

DISCUSSION PAPER SERIES

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Development**

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MARCH 2021

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# Left-Handedness and Economic Development

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## ABSTRACT

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# Left-Handedness and Economic Development\*

This paper studies the interplay between left-handedness and economic development. To explain the decline and subsequent recovery of left-handedness observed over the last few centuries in the Western world, we propose a theory in which economic development influences the prevalence of left-handedness through structural change and a genetic mechanism driven by differential fertility. We further explore the possibility that the prevalence of left-handedness influences growth, finding that the link between handedness and economic performance varies across stages of development. Consistent with the implications of our model, the analysis of US data suggests that left-handedness can positively contribute to growth, once the economy has reached a sufficiently high level of human capital. Our research provides an example of how economic development can shape evolutionary forces, thus improving our understanding of the growth-diversity link.

**JEL Classification:** 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. 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.<sup>1</sup> 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.<sup>2</sup> 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).<sup>3</sup> 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 (rs199512, rs45608532, rs13017199, and rs3094128), three of which are related to brain development and patterning.<sup>4,5</sup>

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 left-handedness is related to economic performance, hinges on intrinsic differences between right- and left-handers. The literature suggests that left-handers have, on average, worse outcomes

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<sup>1</sup>Great apes like chimpanzees and bonobos are only mildly lateralized, as observed by Hopkins et al. (2011) and Marchant and McGrew (2013), who conclude that “human handedness seems to be unique among living hominoids”.

<sup>2</sup>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 thus translate into higher levels of creativity.

<sup>3</sup>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).

<sup>4</sup>A locus is a specific position on a chromosome where a particular gene is located.

<sup>5</sup>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.

than right-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 might be conducive to growth and innovation, such as creativity and divergent thinking (Newland 1981, Coren 1995), competitiveness (Hoffman and Gneezy 2010), and leadership skills (Mukherjee 2017).<sup>6</sup> 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).<sup>7</sup>

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 genetic 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.<sup>8</sup> 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

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<sup>6</sup>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.

<sup>7</sup>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.

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

than their manual ability. The difference in manual ability between left- and right-handed workers 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.

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 on fertility 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 people, 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. We interpret our findings as evidence of a non-monotonic effect of diversity on growth.

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) and Galor and Michalopoulos (2012), among others. We share with these papers the idea that there is a two-way interaction between economic factors and the distribution of genetic traits in the population.<sup>9</sup> 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 that the

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<sup>9</sup>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.

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), Alesina, Harnoss, and Rapoport (2016), Desmet, Ortuño-Ortín, and Wacziarg (2017), Docquier et al. (2020), among others). Like Ashraf and Galor (2013), Ager and Brueckner (2018) and Cook and Fletcher (2018), who explore the impact of genetic diversity on growth and development, we find that the growth effects of diversity vary across different stages of development. We emphasize, however, the possible consequences of one specific dimension of genetic diversity, handedness.

Finally, 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 Stylized facts

In this Section we present and discuss the available evidence on left-handedness rates, over time and across countries. Although our main objective is to establish a robust stylized fact concerning the historical evolution of left-handedness, we also use cross-country data to see whether the prevalence of left-handedness correlates with economic development.

### 2.1 The evolution of left-handedness

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.<sup>10</sup>

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<sup>10</sup>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.

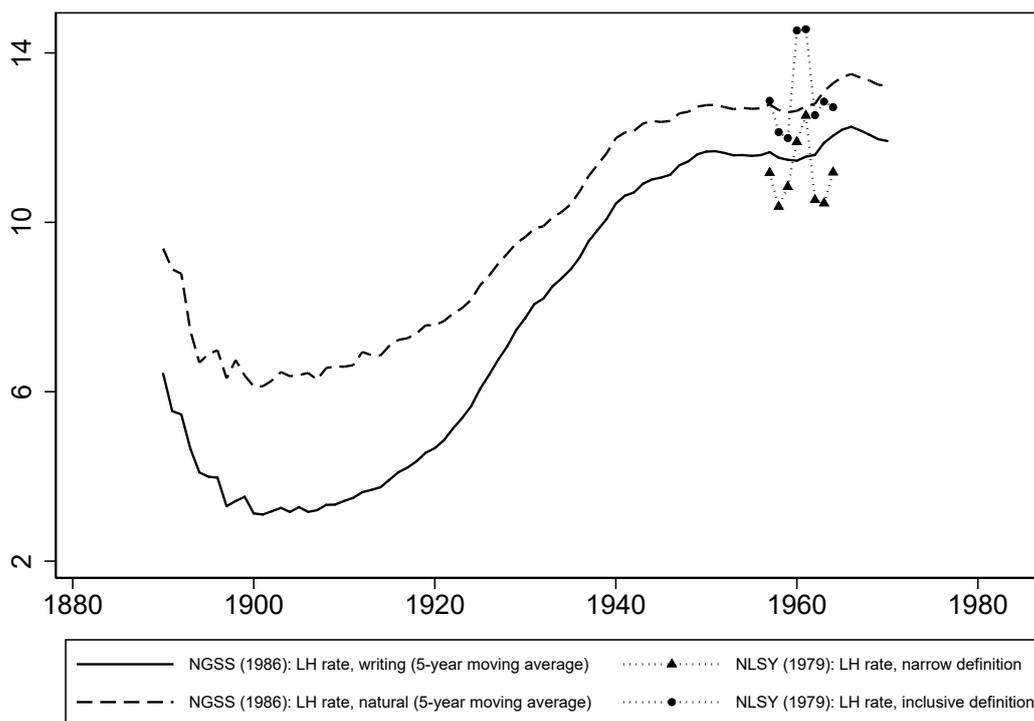


Figure 1: Left-handedness in the United States: 1887-1976.

