert Moffitt. 2007. "Handedness and earnings." *Laterality: Asymmetries of Body, Brain and Cognition* 12 (2): 101–120.

Ruggles, Steven, Sarah Flood, Sophia Foster, Ronald Goeken, Jose Pacas, Megan Schouweiler, and Matthew Sobek. 2021. IPUMS USA: Version 11.0 [dataset]. https://doi.org/10.18128/D010.V11.0. Minneapolis, MN: IPUMS.

Saint-Paul, Gilles. 2007. "On market forces and human evolution." *Journal of Theoretical Biology* 247 (3): 397–412.

Salive, Marcel E, Jack M Guralnik, and Robert J Glynn. 1993. "Left-handedness and mortality." *American Journal of Public Health* 83 (2): 265–267.

Schmitz, Judith, Gerlinde AS Metz, Onur Güntürkün, and Sebastian Ocklenburg. 2017. "Beyond the genome—towards an epigenetic understanding of handedness ontogenesis." *Progress in Neurobiology* 159:69–89.

Somers, Metten, Roel A Ophoff, Maartje F Aukes, Rita M Cantor, Marco P Boks, Meenakshi Dauwan, Kees L de Visser, René S Kahn, and Iris E Sommer. 2015. "Linkage analysis in a Dutch population isolate shows no major gene for left-handedness or atypical language lateralization." *Journal of Neuroscience* 35 (23): 8730–8736.

Spiegler, Brenda J, and Grace H Yeni-Komshian. 1983. "Incidence of left-handed writing in a college population with reference to family patterns of hand preference." *Neuropsychologia* 21 (6): 651–659.

Steele, James, and Simon Mays. 1995. "Handedness and directional asymmetry in the long bones of the human upper limb." *International Journal of Osteoarchaeology* 5 (1): 39–49.

Steenhuis, Runa E, Truls Østbye, and Ruth Walton. 2001. "An examination of the hypothesis that left-handers die earlier: the Canadian study of health and aging." *Laterality: Asymmetries of Body, Brain and Cognition* 6 (1): 69–75.

Taras, John S, Michael J Behrman, and Gregory G Degnan. 1995. "Left-hand dominance and hand trauma." *Journal of Hand Surgery* 20 (6): 1043–1046.

Turner, Chad, Robert Tamura, Sean E. Mulholland, and Scott Baier. 2006. "Education and Income of the States of the United States:1840-2000." *Journal of Economic Growth* 12:101–158.

Vogl, Tom S. 2015. "Differential fertility, human capital, and development." *Review of Economic Studies* 83 (1): 365–401.

Vuoksimaa, Eero, Markku Koskenvuo, Richard J Rose, and Jaakko Kaprio. 2009. "Origins of handedness: a nationwide study of 30161 adults." *Neuropsychologia* 47 (5): 1294–1301.

Wiberg, Akira, Michael Ng, Yasser Al Omran, Fidel Alfaro-Almagro, Paul McCarthy, Jonathan Marchini, David L Bennett, Stephen Smith, Gwenaelle Douaud, and Dominic Furniss. 2019. "Handedness, language areas and neuropsychiatric diseases: insights from brain imaging and genetics." *Brain* 142 (10): 2938–2947.

Windmeijer, Frank. 2005. "A finite sample correction for the variance of linear efficient two-step GMM estimators." *Journal of Econometrics* 126 (1): 25–51.

Witelson, Sandra F. 1985. "The brain connection: the corpus callosum is larger in left-handers." *Science* 229 (4714): 665–668.

Woodley of Menie, Michael, Heitor Fernandes, Satoshi Kanazawa, and Edward Dutton. 2018. "Sinistrality is associated with (slightly) lower general intelligence: A data synthesis and consideration of the secular trend in handedness." *Journal of Comparatve Human Biology* 69 (3): 118–126.

Left-Handedness and Economic Development
— Online Appendix —

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A Left-handedness across countries

To the best of our knowledge, the largest harmonized cross-country survey on handedness was administered by Perelle and Ehrman (1994) to 12,000 subjects in 17 countries, translating into relatively large samples for 13 countries.[1] Figure A.1 displays, in panel (a), the (fully comparable) left-handedness rates observed in these 13 countries against their GDP per capita in 1992 (provided by Bolt et al. 2018), along with a quadratic fit. In panel (b) of Figure A.1, we supplement the data from Perelle and Ehrman (1994) with other estimates of left-handedness rates found in the literature.[2] Overall, a U-shaped relationship between left-handedness and economic development seems to emerge.

Notwithstanding the obvious data limitations, the cross-country pattern in Figure A.1 thus suggests that the evolution of handedness over time described in Figures 1 and 2 of Section 2 may indeed be related to the dynamics of economic development.

B The extensive margin of fertility

In Sections 3 and 4, we explain the observed trajectory of left-handedness through a complex mechanism hinging, among other things, on differential fertility and the demographic transition. In particular, our theory accounts for the 19th century decline of left-handedness in the West through a Malthusian mechanism: since the industrial take-off makes right-handers richer on average, they enjoy a reproductive advantage. As a consequence, the frequency of left-handers in the population declines.

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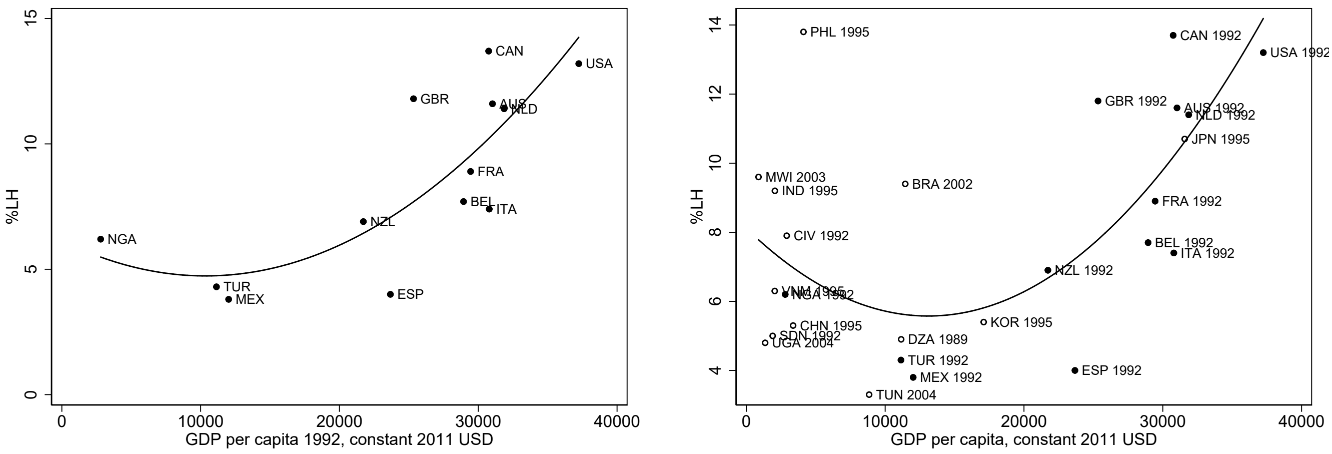
[1] Namely, Australia, Belgium, Canada, France, Italy, Mexico, the Netherlands, New Zealand, Nigeria, Spain, Turkey, United Kingdom and the U.S.

[2] Specifically, we find data for Algeria in Nedjar et al. (1989), for Brazil in Martin and Freitas (2002), for China, India, Japan, Korea, Philippines and Vietnam in Halpern, Haviland, and Killian (1998), for Ivory Coast and Sudan in De Agostini et al. (1997), for Malawi in Zverev (2004), for Tunisia in Fagard and Dahmen (2004), and for Uganda in Holder and Kateeba (2004). As we rely on multiple, heterogenous sources in panel (b) of Figure A.1, it is important to note that (i) handedness is not measured in a fully comparable fashion across observations, and (ii) we match the reported left-handedness rate with GDP per capita measured the year of the survey (or, by default, the year of publication), which varies from one paper to the other.



(a) Perelle and Ehrman (1994).

(b) Perelle and Ehrman (1994) and others.

Figure A.1: Left-handedness and GDP across countries (1981 – 2014).

Whether the fertility was still Malthusian in the 19th century is, however, subject to debate.

In this Appendix, we first discuss what the literature says about fertility differentials in the 19th century, and then show how our model can be modified to deliver results similar to Sections 3 and 4, even in the absence of a Malthusian fertility regime. For this extension we have to consider explicitly the extensive margin of fertility.

B.1 Fertility before the 20th century

Evidence on the income-fertility relationship before the 20th century is mixed. On the one hand, Jones and Tertilt (2006) claim that the U.S. were already in a post-Malthusian regime during the 19th century, at least as far as marital fertility (*i.e.* the intensive margin) is concerned. On the other hand, Baudin, de la Croix, and Gobbi (2015) use the same data as Jones and Tertilt (2006) and find evidence of the existence of Malthusian segments of the fertility-status relationship throughout the 19th century, while Reher (2004) locates the onset of the fertility decline in the United States between 1900 and 1920.

As far as the Old World is concerned, the positive co-movement between income and fertility that characterizes the Malthusian regime in our model is broadly consistent with the behavior of reproduction rates in Europe and in the United Kingdom during the 19th century, as can be seen from Galor (2005) and Galor (2012).[3]

Interestingly, the available historical evidence reports fertility differentials between rural and urban (or agricultural and industrial) areas over the 19th century. In particular, Wrigley (1961) shows that crude birth rates were higher (i) in the urban (rather than rural) parts of the four regions of France that he studies from 1872 to 1902, and (ii) in the industrial (as opposed to non-industrial) areas of the four localities of Prussia that he studies in 1894–96. Haines (1976) observes that, in the Prussian Upper Silesia (Oppeln) between 1831 and 1913, fertility was systematically higher in the industrial part of the province, compared to the countryside. The evidence from Wrigley (1961) and Haines (1976) is reproduced in Table B.1. Since our theory

[3]Clark and Cummins (2015) suggest, however, that the inversion of the income-fertility relationship in Britain may have happened before the 19th century.

Table B.1: Crude birth rates per 1,000.

Source	Country	Area	Period	Agrarian/Rural	Industrial/Urban
Wrigley (1961)	France	Nord	1872–73	24.8	41.4
			1880–82	23.1	36.6
			1890–92	19.9	33.6
			1900–02	26.6	27.4
		Pas-de-Calais	1872–73	29.9	32.7
			1880–82	26.7	36.4
			1890–92	26.8	32.9
			1900–02	28.9	31.8
		Aisne	1872–73	21.2	28.2
			1880–82	22.8	24.9
			1890–92	21.3	23.6
			1900–02	22.2	23.2
		Somme	1872–73	23.6	25.9
			1880–82	23.2	23.7
			1890–92	21.4	22.3
			1900–02	21.2	19.1
	Prussia	Arnsberg	1894–96	35.5	44.4
		Düsseldorf	1894–96	34.8	40.2
		Aachen	1894–96	32.9	38.3
		Münster	1894–96	34.7	51.3
Haines (1976)	Prussia	Oppeln	1831–37	46.26	61.61
			1837–43	43.19	53.30
			1843–46	43.42	49.64
			1846–49	38.50	46.80
			1849–52	43.85	57.94
			1852–55	40.29	51.08
			1855–58	43.51	57.53
			1858–61	44.16	57.55
			1861–64	43.94	55.52
			1864–67	42.82	55.40
			1867–71	41.64	52.74
			1871–75	42.30	54.33
			1875–80	39.77	50.79
			1880–85	39.11	49.54
			1885–90	40.83	51.56
			1890–95	41.45	55.62
			1895–1900	41.27	54.88
			1900–05	39.22	51.30
			1905–10	37	46.82
			1910–13	35.96	41.48

Data come from Wrigley (1961) (Tables 36 and 37 on pp. 135-136) and Haines (1976) (Table 1 on p. 337).

explains the early decline of left-handedness through higher fertility among right-handers, who are over-represented in the modern sector, the existence of a fertility surplus in industrial regions, compared to rural areas, may be interpreted as indirect evidence of a higher fertility rate among right-handed workers. Note also that the urban-rural fertility differentials reported in Table B.1 tend to decline substantially towards the end of the period: this is coherent with both our theory and the evidence on differential fertility by handedness presented in Section 6.1.

B.2 An alternative version of the model without a Malthusian regime

Given the uncertainty surrounding the existence of a Malthusian segment in the 19th century, it is important to discuss whether our model can reproduce the decline of left-handedness rates, without necessarily relying on a (temporarily) positive fertility-income relationship.

This is possible, if we also consider – within our framework – the extensive margin of fertility, by allowing individuals with different characteristics to have a differential access to marriage and reproduction. In particular, lower productivity and earning capacity may translate into a higher probability of remaining single. This looks like a reasonable assumption, as Clark and Cummins (2015) report that the probability of getting married was higher for richer people in 19th-century's England. Similarly, Wrigley, Schofield, and Schofield (1989) find marriage rates in England to be positively correlated with real wages, between the 16th and the 18th century.

Based on the above discussion, we modify our benchmark model along two dimensions. First, we set $\tau = 0$, thus removing the good cost of children. This eliminates the Malthusian segment from the model. The implied optimal choices, in terms of education and fertility, are then given by

$$e_{ij,t} = \begin{cases} 0 & \text{if } w_{ij,t} \leq \dfrac{\theta}{\beta\phi} \\ \dfrac{\beta\phi w_{ij,t} - \theta}{1-\beta} & \text{if } w_{ij,t} > \dfrac{\theta}{\beta\phi} \end{cases}, \tag{B.1}$$

and

$$n_{ij,t} = \begin{cases} \dfrac{\gamma}{(1+\gamma)\phi} & \text{if } w_{ij,t} \leq \dfrac{\theta}{\beta\phi} \\ \dfrac{\gamma(1-\beta) w_{ij,t}}{(1+\gamma)(\phi w_{ij,t} - \theta)} & \text{if } w_{ij,t} > \dfrac{\theta}{\beta\phi} \end{cases}. \tag{B.2}$$

Fertility, as a function of wages, is now described by Figure B.1. The Malthusian, upward-sloping portion of the fertility curve in Figure 3 is replaced by a horizontal segment: as long as agents do not invest in education, wage gaps do not translate into fertility differentials – as in De la Croix and Doepke (2003). By consequence, the channel linking handedness to the intensive margin of fertility through earnings is shut down for relatively low levels of development.

To activate the mechanism related to the extensive margin of fertility in the pre-modern regime, we introduce a second modification to the benchmark model. Rather than assuming that all agents get married with certainty, we suppose that there exists a given probability of marrying, denoted by $\nu_{ij,t}$, which depends on relative income. In particular,

$$\nu_{ij,t} = \begin{cases} \left(\dfrac{w_{ij,t}}{w_{S,t}}\right)^{\psi} & \text{if } w_{ij,t} \leq \dfrac{\theta}{\beta\phi} \\ 1 & \text{if } w_{ij,t} > \dfrac{\theta}{\beta\phi} \end{cases}, \tag{B.3}$$

with $\psi > 0$. This means that, as long as there is no investment in education, skilled agents are certain to find a marriage partner, while the unskilled face a risk of remaining unmarried, which is inversely related to their relative income. This assumption captures the idea that less productive people are disadvantaged on the marriage market. The penalty they suffer on the extensive margin causes their average fertility to be lower than that of richer people, although

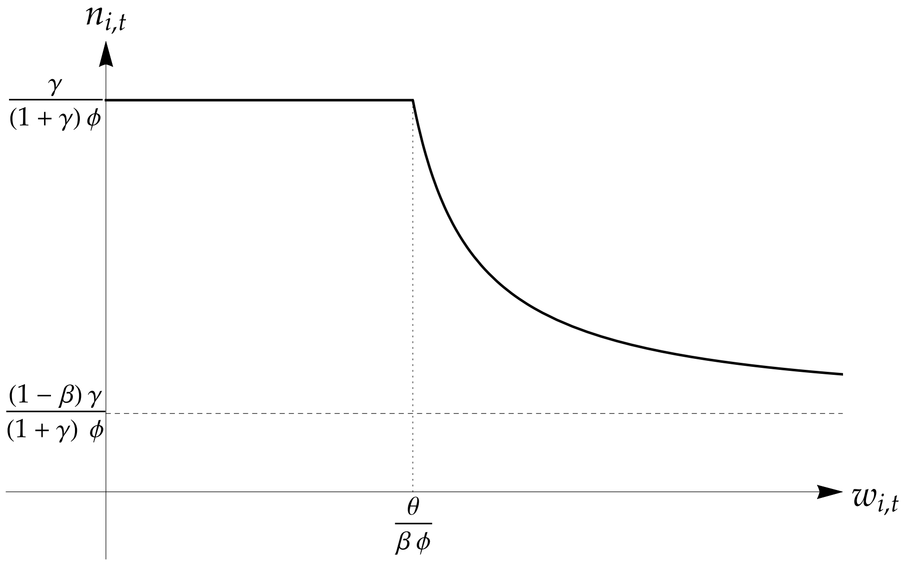


Figure B.1: Endogenous fertility, when $\tau = 0$

income *per se* does not affect the fertility of married people, *i.e.* the intensive margin.[4] Formally, average fertility rates by type can be written as

$$\bar{n}_{ij,t} = \nu_{ij,t} n_{ij,t}. \tag{B.4}$$

Given that in certain stages of development left-handers are the poorest among the unskilled, it is then possible to have $\bar{n}_{LU,t} < \bar{n}_{RU,t}$ when $n_{LU,t} = n_{RU,t}$.

We can examine the dynamics of the modified model, resorting to a numerical simulation comparable with that of Section 4.4. We use the same parameter values, with the exception of $\tau = 0$. In addition, we set the new parameter $\psi = 0.2$. The simulated time paths of the key variables of the model are depicted in Figure B.2. Overall, the model has the same qualitative behavior as the benchmark. In particular, the evolution of left-handedness prevalence over time is comparable, although there is no Malthusian segment in the model. This happens because, even though fertility does not depend on income and all married agents enjoy the same reproductive success, right-handers have better chances of getting married. Figure B.3 further illustrates the mechanism, by showing how a reproductive advantage in favor of right-handers may arise (on average) even in the absence of a difference at the intensive margin.[5]

Overall, this alternative version of the model accommodates our theory to the possibility that the decline of left-handedness might have lasted beyond the tipping point of the income-fertility relationship in the U.S. In fact, it can generate a decrease in the prevalence of left-handedness without relying on an explicit Malthusian mechanism. If unskilled left-handers, being on average poorer, were discriminated on the marriage market during the 19th century, this could have caused the frequency of D genotypes to increase, even in the absence of a positive correlation

[4]The possibility that poorer individuals face a higher risk of remaining single (and are therefore reproductively disadvantaged) may also depend on specific features of the marriage market not modeled here, such as polygyny or the option to divorce. See for instance De la Croix and Mariani (2015).

[5]The model implies a childlessness rate among unskilled agents that ranges between 20% and 30%, for right- and left-handers respectively, for the period over which the differential probability of marriage is relevant. This is in line with average childlessness rate in the U.S. between the end of the 19th and the beginning of the 20th century as measured in Baudin, de la Croix, and Gobbi (2015).