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 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 continuous line depicts the percentage of respondents who say they use their left hand for writing, while the dashed 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 inclusive measure of left-handedness (based on the share of people who write, throw or perform both activities with their left hand) is intended to describe natural handedness, which – distinct from handedness in writing – cannot be influenced by hand-switching practices related to the stigmatization of left-handers.<sup>11</sup> Given our focus on the genetic origin of

<sup>11</sup>There is evidence of such practices, with left-handed pupils being forced to write with their right hand (see for instance Kushner 2012 and Guber 2019). Our data support the existence of hand-switching: the vertical difference between the dashed and the solid 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

handedness, the relevant stylized fact from Figure 1 is then 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 shown by Ellis et al. (1998) for the U.K.<sup>12</sup>

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.<sup>13</sup> 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.<sup>14</sup>

One may also worry about the representativeness of the NGSS sample, and the risk that self-selection biases our measure of left-handedness.<sup>15</sup> 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.<sup>16</sup>

The non-monotonic time-pattern in the NGSS data can also be retrieved from alternative sources, for the U.S. and other Western countries. Panel (a) of Figure 2 displays estimates based on a set of studies in which left-handedness rates are consistently measured for at least two different cohorts. In particular, historical data from Brackenridge (1981) on Australia and New

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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.

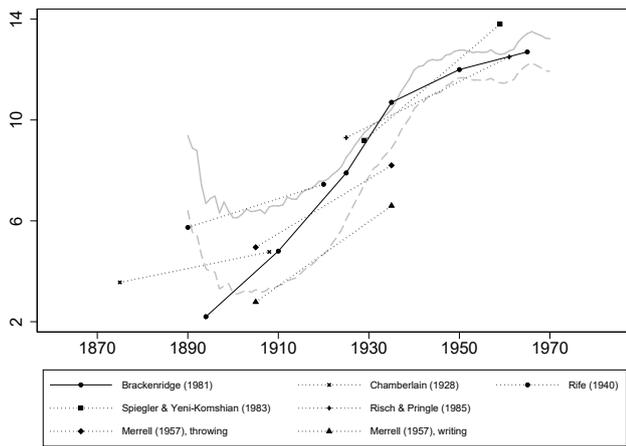
<sup>12</sup>In particular, Ellis et al. (1998) study forced dextrality on a sample of about 6,000 respondents in Lancashire, U.K. Consistent with the NGSS data, their results point to a much lower prevalence of left-handedness among older respondents (born at the end of the 1920s) than among younger 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.

<sup>13</sup>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).

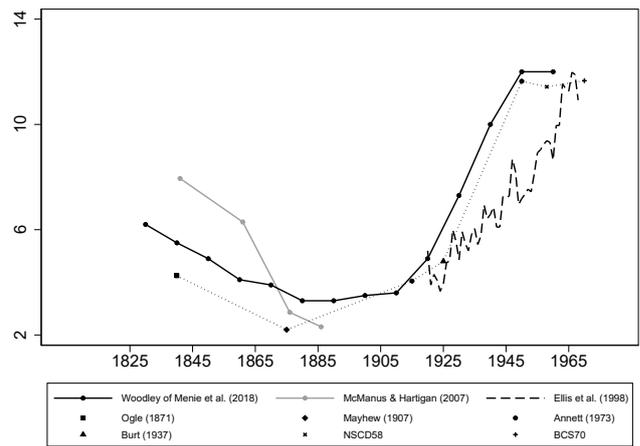
<sup>14</sup>For instance, casualties in WWI and WWII – as reported by Chambers (2000) – amounted to 0.11% and 0.31% of the U.S. population measured in 1920 and 1940, respectively. This depends on U.S. soldiers having relatively low odds of death in war: 1.1% in WWI, 1.8% in WWII and 0.6% in the Korean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

<sup>15</sup>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.

<sup>16</sup>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.



(a) U.S., Australia and New Zealand: 1860-1976.



(b) U.K., Western World: 1800-1970.

Figure 2: Left-handedness over time: additional evidence.

Zealand show an increase in the left-handedness rate from about 2% in 1894 to 13% in 1965. The other observations, based on U.S. studies, also show a trend which is comparable to the NGSS data (depicted in background), thus corroborating the idea that left-handedness became more prevalent throughout the 20th century.<sup>17</sup> As far as the 19th-century decline of left-handedness is concerned, some supplementary evidence is provided in panel (b) of Figure 2, which reports estimates based on a collection of heterogeneous sources, mostly for the U.K.<sup>18</sup> The measures of left-handedness on which these studies are based are heterogeneous (from arm waving in photographs to writing), but together they point to a *U*-shaped pattern, with left-handedness reaching a nadir somewhere in the second half of the 19th century, consistent with Figure 1.

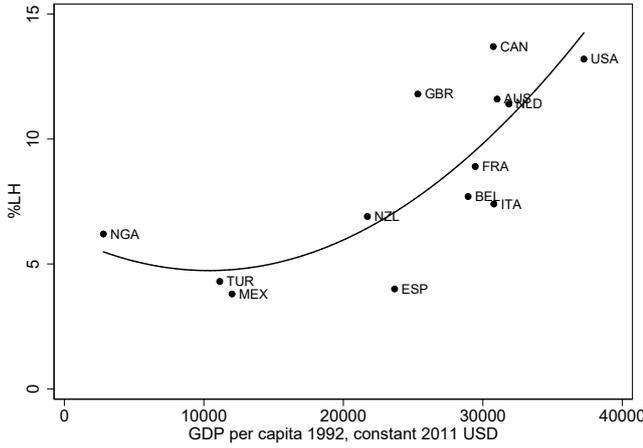
Figures 1 and 2 thus provide evidence that natural left-handedness in the Western World followed a *U*-shaped trajectory over the last two centuries, decreasing in the 19th century, increasing for most of the 20th century, and finally stabilizing. Explaining this stylized fact is one of the main objectives of our paper. In particular, we will relate the evolution of the natural left-handedness rate to the process of structural transformation that characterizes economic development. Accordingly, one may wonder whether a non-monotonic relationship between left-handedness and development can also be observed in cross-country data.

## 2.2 Left-handedness across countries

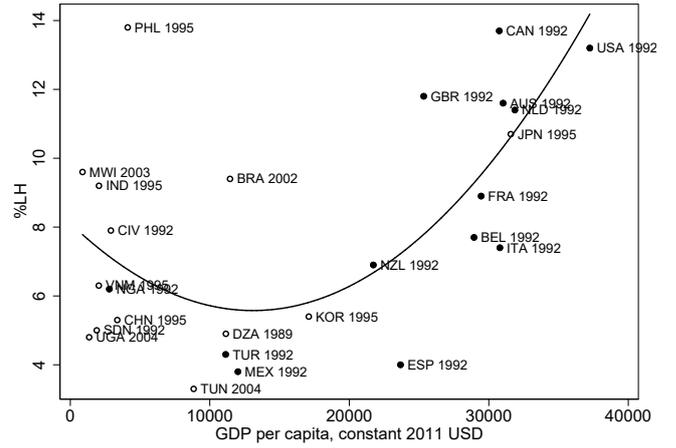
To the best of our knowledge, the largest harmonized cross-country survey on handedness was administered by Perelle and Ehrman (1994) to 12,000 subjects in 17 countries, translating into

<sup>17</sup>The data depicted in panel (a) of Figure 2 come from Chamberlain (1928), Rife (1940), Spiegler and Yeni-Komshian (1983), Risch and Pringle (1985), and Merrell (1957) (in which information is available for both writing and throwing).