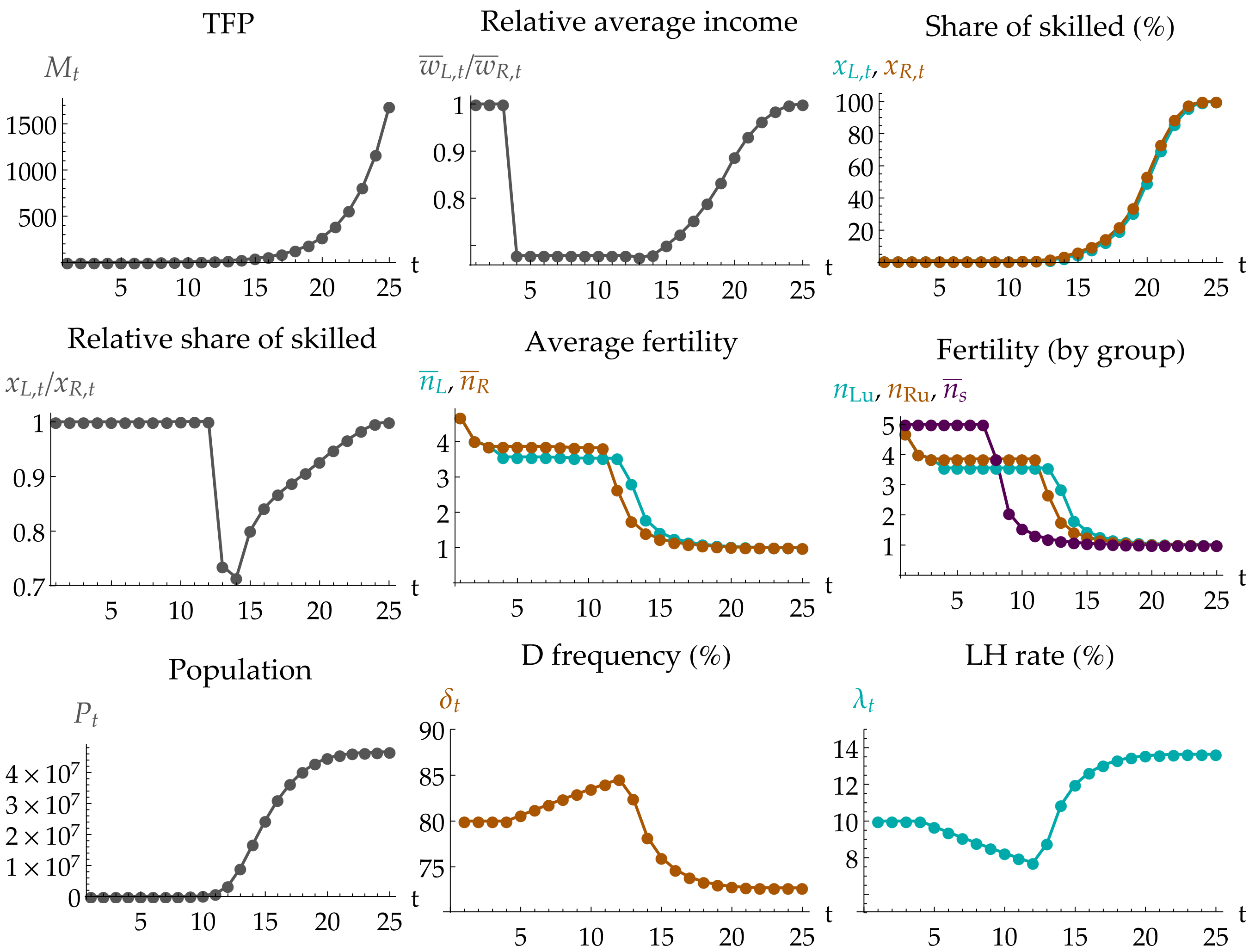


Figure B.2: Simulations of the model with extensive margin of fertility

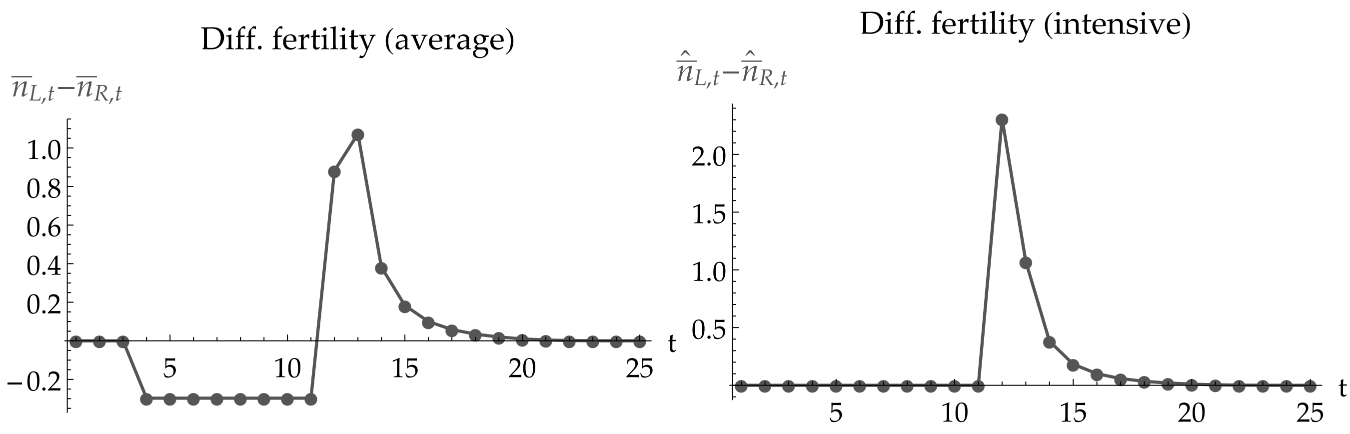


Figure B.3: Simulations of the model with extensive margin of fertility: intensive *vs* average fertility differentials

between income and fertility.[6]

[6]This is consistent with the idea, put forward by McManus (2009), that left-handers were stigmatized and subject to "indirect social pressure", thus encountering more difficulties in producing offspring and transmitting their genes. Bertrand (2008) also suggests that the 19th century was marked by a widespread stigmatization of left-handers, which declined thereafter.

Finally, notice that the extensive margin of fertility may also be easily added to the benchmark model, while still allowing for $\tau > 0$. In that case, the model would feature both the intensive and the extensive margins of fertility, so that Malthusian fertility coexists with income-related differentials in marriage probability.[7] The decline of λ_t would then be faster and/or more pronounced, while the subsequent recovery may be slower, with the model converging to a lower steady-state left-handedness rate. During the first phase, unskilled left-handers would have both lower individual fertility and lower chances of being married than unskilled right-handers. During the second one, they would have higher individual fertility, but lower chances of marrying (with an ambiguous effect on reproductive success).

C Sexual reproduction

In Section 3.4, we have written the genetic part of our model under the assumption that reproduction occurs asexually. This assumption is consistent with our description of optimal choices as emanating from single-parent households. In this Appendix, we show that our analysis remains qualitatively unchanged if we allow for sexual reproduction, thus making our model more appropriate for describing the evolution of humans (who are diploid organisms).

To keep the model tractable, we make the additional assumption that mating is perfectly assortative with respect to economic characteristics: within each household, the two spouses earn the same wage. We will then consider the family (*i.e.* the couple) as a single decision maker, so that economic decisions – namely, fertility and children's education – are analyzed through a unitary model.[8]

In this new setting, handedness can be traced back to two different alleles (*i.e.* manifestations of the same gene), denoted by D ("dexterity") and C ("chance"), respectively. By consequence, four different genotypes may emerge: DD, DC, CD and CC.[9] We further assume that individuals with "homogeneous" genotype DD (CC) carry the allele D (C) with certainty. In the cases of "mixed" genotypes, DC or CD, the D or C alleles are passed on with probability $1/2$.

Note that here the D/C dichotomy intervenes at the allele level, as opposed to the simplified model presented in Section 3.4, where we directly identified genotypes as D or C. The higher degree of genotype differentiation is related to sexual reproduction.

To describe how genotypes translate into phenotypes, we follow McManus (1985) and assume that an individual with a DD-genotype is right-handed with certainty, so that $p(R|DD) = 1$, while having a CC-genotype yields equal probabilities of being right- or left-handed, *i.e.* $p(R|CC) = p(L|CC) = 1/2$. Finally, DC- or CD- genotypes lead to right-handedness with probability $p(R|DC) = p(R|CD) = 3/4$, and to left-handedness with $p(L|DC) = p(L|CD) = 1/4$.[10]

[7] The importance of considering both the intensive and the extensive margins of fertility has been highlighted, in a different context, by De la Croix, Schneider, and Weisdorf (2019).

[8] We can deal away with this type of assortative mating, if we assume that women are all alike and do not work. Accordingly, only men (fathers) – who care exclusively about sons' education – work and make decisions. This is not an unreasonable assumption for the pre-WWII era: according to Goldin (1992), the female labor-force participation rate for married white women in the U.S. remained below 10% (20%) until the 1940s (1950s).

[9] Organisms that reproduce sexually receive one complete copy of their genetic material from each parent. A diploid organism can thus either have two copies of the same allele (homozygous) or one copy each of two different alleles (heterozygous). A genotype is defined by the alleles an individual has at a given locus.

[10] Such probabilities may be re-parameterized, but we prefer to stick to these simple values and remain fully consistent with McManus (1985).

We denote by δ_t the proportion of D-alleles at time t.[11] If $\sigma \in [0,1]$ is the degree of ex-ante genotypic assortative mating, the frequency f of the different genotypes is given by

$$f_{DD} = \delta_t(\sigma + (1-\sigma)\delta_t), \tag{C.1}$$

$$f_{CC} = (1-\delta_t)(\sigma + (1-\sigma)(1-\delta_t)), \tag{C.2}$$

and

$$f_{CD} = f_{DC} = 2(1-\delta_t)(1-\sigma)\delta_t. \tag{C.3}$$

If $\sigma = 0$, there is perfectly random mating by genotype, implying for instance that $f_{DD} = \delta^2$. If instead $\sigma = 1$, there is perfect genotypic assortative mating, implying that $f_{DD} = \delta$.[12]

Given the frequency of each genotype, and keeping in mind how genotypes can manifest themselves into phenotypes, the relative number of right-handers in the population is

$$1 - \lambda_t = p(R|DD)f_{DD} + p(R|CC)f_{CC} + p(R|DC)f_{DC} + p(R|CD)f_{CD}. \tag{C.4}$$

Solving for λ, we obtain that the left-handedness rate at time t is given by

$$\lambda_t = \frac{1-\delta_t}{2}. \tag{C.5}$$

At time $t+1$, allele frequency depends on the reproductive success of left- and right-handed individuals at time t. Denoting the average fertility of right- and left-handers as $\bar{n}_{R,t}$ and $\bar{n}_{L,t}$, respectively, we have that

$$\delta_{t+1} = \frac{\delta_t((1-\delta_t)(1-\sigma)\bar{n}_{L,t} + (3+\delta_t+\sigma(1-\delta_t))\bar{n}_{R,t})}{2((1-\delta_t)\bar{n}_{L,t} + (1+\delta_t)\bar{n}_{R,t})}. \tag{C.6}$$

We can therefore write

$$\Delta\delta_t = -\frac{(1-\delta_t)\delta_t(1+\sigma)(\bar{n}_{L,t} - \bar{n}_{R,t})}{2(1-\delta_t)\bar{n}_{L,t} + 2(1+\delta_t)\bar{n}_{R,t}}, \tag{C.7}$$

and describe the implication of differential fertility for allele frequency and left-handedness rate.

Lemma C.1 *The frequency of D-alleles increases (decreases), and the proportion of left-handers decreases (increases), when the average fertility of right-handers is higher (lower) than that of the left-handers. If reproductive success is the same across different agents, allele frequency stabilizes.*

Proof. Follows directly from Equations (C.5) and (C.7). ■

Note that Equations (C.5), (C.6) and (C.7) are the counterparts of Equations (22), (23) and (24) in the benchmark model. Similarly, Lemma C.1 is the diploid version of Lemma 1. Overall,

[11] In Section 3.4, δ_t was used to denote the proportions of D-genotypes.

[12] On the importance of assortative mating by genotype, see Conley et al. (2016) and Hugh-Jones et al. (2016). Our simulations show that the dynamics of the whole model are not very sensitive to the value assigned to σ.

introducing sexual reproduction allows us to obtain a more complete and realistic description of the genetic mechanism at the core of our theory, but does not alter its main results.

D An alternative characterization of the traditional sector

In the benchmark model, production in the traditional sector is characterized by decreasing returns to the number of workers P_t^T, but constant returns to the working time of each worker. The latter is equal to the amount of time that exceeds that devoted to child rearing, *i.e.* $1 - \phi n_t$, where n_t is fertility. The assumption of constant returns to hours worked greatly simplifies the model, allowing us to obtain an analytical characterization of several results. However, one may wonder whether this assumption is at least partially responsible for our theoretical findings. In this Appendix, we show that this is not the case.

In order to do so, we now assume that production in the traditional sector takes place according to the following aggregate production function:

$$Y_t^T = T_t X^\alpha ((1 - \phi n_t) P_t^T)^{1-\alpha}, \tag{D.1}$$

which exhibits decreasing returns in both the number of workers and hours worked. As in the benchmark model, we normalize land to one, so that $X = 1$.

As labor is remunerated at its average product, the wage per unit of time in the T-sector is given by

$$w_t^T = T_t ((1 - \phi n_t) P_t^T)^{-\alpha}, \tag{D.2}$$

where optimal fertility n_t in turn depends on wages according to Equation (8).

The wage in the traditional sector, $w_t^T(P_t^T)$, must thus be determined as the solution of Equation (D.2), after replacing n_t with its expression in Equation (8).[13]

Since n_t is a piecewise function of wages, the solution to Equation (D.2) is also piecewise. We can then rewrite (D.2) under two alternative forms, one for each demographic regime:

$$w_t^T = T_t \left(\left(1 - \frac{\phi \gamma w_t^T}{(1+\gamma)(\tau + \phi w_t^T)} \right) P_t^T \right)^{-\alpha}, \tag{D.3}$$

and

$$w_t^T = T_t \left(\left(1 - \frac{\phi \gamma (1-\beta) w_t^T}{(1+\gamma)(\tau + \phi w_t^T - \theta)} \right) P_t^T \right)^{-\alpha}. \tag{D.4}$$

Note that in Equation (D.3) we have introduced the fertility function corresponding to the Malthusian regime, *i.e.* the corner situation in which agents do not invest in education, while Equation (D.4) corresponds to the "modern" regime, characterized by interior solutions for both fertility and education (see Section 3.2).

Equations (D.3) and (D.4) do not have closed-form, explicit solutions. Let us then denote by $\widetilde{w}_t^{\circ}(P_t^T)$ and $\widetilde{w}_t^{\diamond}(P_t^T)$ the values of w_t^T that solve Equations (D.3) and (D.4), respectively. Knowing

[13] Here, the wage equates demand and supply of labor in the T-sector, without considering for the moment the possibility that workers can also be employed in the M-sector. This boils down to finding the equivalent of Equation (11) in Section 3.3.1.

that $(\theta - \beta\tau)/(\beta\phi)$ is the threshold value of wages that discriminates between Malthusian and modern fertility in Equation (8), we can define

$$\overline{P}_t^T \equiv \frac{(1+\gamma)\theta}{\theta+\beta\gamma\tau}\left(\frac{\beta\phi T_t}{\theta-\beta\tau}\right)^{\frac{1}{\alpha}} \tag{D.5}$$

as the value of P_t^T such that $\widetilde{w}_t^{\circ}(P_t^T) = \widetilde{w}_t^{\diamond}(P_t^T) = (\theta - \beta\tau)/(\beta\phi)$.

The wage in the traditional sector can thus be written as

$$w_t^T(P_t^T) = \begin{cases} \widetilde{w}_t^{\diamond}(P_t^T) & \text{if } P_t^T \leq \overline{P}_t^T \\ \widetilde{w}_t^{\circ}(P_t^T) & \text{if } P_t^T > \overline{P}_t^T \end{cases}. \tag{D.6}$$

It is then possible to prove the following.

Lemma D.1 *In the traditional sector, the wage per unit of time is decreasing in the number of workers.*

Proof. See Appendix E.3. ■

As w_t^T is decreasing in P_t, just like its benchmark-model counterpart in Equation (11), the analysis of the alternative model is also qualitatively the same as in Sections 3 and 4 – the only difference being that we cannot rely on closed-form solutions for wages in the traditional sector, unless they are pinned down by modern-sector wages.

In particular, as far as the dynamics of the model are concerned, changing the description of the T-sector requires us to redefine the boundaries of the four stages of development characterized in Section 4.1. To this end, let us denote by $w_t^T(P_{U,t})$ and $w_t^T(P_{LU,t})$ the values taken by $w_t^T(P_t^T)$ in Equation (D.6) when $P_t^T = P_{U,t}$ and $P_t^T = P_{LU,t}$, respectively. With reference to Proposition 1, we have that stage (1) is defined by the condition $M_t < w_t^T(P_{U,t})/\rho$, stage (2) by $w_t^T(P_{U,t})/\rho \leq M_t < w_t^T(P_{LU,t})/\rho$, stage (3) by $w_t^T(P_{LU,t})/\rho \leq M_t < w_t^T(P_{LU,t})$ and stage (4) by $M_t \geq w_t^T(P_{LU,t})$.

Note also that – due to the assumption of perfect mobility of workers across sectors – wages in the T-sector are fully determined by the technological level of the M-sector in stages (2) and (4), so that the wages of left- and right-handers are the same as in the benchmark model in all but two cases. First, within stage (1) of Proposition 1, we would now have that $w_{LU,t} = w_{RU,t} = w_t^T(P_{U,t})$. Second, within stage (3), we have $w_{LU,t} = w_t^T(P_{LU,t})$.

To sum it up, if we had to redraw the equivalent of Figures 4 and 5, we would end up with similar pictures. As far as Figure 4 is concerned, the green line describing wages in agriculture would be different, but still decreasing. The "new" Figure 5 would also look very similar, with the boundaries between stages still described by downward-sloping curves.[14] The example described in Section 4.3 and the dynamics of left-handedness summarized in Table 1 would also hold qualitatively unchanged.

One may worry, however, that the dynamic results of the alternative version of the model might be substantially different from the benchmark – from a quantitative viewpoint. To deal

[14] The lack of closed-form solutions for T-sector wages would prevent us, however, from obtaining closed-form conditions for the different regions highlighted in Lemmas 2.1-2.4.

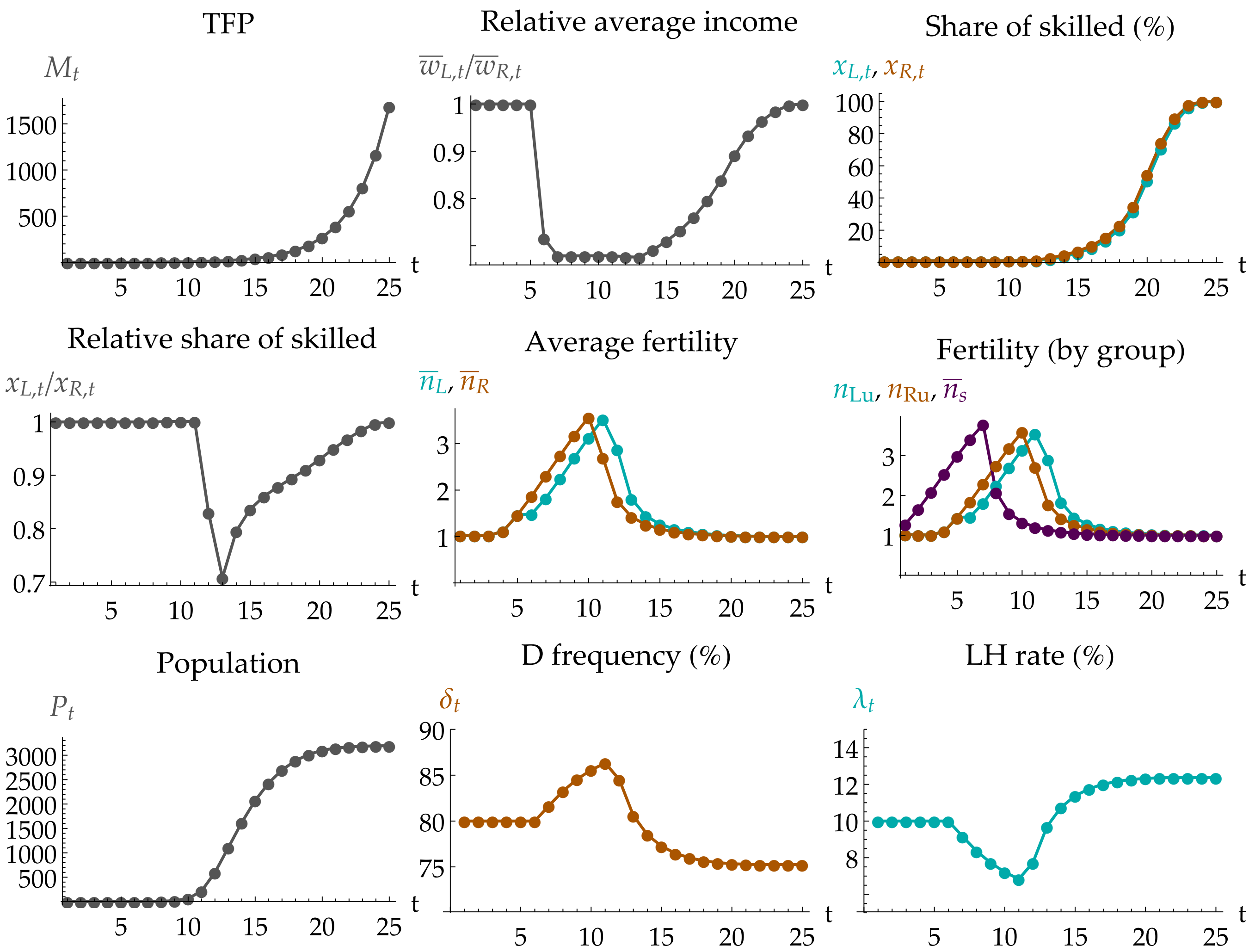


Figure D.1: Simulations: the alternative model

with this issue, we have run a simulation of our model under the alternative characterization of the traditional sector, but without changing the parameter values and the initial conditions used in Section 4.4.