<sup>18</sup>Historical evidence for the U.K. is collected from McManus and Hartigan (2007), Ellis et al. (1998), 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. Finally, Woodley of Menie et al. (2018) reconstruct a trend for the Western World, based on multiple data sources, including British ones.



(a) Perelle and Ehrman (1994).



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

Figure 3: Left-handedness and GDP across countries (1981 – 2014).

relatively large samples for 13 countries.<sup>19</sup> Figure 3 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. Although based on a small sample, a  $U$ -shaped pattern seems to emerge. In panel (b) of Figure 3, we supplement the data from Perelle and Ehrman (1994) with other estimates of left-handedness rates found in the literature, and still observe a  $U$ -shaped relationship between left-handedness and economic development.<sup>20</sup>

Notwithstanding the obvious data limitations, the cross-country pattern in Figure 3 suggests that the evolution of handedness over time described in Figures 1 and 2 may indeed be related to the dynamics of economic development.

### 3 The model

We consider an overlapping-generations economy extending over infinite discrete time. The structure of our model is sketched in Figure 4. 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 ( $\lambda_t$ ), 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.

<sup>19</sup>Namely, Australia, Belgium, Canada, France, Italy, Mexico, the Netherlands, New Zealand, Nigeria, Spain, Turkey, United Kingdom and the U.S.

<sup>20</sup>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 3, 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.

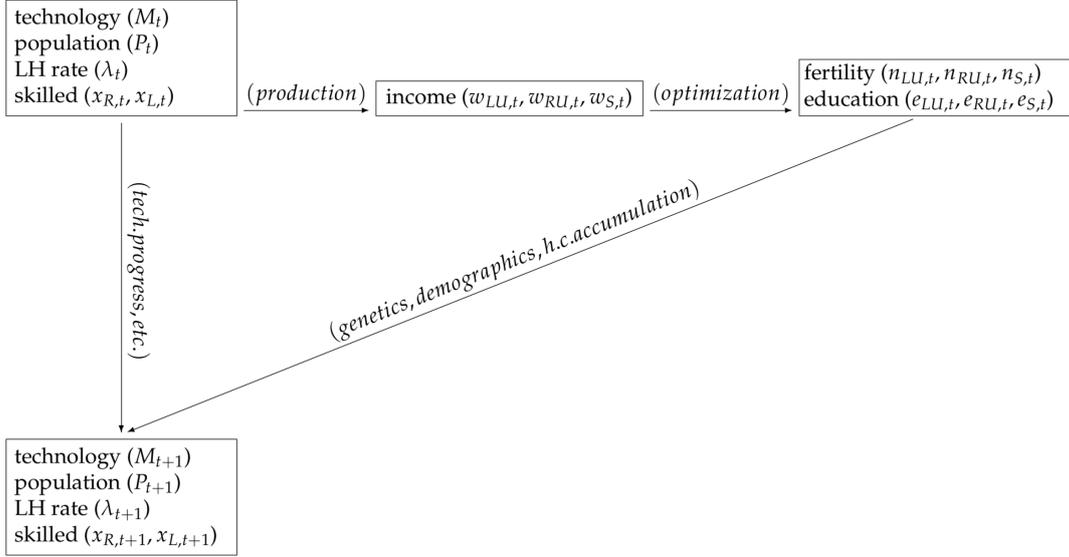


Figure 4: The structure of the model

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  $\lambda_t$  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

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

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

$$x_{i,t} = \frac{P_{iS,t}}{P_{i,t}}. \quad (2)$$

where  $i = L, R$ .

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

write:

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

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

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

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,

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

where  $\xi > 0$ ,  $\theta > 0$  and  $\beta \in (0, 1)$ . The parameter  $\xi$  is a scale parameter, while the main role of  $\theta$  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  $\beta$  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

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

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  $e_{ij,t}$  to maximize (4). The resulting optimal choices are given by

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

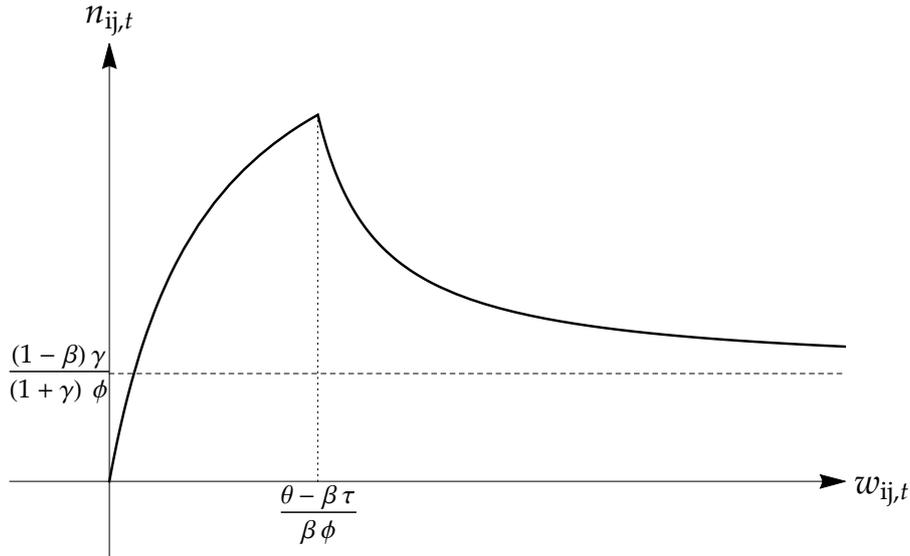


Figure 5: Endogenous fertility

and

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

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, so that  $e_{ij,t} = 0$  and fertility is increasing in income, as  $\partial n_{ij,t}/\partial w_{ij,t} > 0$ . This defines a Malthusian fertility regime. Above the threshold, parents' educational expenditure is given by an interior solution,  $e_{ij,t} > 0$ , while fertility is a decreasing function of wage, as  $\partial n_{ij,t}/\partial w_{ij,t} < 0$ . The fertility function is depicted in Figure 5, where we also take into account that  $\lim_{w_{ij,t} \rightarrow \infty} n_{ij,t} = (1-\beta)\gamma/((1+\gamma)\phi)$ .

The endogenous fertility pattern described in Figure 5 implies that higher productivity (and wage) 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 left-handedness prevalence in the population. 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.<sup>21</sup> We demonstrate this in Appendix A, where we introduce the extensive margin of fertility, thereby implying that individuals with different incomes have a differential access to marriage and reproduction.

<sup>21</sup>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).

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 B.

### 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 labor in agriculture, and constant returns in the modern sector. 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:

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

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

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

and the wage per unit of time can be written as

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

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

#### 3.3.2 The modern sector

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

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

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  $\zeta_{ij}$  accounts for type-specific productivity, with

$$\zeta_{LU,t} = 1, \quad (13)$$

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

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 which are, in most cases, designed for right-handers.

Wages per unit of time in the modern sector can be written as

$$w_{ij,t}^M = M_t \zeta_{ij,t}, \quad (16)$$

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

### 3.3.3 Labor allocation and structural change

At every  $t$ , we must have

$$P_{ij,t} = P_{ij,t}^T + P_{ij,t}^M. \quad (17)$$

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

$$w_{ij,t}^M = w_{ij,t}^T, \quad (18)$$

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.<sup>22</sup> This means that  $P_{S,0}^T = 0$  and  $P_{U,0}^M = 0$ . Whether the  $M$ -sector eventually becomes attractive to unskilled workers, thus bringing about industrialization, depends on the relationship between  $w_t^T$  and  $w_{iU,t}^M$ . Intuitively, the modern sector can become viable to (some of) them because (i)

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<sup>22</sup>The idea is that there are always a few intellectual, skilled workers, even in pre-industrial societies.

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 second mechanism above, we introduce exogenous technological progress, so that

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

and

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

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  $T_t = 1, \forall t$ .

### 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.<sup>23</sup> 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, compatible with sexual reproduction, will be considered in Appendix B. There, we will see 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.

We trace handedness back to two different genotypes, denoted by  $D$  (“dexterity”) and  $C$  (“chance”), respectively. These genotypes are assumed 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 B.

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

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<sup>23</sup>That handedness runs in families is a well-known fact, as explained in the Introduction. As far as monozygotic discordance is concerned, it has been shown (by McManus and Bryden (1992) and Vuoksima et al. (2009), among others) 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, Davison, and Armour 2013). 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.

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  $\omega$  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  $\delta_t$  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 time  $t$  is then

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

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

$$\lambda_t = \omega(1 - \delta_t). \quad (22)$$

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

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

We can therefore write

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

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

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

Similarly,

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

$$p_t(L|L) = \omega, \quad (27)$$

and

$$p_t(R|L) = 1 - \omega. \quad (28)$$

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  $\delta$  and  $\lambda$  (Equation (22)), the process of development described by Figure 4 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

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

The first three difference equations (for  $M$ ,  $P$  and  $\delta$ ) correspond to Equations (20), (3) and (24), 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 ( $\delta_t$ ), 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

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

and

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

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

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

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

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 6. 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),