The simulated time paths of the key dynamic variables of the alternative version of our model are reported in Figure D.1. The results are remarkably close to those of the benchmark model, displayed in Figure 6. As hinted at above, this is mainly due to the fact that equilibrium wages – which drive most dynamic variables – are in most cases determined by productivity in the modern sector, which is not affected by the changes introduced in this Appendix.

Finally, the simulated dynamics of the alternative version of the model can also closely reproduce those of the benchmark if we allow for a feedback effect of left-handedness rates on growth (Figure 7, Section 5), or if we shut down the Malthusian fertility behavior and consider the extensive margin of fertility only (Figure B.2, Appendix B.2).[15]

E Proofs

In this Appendix, we presents the proofs of Proposition 1, Lemmas 2.1 to 2.4 and Lemma D.1.

[15]Simulation results are available upon request.

E.1 Proof of Proposition 1

In Proposition 1, we have characterized the behavior of our model economy – in terms of wages and sectoral allocation of unskilled labor – throughout the different stages of development. Here, we present the formal derivation of the main results of the Proposition.

E.1.1 Stage (1)

In our economy, all unskilled workers are employed in agriculture at time t if, $\forall i$, $w_t^T > w_{iU,t}^M$. Consider the expression for wages in Equations (11) and (16): since the highest possible wage for the unskilled in manufacturing is $w_{RU,t}^M = \rho M_t$, all unskilled workers are employed in agriculture if population is such that

$$P_{U,t}^{-\alpha} > \rho M_t. \tag{E.1}$$

In this case, all workers earn the same wage

$$w_{LU,t} = w_{RU,t} = P_{U,t}^{-\alpha}. \tag{E.2}$$

The situation is depicted in panel (1) of Figure 4.

E.1.2 Stage (2)

When relative productivity increases sufficiently, unskilled right-handers start switching to the modern sector. This happens when the wage that unskilled right-handers can earn in the modern sector is not lower than that prevailing in the traditional sector, if the latter employs all the unskilled workers. For this to be the case, we need that

$$\left(P_{U,t}^T\right)^{-\alpha} \leq \rho M_t. \tag{E.3}$$

Some right-handed, and all left-handed workers, remain in the traditional sector as long as the wage of right-handers in the modern sector remains lower than that prevailing in the traditional one, if the latter does not employ right-handers, *i.e.*

$$\left(P_{LU,t}^T\right)^{-\alpha} > \rho M_t. \tag{E.4}$$

The number of unskilled, right-handed workers in the traditional sector can be retrieved from

$$\left(P_{U,t}^T\right)^{-\alpha} = \left(P_{LU,t} + P_{RU,t}^T\right)^{-\alpha} = \rho M_t. \tag{E.5}$$

This gives

$$P_{RU,t}^T = (\rho M_t)^{-\frac{1}{\alpha}} - P_{LU,t}. \tag{E.6}$$

Since labor is perfectly mobile across sectors, unskilled right-handers must earn the same wage regardless of whether they work in the traditional or the modern sector. Left- and right-handers being perfect substitutes in the traditional sector, all unskilled workers in the economy must earn the same wage:

$$w_{LU,t} = w_{RU,t} = \rho M_t. \tag{E.7}$$

Stage (2) is illustrated in panel (2) of Figure 4.

E.1.3 Stage (3)

Stage (3) is similar to stage (2), with the difference that the relative productivity M is high enough to yield perfect segregation by handedness. All unskilled, right-handed workers are employed in the modern sector, while all unskilled left-handers work in the traditional sector if $w^M_{LU,t} < w^T_{LU,t} \leq w^M_{RU,t}$. This is the case if

$$M_t < \left(P^T_{LU,t}\right)^{-\alpha} \leq \rho M_t. \tag{E.8}$$

Since all unskilled right-handers work in the modern sector, we shall have

$$w_{RU,t} = w^M_{RU,t}. \tag{E.9}$$

This is higher than the wage received by left-handers:

$$w_{RU,t} \geq w_{LU,t} = w^T_{LU,t}. \tag{E.10}$$

This case with perfect segregation by handedness is represented in panel (3) of Figure 4.

E.1.4 Stage (4)

In stage (4), productivity in the modern sector is high enough to also attract left-handed workers. This happens as soon as

$$\left(P^T_{LU,t}\right)^{-\alpha} \leq M_t, \tag{E.11}$$

which implies that

$$w^T_{LU,t} \leq w^M_{LU,t}. \tag{E.12}$$

In particular, the number of unskilled, left-handed workers who are still employed in the traditional sector can be retrieved from Equation (E.11), and is given by

$$P^T_{LU,t} = M_t^{-1/\alpha}. \tag{E.13}$$

Accordingly,

$$P^M_{LU,t} = P_{LU,t} - M_t^{-1/\alpha}, \tag{E.14}$$

which is strictly positive.

Since $\rho > 1$, all unskilled right-handers still work in the modern sector.

Stage (4) is depicted in panel (4) of Figure 4.

E.2 Proofs of Lemmas 2.1 to 2.4

The proofs of Lemma 2.1 to 2.4 require to compute, for each group of agents, the optimal education and fertility choices corresponding to the wage prevailing at each stage of development. Given that the formal structure is the same for each Lemma, here we provide the details for Lemma 2.1 only. To complete the proof, we shall also prove and explain the reversal in the differential fertility pattern observed in regions (3b) and (4b) in Lemma 2.3 and 2.4, respectively.

E.2.1 Lemma 2.1 (stage (1))

In stage (1), wages are such that $w_{LU,t} = w_{RU,t} = P_{U,t}^{-\alpha}$.

From Equations (7) and (8), we can then establish that, if

$$P_{U,t} > \left(\frac{\theta - \beta\tau}{\beta\phi}\right)^{-1/\alpha}, \tag{E.15}$$

we have

$$e_{RU,t} = e_{LU,t} = 0 \tag{E.16}$$

and

$$n_{RU,t} = n_{LU,t}. \tag{E.17}$$

We are then in a Malthusian regime, corresponding to region (1a) in Figure 5. Notice that in this case the probability of having a skilled child, $\pi_{ij,t}$, is equal to $\xi\theta^{\beta}$ – as can be inferred from Equation (5).

If instead

$$P_{U,t} \leq \left(\frac{\theta - \beta\tau}{\beta\phi}\right)^{-1/\alpha}, \tag{E.18}$$

then

$$e_{RU,t} = e_{LU,t} = \frac{\beta(\tau + \phi P_{U,t}^{-\alpha}) - \theta}{1-\beta} > 0, \tag{E.19}$$

and

$$n_{RU,t} = n_{LU,t}. \tag{E.20}$$

In this case, the probability of having a skilled child depends on education, as can be seen from Equation (5). In particular, from Equations (5) and (7), we can check that $\pi_{ij} \in (0,1)\ \forall i,j$ as long as

$$P_{U,t} > \left(\frac{(1-\beta)\xi^{-1/\beta} + \beta(\theta - \tau)}{\beta\phi}\right)^{-1/\alpha}, \tag{E.21}$$

which – together with Equation (E.18) – defines region (1b) in Figure 5. We will instead have $\pi_{ij} = 1$ as soon as

$$P_{U,t} \leq \left(\frac{(1-\beta)\xi^{-1/\beta} + \beta(\theta - \tau)}{\beta\phi}\right)^{-1/\alpha}. \tag{E.22}$$

The above condition identifies region (1c) in Figure 5, which corresponds to the limit case in which every member of the current generation has skilled children.

To understand why the conditions delimiting the regions within stage (1) do not depend on M, consider that in stage (1) all unskilled agents work in agriculture, so that unskilled wages do not depend on productivity in the modern sector – and do not vary by handedness. Accordingly, income, and therefore education and fertility choices, depend only on the size of the workforce employed in agriculture. Given the production function (9), the higher $P_{U,t}$, the lower the wage, independently of M_t.

E.2.2 Lemma 2.2 (stage (2))

The proof can be worked out along the same lines as Lemma 2.1, using the expression for wages in stage (2), *i.e.* $w_{LU,t} = w_{RU,t} = \rho M_t$. As wages – contrary to stage (1) – do not depend on population, the borders between regions (2a), (2b) and (2c) are vertical segments in Figure 5, corresponding to threshold values of M_t.

E.2.3 Lemma 2.3 (stage (3))

With the exception of region (3b), the proof proceeds along the same lines as Lemma 2.1, using the expression for wages in stage (3), *i.e.* $w_{RU,t} = \rho M_t$ and $w_{LU,t} = P_{LU,t}^{-\alpha}$.

In region (3b), wages are no longer independent of handedness. In particular the wage differential in favor of right-handers makes them switch from the Malthusian fertility regime of region (3a) to the modern one, while left-handers are still stuck in the Malthusian regime. Hence, the relative fertility of right-handers will become decreasing in M_t. Since in region (3a) the relative fertility of right-handers is above 1 and increasing in M_t, there must exist a value of the relative wage such that the relative fertility is equal to 1 in (3b). To find this value, consider the expression of fertility for right- and left-handers in this region, *i.e.*

$$n_{LU,t} = \frac{\gamma w_{LU,t}}{(1+\gamma)(\tau + \phi w_{LU,t})} \tag{E.23}$$

and

$$n_{RU,t} = \frac{\gamma(1-\beta) w_{RU,t}}{(1+\gamma)(\tau + \phi w_{RU,t} - \theta)}, \tag{E.24}$$

respectively. After substituting wages, *i.e.* $w_{RU,t} = \rho M_t$ and $w_{LU,t} = P_{LU,t}^{-\alpha}$, we can solve $n_{RU,t} = n_{LU,t}$ for M_t, and obtain

$$\tilde{M}_t = \frac{(\theta - \tau)}{\beta\rho\phi - P_{LU,t}^{\alpha}(1-\beta)\rho\tau}. \tag{E.25}$$

When the economy is in region (3b) and $M_t > \tilde{M}_t$ ($M_t < \tilde{M}_t$), fertility choices are such that $n_{RU,t} < n_{LU,t}$ ($n_{RU,t} > n_{LU,t}$) and λ increases (decreases) from t to $t+1$.

Within region (3b), the threshold function $\tilde{M}_t$ is increasing and concave in $P_{LU,t}$. It is represented by a dashed line in Figure E.1, which zooms in Figure 5 on regions (3b) and (4b).