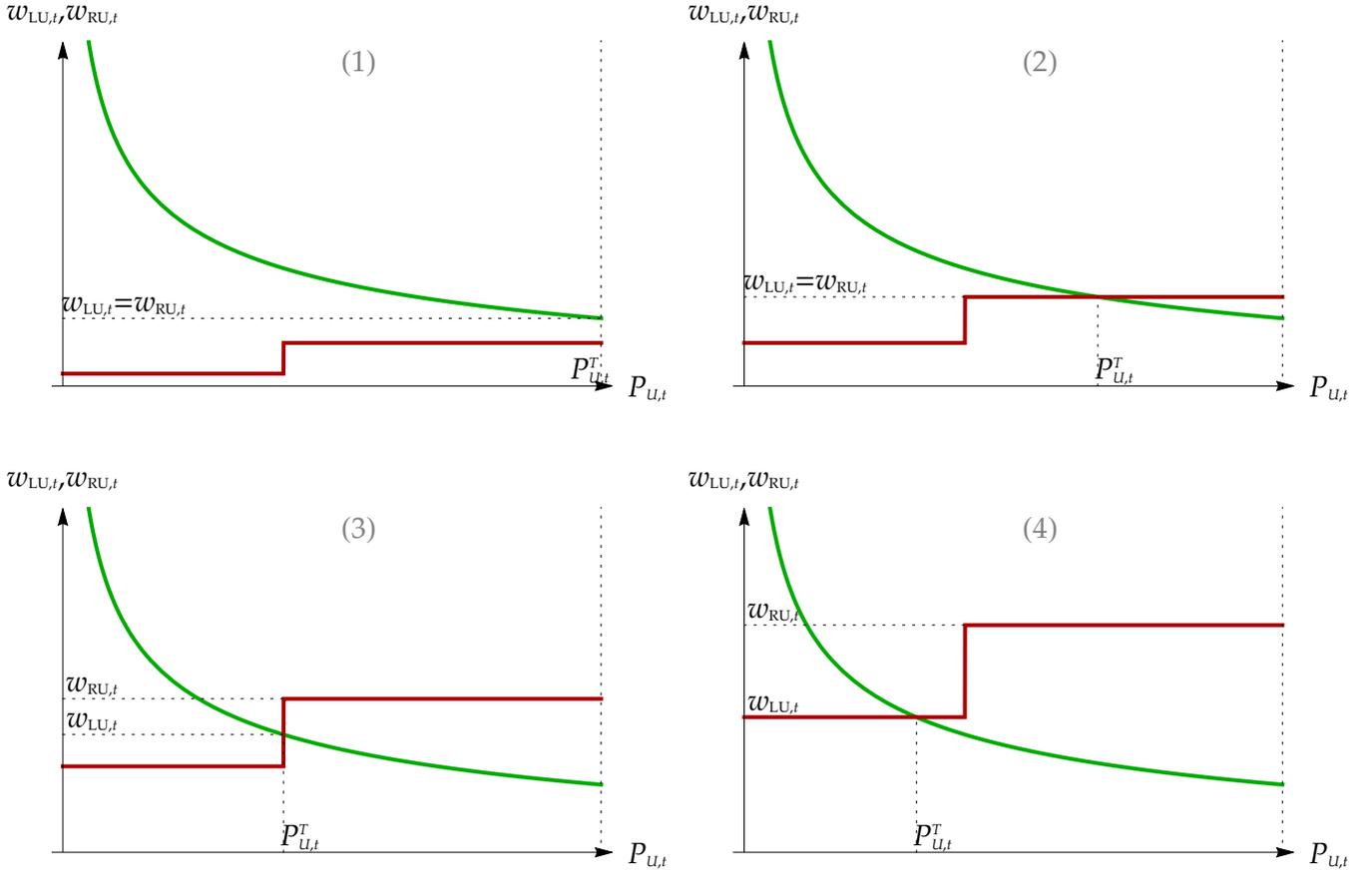


Figure 6: Structural change: traditional (green) *vs* modern (red) sector.

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*

$$P_{LU,t}^M = P_{RU,t}^M = 0; \quad (33)$$

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

*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

$$P_{LU,t}^M = 0, \quad (35)$$

$$0 < P_{RU,t}^M \leq P_{RU,t}; \quad (36)$$

$$w_{LU,t} = w_{RU,t} = \rho M_t. \quad (37)$$

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

$$P_{LU,t}^M = 0, \quad (38)$$

$$P_{RU,t}^M = P_{RU,t}; \quad (39)$$

$$w_{RU,t} = \rho M_t, \quad (40)$$

$$w_{LU,t} = P_{LU,t}^{-\alpha}. \quad (41)$$

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

$$0 < P_{LU,t}^M \leq P_{LU,t}; \quad (42)$$

$$P_{RU,t}^M = P_{RU,t}; \quad (43)$$

$$w_{RU,t} = \rho M_t, \quad (44)$$

$$w_{LU,t} = M_t. \quad (45)$$

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 D. ■

## 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 5. 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.<sup>24</sup>

Second, the average fertility of left- and right-handers in the economy 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.<sup>25</sup>

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  $\delta$ , the proportion of D-genotypes. However, based on the one-to-one relationship between  $\delta$  and the left-handedness rate  $\lambda$  established by Equation (22), we can determine the implications of differential fertility for  $\lambda$ , which is our main variable of interest.

To give a general illustration of the dynamic evolution of left-handedness, in Figure 7 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,  $\lambda_t$ , 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 7 can be thought of as an instantaneous picture of the model at time  $t$ , shedding light on the motion of  $\lambda$  from time  $t$  to time  $t + 1$ . Drawn for given values of  $\lambda_t$ ,  $x_{L,t}$  and  $x_{R,t}$ , Figure 7 thus tells us how  $\lambda$  changes from  $t$  to  $t + 1$  for any possible combination of  $M_t$  and  $P_t$ . Note, however, that Figure 7 is not a phase diagram, for the boundaries between the different regions

<sup>24</sup>They also have lower average human capital than right-handers. 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*.

<sup>25</sup>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 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.

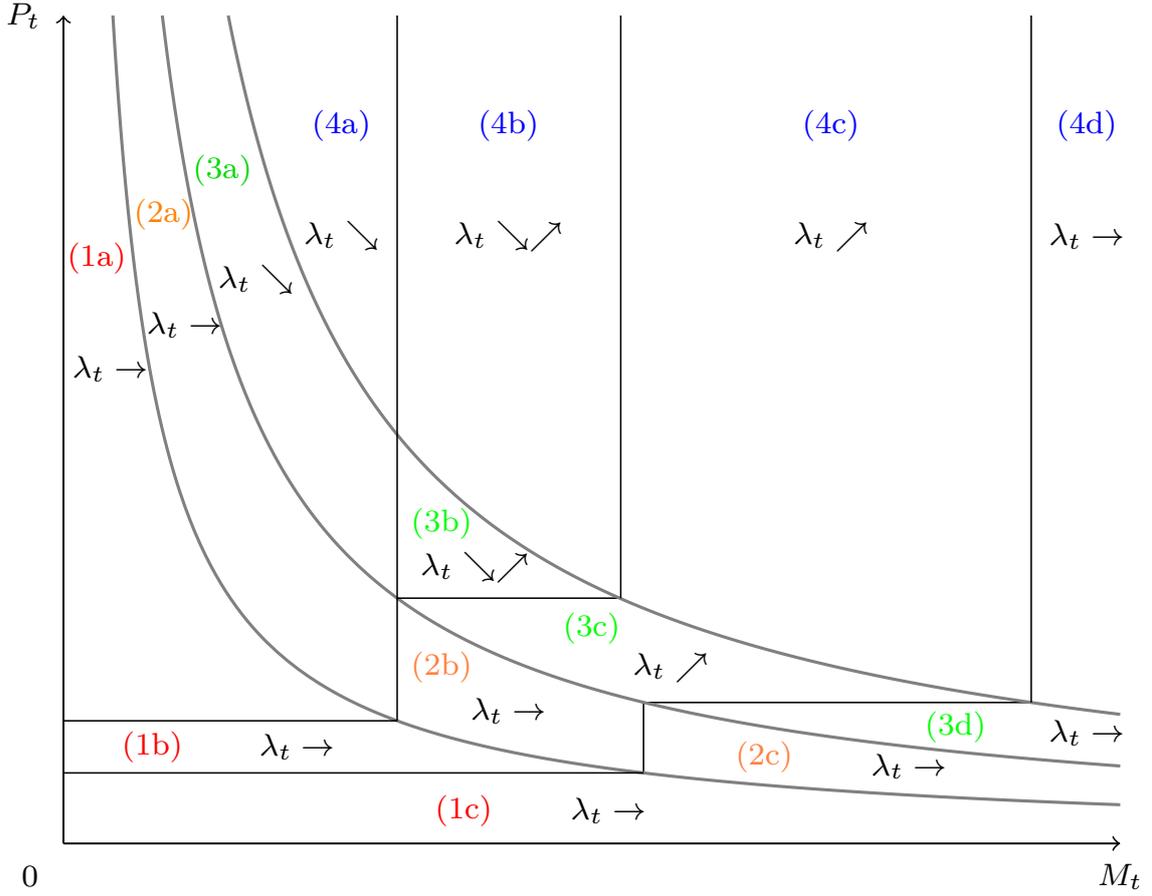


Figure 7: The dynamics of  $\lambda$  depending on technology and population

change over time and must be updated when the values of  $\lambda$ ,  $x_L$  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.<sup>26</sup> We will then draw implications for the dynamics of  $\lambda$  in the subsequent Proposition 2.

<sup>26</sup>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 7, for given  $\lambda$  and  $x_i$ . It can indeed be proven that

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

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

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

(1c) If  $P_{U,t} \leq \left(\frac{(1 - \beta)\xi^{-1/\beta} + \beta(\theta - \tau)}{\beta\phi}\right)^{-1/\alpha}$ , 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 D. ■

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

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

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

(2c) If  $M_t \geq \frac{(1 - \beta)\xi^{-1/\beta} + \beta(\theta - \tau)}{\beta\phi\rho}$ , 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 D. ■

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.<sup>27</sup> 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 6).

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

<sup>27</sup>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.

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

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

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

(3d) If  $P_{LU,t} \leq \left(\frac{(1 - \beta)\xi^{-1/\beta} + \beta(\theta - \tau)}{\beta\phi}\right)^{-1/\alpha}$ , 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 D. ■

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

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

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

(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 D. ■

Lemmas 2.3 and 2.4 illustrate how the emergence of human capital inverts 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 ( $\delta$ ) and the prevalence of left-handedness ( $\lambda$ ) evolve, conditional on the state of the economy. For ease of presentation, the following Proposition focuses on phenotypical dynamics, showing how  $\lambda$  moves within each phase of development. Given the one-to-one relationship between  $\delta$  and  $\lambda$  highlighted by Equation (22), the underlying dynamics of  $\delta$  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 7. Suppose for instance that the values of  $M_t$  and  $P_t$  (given  $x_{L,t}$ ,  $x_{R,t}$  and  $\delta_t$ ) 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  $\lambda$  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.

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

$$\frac{\gamma}{1+\gamma} \geq \max\left(\frac{\tau}{M_0} + \phi, \frac{\phi}{1-\beta}\right).^{28} \quad (46)$$

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

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

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<sup>28</sup>This (sufficient) condition is obtained by imposing that minimum fertility, in both the Malthusian and modern regimes, must not be lower than 1.

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

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

The idea is to avoid a chronological mismatch between the demographic transition and the structural transformation of the economy. In particular, we would like 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 7 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  $\lambda$ ). 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,  $\lambda$  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 no investment in education. The proportion of left-handers  $\lambda$  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  $\lambda$ , 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  $\lambda$  reaches its final steady-state.

Overall, the dynamic behavior of  $\lambda$  is in line with the stylized facts emphasized in Section 2.<sup>29</sup> 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 7, such as (4a) or (4b) for instance, without changing qualitatively the dynamics of left-handedness.

## 4.4 Simulations

Figure 7 allows us to understand the dynamic behavior of  $\lambda$ , our main variable of interest. The underlying evolution of  $\delta$  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 quantitative 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  $\chi$  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  $\chi = 0.443$ . We further set  $\alpha = 0.27$ , which corresponds to the 1688 rent share in the English national accounts according to Doepke (2004).<sup>30</sup>

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.<sup>31</sup>

We further choose  $\theta = 1$ ,  $\xi = 0.01$ ,  $\rho = 1.5$  and  $h = 5.5$ . As initial conditions, we set  $T_0 = 1$ ,  $M_0 = 0.2$  and  $\delta_0 = 0.8$  (so that the initial prevalence of left-handedness is 10%). Initial population is normalized to 1. Note that parameters and initial conditions satisfy the condition

<sup>29</sup>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 C (see also Billiard, Faurie, and Raymond 2005).

<sup>30</sup>In the literature, the parameter  $\alpha$  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.

<sup>31</sup>The values for  $\beta$  and  $\gamma$  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  $\lim_{w_{ij,t} \rightarrow \infty} n_{ij,t}$  for both the corner and interior solutions in Equation (8). We thus obtain  $\bar{n} = \gamma / (\phi(1 + \gamma))$  and  $\underline{n} = (1 - \beta)\gamma / ((1 + \gamma)\phi)$ .  $\bar{n}$  is a hypothetical upper bound to fertility under the Malthusian regime, should the demographic transition never occur. Relying on the literature, we estimate  $\bar{n} = 5$ , *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  $\bar{n} = 2.5$ ) and Pensieroso and Sommacal (2019) (who suggest  $\bar{n} = 7.5$ , 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  $\phi$  and  $\gamma$ , from  $\underline{n} = 1$  we can residually determine  $\beta = 0.8$ , which lies in the range generally accepted by the literature.