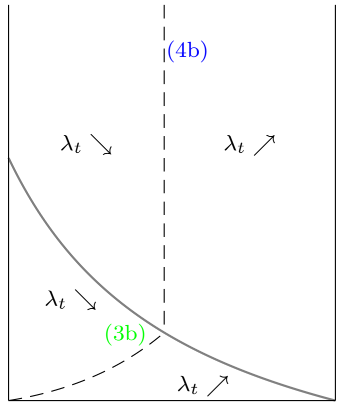


Figure E.1: The dynamics of λ: the reversal of the fertility differential in regions (3b) and (4b)

Note that $\tilde{M}_t$ passes through the point of intersection of the (perpendicular) frontiers between (3a) and (3b), and (3b) and (3c) (see also Figure 5). This can be verified by substituting the coordinates of this point, *i.e.*

$$M_t = \frac{\theta - \beta\tau}{\beta\phi\rho}$$

and

$$P_{LU,t} = \left(\frac{\theta - \beta\tau}{\beta\phi}\right)^{-1/\alpha}$$

into Equation (E.25).

For later use, we can also characterize the intersection between the function $\tilde{M}_t$ and the frontier separating stage (3) from stage (4). By solving $\tilde{M}_t = P_{LU,t}^{-\alpha}$ for $P_{LU,t}$, we can obtain

$$P_{LU,t} = \left(\frac{\theta - (1 - \rho(1-\beta))\tau}{\beta\rho\phi}\right)^{-\frac{1}{\alpha}}. \tag{E.26}$$

E.2.4 Lemma 2.4 (stage (4))

With the exception of region (4b), the proof reproduces that of Lemma 2.1.

For region (4b), we can proceed as we did for region (3b). Knowing that wages are now $w_{RU,t} = \rho M_t$ and $w_{LU,t} = M_t$, we solve $n_{RU,t} = n_{LU,t}$ for M_t and obtain

$$\hat{M}_t = \frac{\theta - (1 - \rho(1-\beta))\tau}{\beta\rho\phi}. \tag{E.27}$$

This is a straight vertical line in the (P_t, M_t) space, which intersects the frontier between stages (3) and (4) at the same point as $\tilde{M}_t$. In fact, by solving $\hat{M}_t = P_{LU,t}^{-\alpha}$ for $P_{LU,t}$, one gets the same expression as in (E.26). This is illustrated in Figure E.1.

It can be further checked that, within region (4b), if $M_t > \hat{M}_t$ ($M_t < \hat{M}_t$), then fertility choices are such that $n_{RU,t} < n_{LU,t}$ ($n_{RU,t} > n_{LU,t}$) and λ increases (decreases) from t to $t+1$.

E.3 Proof of Lemma D.1

In the context of the model presented in Appendix D, we need to prove that w_t^T, the wage (per unit of time) in the traditional sector, is a decreasing function of P_t^T, the employment in that sector.

As can be seen from Equation (D.6), $w_t^T(P_t^T)$ is a piecewise function. We will then consider successively the behavior of its two portions.

If $P_t^T > \overline{P}_t^T$, the relevant function is $\widetilde{w}_t^{\circ}(P_t^T)$, *i.e.* the solution to Equation (D.3). The latter can be rewritten as

$$w_t^T \left(1 - \frac{\phi\gamma w_t^T}{(1+\gamma)(\tau + \phi w_t^T)}\right)^{\alpha} = T_t(P_t^T)^{-\alpha}. \tag{E.28}$$

It can be checked that the left-hand side of the above equation, which does not depend on P_t^T, is increasing in w_t^T. In fact, its derivative with respect to w_t^T writes as

$$\frac{((1+\gamma)\tau^2 + ((2+(1-\alpha)\gamma)\tau + \phi w_t^T)\phi w_t^T)}{(\tau + \phi w_t^T)((1+\gamma)\tau + \phi w_t^T)} \left(1 - \frac{\phi\gamma w_t^T}{(1+\gamma)(\tau + \phi w_t^T)}\right)^{\alpha},$$

which is always positive (the second factor is positive as the expression in parentheses is working time). The right-hand side of Equation (E.28) does not depend on w_t^T, but decreases with P_t^T. This implies that, for the equality in Equation (E.28) to hold, any increase in P_t^T must be matched by a decrease in w_t^T. It follows that the function $\widetilde{w}_t^{\circ}(P_t^T)$ must be decreasing.

If instead $P_t^T \leq \overline{P}_t^T$, the relevant wage function is $\widetilde{w}_t^{\diamond}(P_t^T)$, *i.e.* the solution to Equation (D.4), which can be rewritten as

$$w_t^T \left(1 - \frac{\phi\gamma(1-\beta) w_t^T}{(1+\gamma)(\tau + \phi w_t^T - \theta)}\right)^{\alpha} = T_t(P_t^T)^{-\alpha}. \tag{E.29}$$

Symmetrically to what we did above, we just need to prove that the left-hand side of Equation (E.29) is an increasing function of w_t^T. To check whether this is the case, we have to show that its derivative with respect to w_t^T is positive, *i.e.*

$$\left(1 - \frac{\phi\gamma(1-\beta) w_t^T}{(1+\gamma)(\tau + \phi w_t^T - \theta)}\right)^{\alpha} \left(1 + \frac{\alpha(1-\beta)\gamma(\theta-\tau)\phi w_t^T}{(\tau + \phi w_t^T - \theta)((1+\beta\gamma)\phi w_t^T - (1+\gamma)(\theta - \tau))}\right) > 0.$$

The first factor is positive since the expression in parentheses represents working time net of child rearing, which is positive. As far as the second one is concerned, it can be shown that the numerator of the fraction is positive as long as $\theta > \tau$, as previously assumed (see Section 3.2). For the denominator to be positive it is sufficient to have that $w_t^T > (1+\gamma)(\theta - \tau)/(\phi(1+\beta\gamma))$ and $w_t^T > (\theta - \tau)/\phi$. The first condition must always hold, for agents' working time ought to be positive. The second is also satisfied, since it is implied by $w_t^T > (\theta - \beta\tau)/(\beta\phi)$, which defines the modern fertility regime (corresponding to $P_t^T \leq \overline{P}_t^T$). We can then conclude that $\widetilde{w}_t^{\diamond}(P_t^T)$ is also decreasing in w_t^T, thus establishing the claim of Lemma D.1.

F The distant past

Our analysis, both theoretical and empirical, is mainly concerned with the evolution and effects of human handedness over the last two centuries. One may wonder, however, how an economy reaches its pre-industrial stationary left-handedness rate, and why the latter is not one half.

Here, we present a simple model of the pre-industrial evolution of handedness, based on a purely agricultural economy, Malthusian fertility and a simple mechanism of frequency-dependent selection that may be relevant in the very long-run. For ease of presentation, we assume that everybody is unskilled.

In this setting, income derives only from agriculture and, in the absence of property rights on land, individuals fight to secure their crop. Initially, every individual is endowed – as in Section 3 – with the same quantity of land $1/P$. Then, one-on-one fighting over crops occurs between randomly matched pairs of individuals.

Fighting is modeled as an activity in which right-handers have an intrinsic, individual advantage. This is consistent with left-handers being on average more clumsy with tools or less able than right-handers, as previously discussed. Left-handers, however enjoy a frequency-dependent aggregate advantage. In particular, left-handers would benefit from their relative scarcity if they are the minority, since right-handers are less used to compete against them – just like in modern sports.[16]

If two right-handers or two left-handers fight against each other, nobody prevails: both keep their crops intact and have an income equal to $P^{-\alpha}$. If instead two agents of opposed dominant hand fight, the probability that the left-handed one prevails is given by

$$\kappa(1-\lambda_t)-\eta,$$

with $\kappa, \eta > 0$. This simple formulation captures both the individual superiority of right-handers (as measured by η) and the scarcity-related advantage of left-handers (through κ).

Since each left-handed individual has a chance $(1-\lambda_t)$ of being randomly matched with a right-handed individual for a fight, the expected income of left-handers can be written as

$$w_{L,t} = (\lambda_t + (1-\lambda_t)(1+(1-\lambda_t)\kappa - \eta))P^{-\alpha}. \tag{F.1}$$

Symmetrically,

$$w_{R,t} = ((1-\lambda_t) + \lambda_t(1-(1-\lambda_t)\kappa + \eta))P^{-\alpha}. \tag{F.2}$$

In this pre-industrial economy, fertility is Malthusian and increases with income. The evolutionary stable left-handedness rate must be such that average incomes of left- and right-handers are equalized. It is then given by

$$\lambda^* = 1 - \eta/\kappa, \tag{F.3}$$

thus depending on the two parameters, κ and η, which determine the outcome of fighting.

[16]On the superior performance of lefties in interactive sports (especially individual ones), see for instance Raymond et al. (1996), Brooks et al. (2004), Harris (2010), Loffing, Hagemann, and Strauss (2012), Loffing and Hagemann (2016) and Fagan, Haugh, and Cooper (2019).

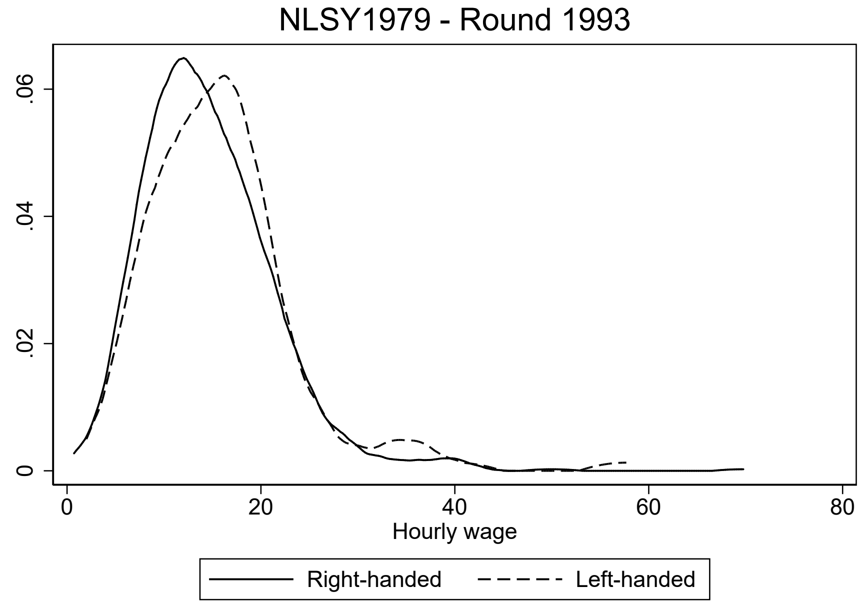


Figure G.1: Distribution of earnings by handedness (education >16 years)

Our simple story is related to some existing literature, which explain the evolutionary stable rate of left-handedness through the "fighting hypothesis", or other forms of frequency-dependent selection (see Billiard, Faurie, and Raymond 2005, Ghirlanda, Frasnelli, and Vallortigara 2009, Abrams and Panaggio 2012, among others). The assumption that frequency-dependent selection is related to fighting (and violence) in pre-industrial times is further corroborated by the findings of Faurie and Raymond (2005), according to whom the prevalence of left-handedness across traditional societies is positively correlated with homicide rates.