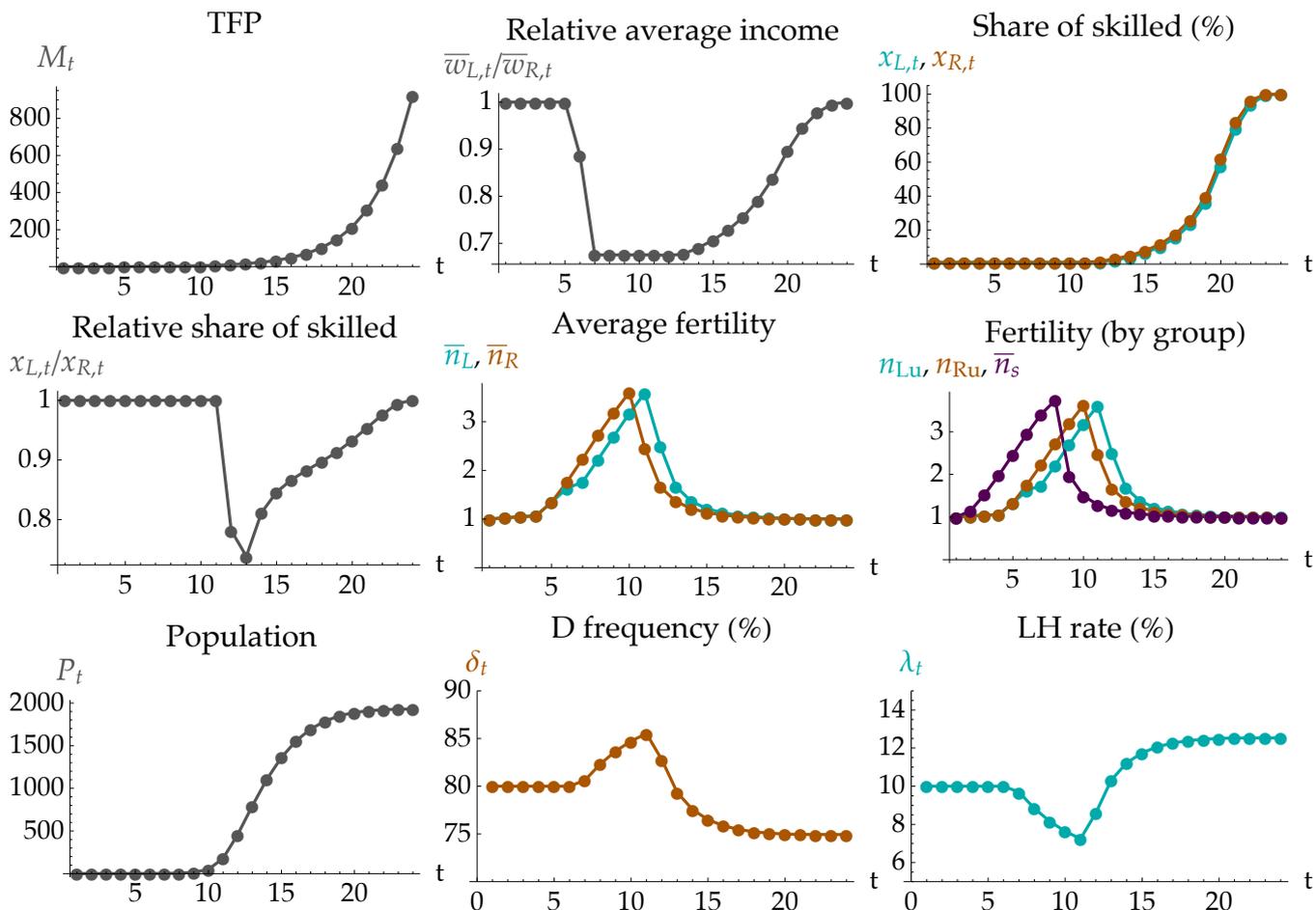


Figure 8: Simulations: the benchmark model

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.

The simulated time paths of the key variables of our model are depicted in Figure 8.

We start by discussing production- and education-related variables. The first panel of Figure 8 reproduces the evolution of  $M$ , which grows at the exogenously constant rate  $\chi$ . 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 8 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 8 (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  $\delta$  and  $\lambda$  represented in the last two panels of Figure 8. As discussed in Section 4.2, the behavior of  $\lambda$  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 twenty more years to reach 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.<sup>32</sup>

As far as the first panel of the third row of Figure 8 is concerned, it 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.

## 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.

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

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<sup>32</sup>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.

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).<sup>33</sup> 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).<sup>34</sup>

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:

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

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

In this reduced-form formulation, 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. Notice that human capital has an indirect effect on productivity growth through the average wage gap, which in turn depends on the diffusion of human capital, *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. In fact, it can be proven that  $\partial(\Delta M_{t+1}/M_t)/\partial\lambda_t > 0$  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 left-handed workers may positively contribute to

<sup>33</sup>In Appendix E.1, we use the NLSY data to show that the distribution of wages for individuals with more than 16 years of education favors left-handers.

<sup>34</sup>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.

the TFP growth through creativity and divergent thinking – which are arguably more important when production is intensive in human capital.<sup>35</sup>

Note that this extension of our model emphasizes that left-handedness influences 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 8, Figure 9 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  $\lambda$ .

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 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 10, 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.<sup>36</sup> The feedback effect from left-handedness to growth also accentuates the dynamics of  $\lambda$ , which declines more substantially during the industrial take-off, but recovers faster and reaches a higher stationary value when human capital becomes more important than manual ability.

As a further step in our theoretical appraisal of the handedness-growth relationship, in Figure 11 we plot the co-movement of the left-handedness rate and GDP per capita resulting from

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<sup>35</sup>Although different, this mechanism echoes the idea put forward by Ashraf and Galor (2012), according to whom diversity may hamper an economy's ability to exploit efficiently the existing technological frontier, but contributes to push the frontier further.

<sup>36</sup>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.