One may also think that frequency-dependent selection progressively loses importance, so that – as violence declines and property rights are protected by formal institutions – the dynamics of handedness are eventually governed by the economic and technological forces highlighted in Sections 3 and 4. On the pre-industrial decline of violence, see Lagerlöf (2013).

G Additional stylized facts for the U.S.

Here, we present additional evidence from U.S. data. Namely, we look at differential outcomes by handedness and the correlation between left-handedness rates and economic performance.

G.1 Left- *vs* right-handers

We resort to the NLSY to see whether left-handers are over-represented at the top of the ability distribution. This provides additional motivation for exploring the possible feedback effect of the prevalence of left-handedness on growth, along the lines of Section 5.

To do so, in Figure G.1 we plot the distribution of wages for left- and right-handers with more than 16 years of education. The data, taken from the 1993 wave of the NLSY, reveal that – among the highly educated – left-handers earn higher wages, which could in turn reflect higher productivity. This difference in earnings is statistically significant, as reported in Table G.1.

Table G.1: Wage differentials (education >16 years)

	RH	LH	Difference
Wage	14.603	15.862	-1.259* (0.679)
Wage > median	0.487	0.605	-0.118** (0.049)
Nb of obs.	957	119	1,076

Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

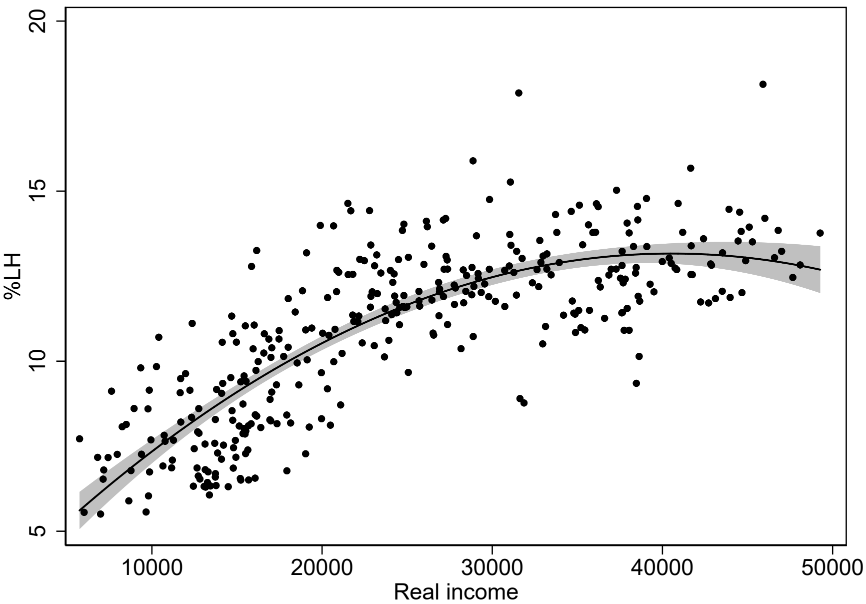


Figure G.2: Left-handedness and income across the U.S. states, 1910 – 1980.

G.2 Left-handedness and income

In Figure G.2, we plot left-handedness rates by state and decade of birth (from the NGSS) against real income per capita by state and decade (from Turner et al. 2006), with each dot representing a state–decade pair. We observe a positive correlation between left-handedness and income at low levels of income, which eventually flattens out for higher levels of income.

This concave relationship is in line with the prediction of our simulated model, as illustrated by Figure 9 that shows the correlation between income and left-handedness after the nadir of left-handedness.

H Fertility by cohort: sensitivity to alternative cutoff years

In Section 6.1, we have shown the existence of a positive fertility differential in favor of left-handers, for cohorts born until 1922. In this Appendix, we assess the sensitivity of this result to alternative choices of the relevant cohort, by re-estimating the first column of panel (b) in Table 2 for alternative cutoff years. Figure H.1 reports the resulting point estimates for the coefficient of LH, as well as the 90% confidence intervals.

All the cutoffs before 1924 but one yield a coefficient for LH that is significantly positive – though earlier cutoffs are associated with smaller samples that translate into larger standard

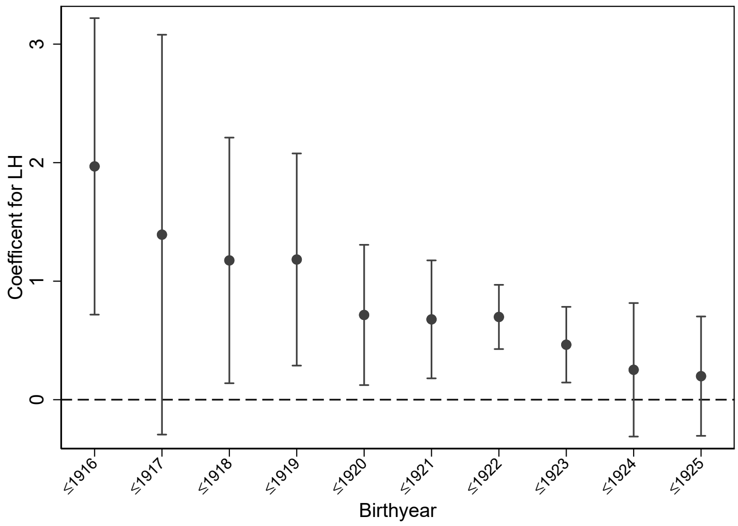


Figure H.1: Left-handedness and differential fertility: sensitivity to alternative cutoffs.

errors. The estimated coefficient of interest tends to decrease and becomes non significantly different from zero when we include younger cohorts – a result which is very much in line with the prediction of the model. Note that the 1922 cutoff year is the one that delivers the most precise point estimate.

I Measuring left-handedness: alternative definitions of the reference age group

The benchmark regression results displayed in Table 4 are based on the left-handedness rate measured among individuals aged 15 to 60. In this Appendix, we check whether our results are robust to alternative definitions of the age group for which we measure the prevalence of left-handedness.

For instance, we could consider an earlier upper bound to focus on younger individuals, aged 15-45. This age group includes the most productive or creative persons in the population, who arguably play a decisive role for the advancement of the technological frontier – as described in our model. Alternatively, it could be interesting to exclude from our benchmark age group younger individuals, who may not have reached their full productivity potential yet, and focus on those aged 30-60. Finally, one could combine the previous two restrictions and measure left-handedness among individuals in the central stage of their working life (30-45).[17]

Table I.1 reports the regression outputs when these three alternative age groups are used to measure the prevalence of left-handedness. The results prove very stable and corroborate those of Table 4, with a positive relationship between left-handedness and growth appearing in recent times (columns (1) and (3)), or when education reaches a sufficiently high level (column (4)).[18]

[17] In the specification with left-handedness in 1990 (Equation (50)), considering a shorter age segment like 30-45 further assuages the concern – mentioned in Section 6.2 – that migration biases our state-level measure of handedness if NGSS respondents were not, at the time of the survey, residing in the state where they spent (most of) their career. In this case, the 30-45 age group gathers persons who filled the NGSS questionnaire when aged 26 to 41.

[18] Running 2SLS and sGMM regressions using these three alternative age groups yields results that are also similar to those in Table 5.

Table I.1: Left-handedness and output growth: alternative cohort definitions.

Dependent variable: Δln*(real output per worker)*	(1) OLS, 1990-2000	(2)	(3) FE	(4)
Panel A: 15 – 45				
LH (%)	0.0270***	-0.0162	-0.0196	-0.336**
	(0.00994)	(0.0169)	(0.0165)	(0.145)
LH (%) × Post-1980 (dummy)			0.0189**	
			(0.00883)	
LH (%) × Schooling (ln)				0.129**
				(0.0589)
R-squared	0.243	0.770	0.779	0.785
Panel B: 30 – 60				
LH (%)	0.0291***	0.00690	-0.00247	-0.231*
	(0.00930)	(0.0200)	(0.0210)	(0.118)
LH (%) × Post-1980 (dummy)			0.0173**	
			(0.00834)	
LH (%) × Schooling (ln)				0.0941**
				(0.0434)
R-squared	0.295	0.768	0.777	0.782
Panel C: 30 – 45				
LH (%)	0.0272***	-0.00710	-0.0124	-0.230**
	(0.00831)	(0.00979)	(0.0104)	(0.103)
LH (%) × Post-1980 (dummy)			0.0176**	
			(0.00751)	
LH (%) × Schooling (ln)				0.0888**
				(0.0390)
R-squared	0.277	0.768	0.778	0.782
Population (ln)	✓	✓	✓	✓
State fixed-effects		✓	✓	✓
Period dummies		✓	✓	✓
Post-1980 (dummy)			✓	
Schooling (ln)				✓
Observations	51	204	204	204
Number of states	51	51	51	51

Robust standard errors clustered at the state level in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

LH (%) is the prevalence of left-handedness among the population of the specified cohort, measured in the first year of each decade. *Population* (ln) and *Schooling* (ln) are also measured in the first year of the decade, the latter variable being equal to the average number of years of schooling among the population of the specified cohort.

J Left-handedness and TFP growth

Our empirical analysis in Section 6.2 is compatible with the existence of a non-monotonic correlation between left-handedness and growth, possibly shaped by a non-trivial causal effect of the prevalence of left-handedness on aggregate economic performance, as implied by our theoretical analysis (Section 5). As our model relies on the specific hypothesis that left-handedness affects

Table J.1: Left-handedness and TFP growth – I.

Dependent variable: Δln*(TFP)*	(1) OLS, 1990-2000	(2) FE	(3) FE	(4) FE
Initial TFP (ln)	-0.121	-0.615***	-0.630***	-0.653***
	(0.0924)	(0.0941)	(0.0878)	(0.0868)
LH (%)	0.0271***	0.000949	-0.00606	-0.330***
	(0.00989)	(0.0295)	(0.0290)	(0.116)
LH (%) × Post-1980 (dummy)			0.0193**	
			(0.00776)	
LH (%) × Schooling (ln)				0.134***
				(0.0481)
Population (ln)	✓	✓	✓	✓
State fixed-effects		✓	✓	✓
Period dummies		✓	✓	✓
Post-1980 (dummy)			✓	
Schooling (ln)				✓
Observations	51	204	204	204
Number of states	51	51	51	51
R-squared	0.257	0.817	0.826	0.831

Robust standard errors clustered at the state level in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.
LH (%) is the prevalence of left-handedness among the population aged 15 to 60, measured in the first year of each decade. *Population* (ln) and *Schooling* (ln) are also measured in the first year of the decade, the latter variable being equal to the average number of years of schooling among the 15-60.

the growth rate of total factor productivity, we can also ask the data whether left-handedness rates correlate with productivity. We thus run the same estimations as in Section 6.2, using a proxy for the growth rate of TFP as dependent variable. In particular, we compute TFP as the ratio between the level of output per worker and the average number of years of schooling of the labor force – with both variables taken from Turner et al. (2006). This is a raw measure of productivity, but it has the merit of being consistent with our theory, where the only factors entering the production function in the modern sector are labor and human capital.

The results of this exercise are reported in Tables J.1 and J.2, which are immediately comparable with Tables 4 and 5. Similar to what we found for output growth, we observe a positive and significant correlation between left-handedness in 1990 and TFP growth (over the 1990 – 2000 period), which vanishes in the panel specification. However, once interactions are introduced, left-handedness appears to be significantly and positively related to TFP growth after the 1980s, or for a sufficiently high level of development (as proxied by education). These findings are robust to the IV and GMM specifications, as shown in Table J.2. Overall, our results on TFP growth are compatible with the hypothesis that left-handedness influences economic development through the productivity channel.

Table J.2: Left-handedness and TFP growth – II.

Dependent variable: $\Delta\ln(TFP)$	(1) 2SLS, 1990-2000	(2)	(3) sGMM	(4)
Initial TFP (ln)	-0.118	-0.102**	-0.144**	-0.109***
	(0.0806)	(0.0478)	(0.0569)	(0.0408)
LH (%)	0.0331***	0.0169***	0.000509	-0.0544*
	(0.00888)	(0.00515)	(0.00611)	(0.0314)
LH (%) × Post-1980 (dummy)			0.0258***	
			(0.00846)	
LH (%) × Schooling (ln)				0.0256**
				(0.0122)
Population (ln)	✓	✓	✓	✓
State fixed-effects		✓	✓	✓
Period dummies		✓	✓	✓
Lagged dependent	✓			
Post-1980 (dummy)			✓	
Schooling (ln)				✓
Observations	51	204	204	204
Number of states	51	51	51	51
R-squared	0.304			
First stage F-test	44.77			
Number of instruments		49	50	55
AR1 test (p-val)		0.001	0.000	0.001
AR2 test (p-val)		0.114	0.325	0.148
Hansen test of joint instrument validity (p-val)		0.326	0.413	0.510
Difference-in-Hansen test of instrument subsets (p-val):				
Instruments for levels		0.161	0.373	0.596
Instruments for initial output		0.627	0.640	0.760

Col (1): robust standard errors clustered at the state level in parentheses. Col (2)-(4): Windmeijer-corrected standard errors clustered at the state level in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

LH (%) is the prevalence of left-handedness among the population aged 15 to 60, measured in the first year of each decade. *Population (*ln*)* and *Schooling (*ln*)* are also measured in the first year of the decade, the latter variable being equal to the average number of years of schooling among the 15-60.

In columns (2) and (3), we use the second to fifth lags (both in differences and in levels) as instruments. In column (4), we use the second to fourth lags.

References

Abrams, Daniel M, and Mark J Panaggio. 2012. "A model balancing cooperation and competition can explain our right-handed world and the dominance of left-handed athletes." *Journal of the Royal Society Interface* 9 (75): 2718–2722.

Baudin, Thomas, David de la Croix, and Paula E Gobbi. 2015. "Fertility and childlessness in the United States." *American Economic Review* 105 (6): 1852–1882.

Bertrand, Pierre Michel. 2008. *Histoire des gauchers*. Editions Imago.

Billiard, Sylvain, Charlotte Faurie, and Michel Raymond. 2005. "Maintenance of handedness polymorphism in humans: a frequency-dependent selection model." *Journal of Theoretical Biology* 235 (1): 85 – 93.

Bolt, Jutta, Robert Inklaar, Herman de Jong, and Jan Luiten Van Zanden. 2018. "Rebasing Maddison: new income comparisons and the shape of long-run economic development." *GGDC Research Memorandum*, vol. 174.

Brooks, Robert, Luc F Bussiere, Michael D Jennions, and John Hunt. 2004. "Sinister strategies succeed at the cricket World Cup." *Proceedings of the Royal Society of London. Series B: Biological Sciences* 271 (suppl_3): S64–S66.

Clark, Gregory, and Neil Cummins. 2015. "Malthus to modernity: wealth, status, and fertility in England, 1500–1879." *Journal of Population Economics* 28 (1): 3–29.

Conley, Dalton, Thomas Laidley, Daniel W Belsky, Jason M Fletcher, Jason D Boardman, and Benjamin W Domingue. 2016. "Assortative mating and differential fertility by phenotype and genotype across the 20th century." *Proceedings of the National Academy of Sciences* 113 (24): 6647–6652.

De Agostini, Maria, Amar Hassan Khamis, Ama Marthe Ahui, and Georges Dellatolas. 1997. "Environmental influences in hand preference: An African point of view." *Brain and Cognition* 35 (2): 151–167.

De la Croix, David, and Matthias Doepke. 2003. "Inequality and growth: why differential fertility matters." *American Economic Review* 93 (4): 1091–1113.

De la Croix, David, and Fabio Mariani. 2015. "From polygyny to serial monogamy: a unified theory of marriage institutions." *The Review of Economic Studies* 82 (2): 565–607.

De la Croix, David, Eric B Schneider, and Jacob Weisdorf. 2019. "Childlessness, celibacy and net fertility in pre-industrial England: the middle-class evolutionary advantage." *Journal of Economic Growth* 24 (3): 223–256.

Fagan, Francois, Martin Haugh, and Hal Cooper. 2019. "The advantage of lefties in one-on-one sports." *Journal of Quantitative Analysis in Sports* 15 (1): 1–25.

Fagard, Jacqueline, and Riadh Dahmen. 2004. "Cultural influences on the development of lateral preferences: a comparison between French and Tunisian children." *Laterality: Asymmetries of Body, Brain and Cognition* 9 (1): 67–78.

Faurie, Charlotte, and Michel Raymond. 2005. "Handedness, homicide and negative frequency-dependent selection." *Proceedings of the Royal Society B: Biological Sciences* 272 (1558): 25–28.

Galor, Oded. 2005. "From stagnation to growth: unified growth theory." *Handbook of Economic Growth* 1:171–293.

———. 2012. "The demographic transition: causes and consequences." *Cliometrica* 6 (1): 1–28.

Ghirlanda, Stefano, Elisa Frasnelli, and Giorgio Vallortigara. 2009. "Intraspecific competition and coordination in the evolution of lateralization." *Philosophical Transactions of the Royal Society B: Biological Sciences* 364 (1519): 861–866.

Goldin, Claudia D. 1992. *Understanding the Gender Gap: An Economic History of American Women*. Oxford University Press.

Haines, Michael R. 1976. "Population and economic change in nineteenth-century Eastern Europe: Prussian Upper Silesia, 1840–1913." *Journal of Economic History* 36 (2): 334–358.

Halpern, Diane F, Mark G Haviland, and Charles D Killian. 1998. "Handedness and Sex Differences in Intelligence: Evidence from the Medical College Admission Test." *Brain and Cognition* 38:87–101.

Harris, Lauren Julius. 2010. "In fencing, what gives left-handers the edge? Views from the present and the distant past." *Laterality: Asymmetries of Body, Brain and Cognition* 15 (1-2): 15–55.

Holder, MK, and Deo Kateeba. 2004. "Hand preference survey of 5136 school children in Western Uganda." *Laterality: Asymmetries of Body, Brain and Cognition* 9 (2): 201–207.

Hugh-Jones, David, Karin JH Verweij, Beate St Pourcain, and Abdel Abdellaoui. 2016. "Assortative mating on educational attainment leads to genetic spousal resemblance for polygenic scores." *Intelligence* 59:103–108.

Jones, Larry E., and Michele Tertilt. 2006. "An Economic History of Fertility in the U.S.: 1826-1960." *NBER Working Paper*, no. 12796.

Lagerlöf, Nils-Petter. 2013. "Violence and property rights." *Journal of Economic Dynamics & Control* 37:312–328.

Loffing, Florian, and Norbert Hagemann. 2016. "Performance differences between left-and right-sided athletes in one-on-one interactive sports." In *Laterality in sports*, 249–277. Elsevier.

Loffing, Florian, Norbert Hagemann, and Bernd Strauss. 2012. "Left-handedness in professional and amateur tennis." *PLoS One* 7, no. 11.

Martin, William Lee Berdel, and Monique Barbosa Freitas. 2002. "Mean mortality among Brazilian left-and right-handers: Modification or selective elimination?" *Laterality: Asymmetries of Body, Brain and Cognition* 7 (1): 31–44.

McManus, Ian Christopher. 1985. "Handedness, language dominance and aphasia: A genetic model." *Psychological Medicine.* 8:3–40.

———. 2009. "The history and geography of human handedness." Chapter 3 of *Language lateralization and psychosis*, edited by Iris E. C. Sommer and René S. Kahn, 37–57. Cambridge University Press.

Nedjar, Taïeb, Mahmoud Touari, Mounir Mesbah, Joseph Lellouch, and Georges Dellatolas. 1989. "La préférence manuelle dans une population d'étudiants algériens francophones et comparaison avec la population française." *L'Année psychologique* 89 (2): 239–253.

Perelle, Ira B, and Lee Ehrman. 1994. "An international study of human handedness: The data." *Behavior Genetics* 24 (3): 217–227.

Raymond, Michel, Dominique Pontier, Anne-Beatrice Dufour, and Anders Pape Møller. 1996. "Frequency-dependent maintenance of left handedness in humans." *Proceedings of the Royal Society of London. Series B: Biological Sciences* 263 (1377): 1627–1633.

Reher, David S. 2004. "The demographic transition revisited as a global process." *Population, Space and Place* 10 (1): 19–41.

Turner, Chad, Robert Tamura, Sean E. Mulholland, and Scott Baier. 2006. "Education and Income of the States of the United States:1840-2000." *Journal of Economic Growth* 12:101–158.

Wrigley, Edward Anthony. 1961. *Industrial growth and population change.* Cambridge University Press.

Wrigley, Edward Anthony, Roger S Schofield, and Roger Schofield. 1989. *The population history of England 1541-1871.* Volume 46. Cambridge University Press.

Zverev, Yuriy. 2004. "Prevalence of the three categories of handedness among Malawian school children." *Collegium Antropologicum* 28 (2): 755–760.

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