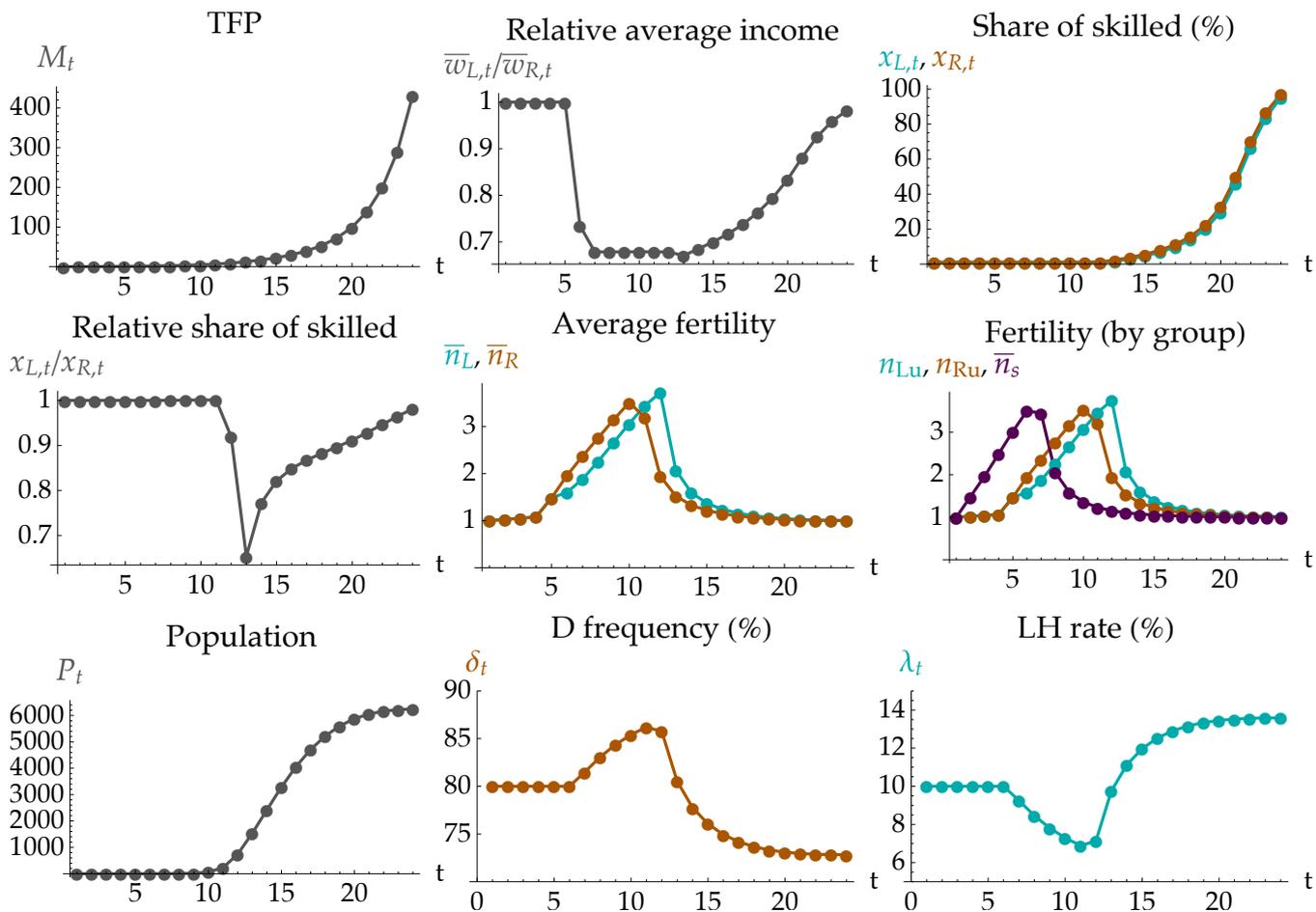


Figure 9: Simulations: endogenous growth

the simulations of the benchmark and extended models. For ease of presentation, Figure 11 only considers the simulated values of our variables of interest from  $t = 13$ , corresponding to the nadir of left-handedness. From that point on, the key endogenous variables evolve monotonically, making the interpretation of the results more straightforward, 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 E.2 (Figure 17) 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 11. 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

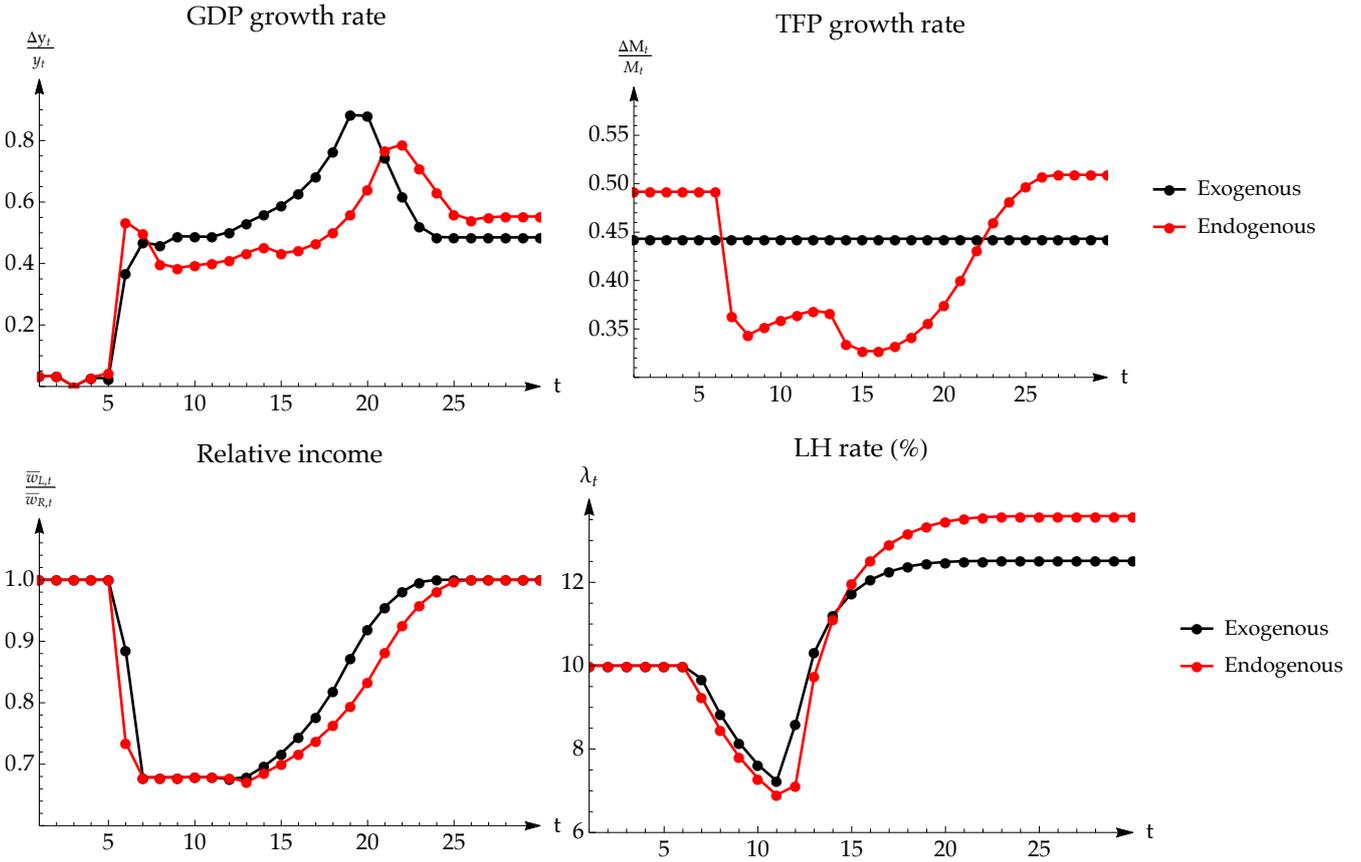


Figure 10: Endogenous vs exogenous growth

on growth. The sign of the correlation between  $\lambda$  and the growth rate of GDP per capita changes over time – or better, across different stages of development. 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 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 in line 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 provides

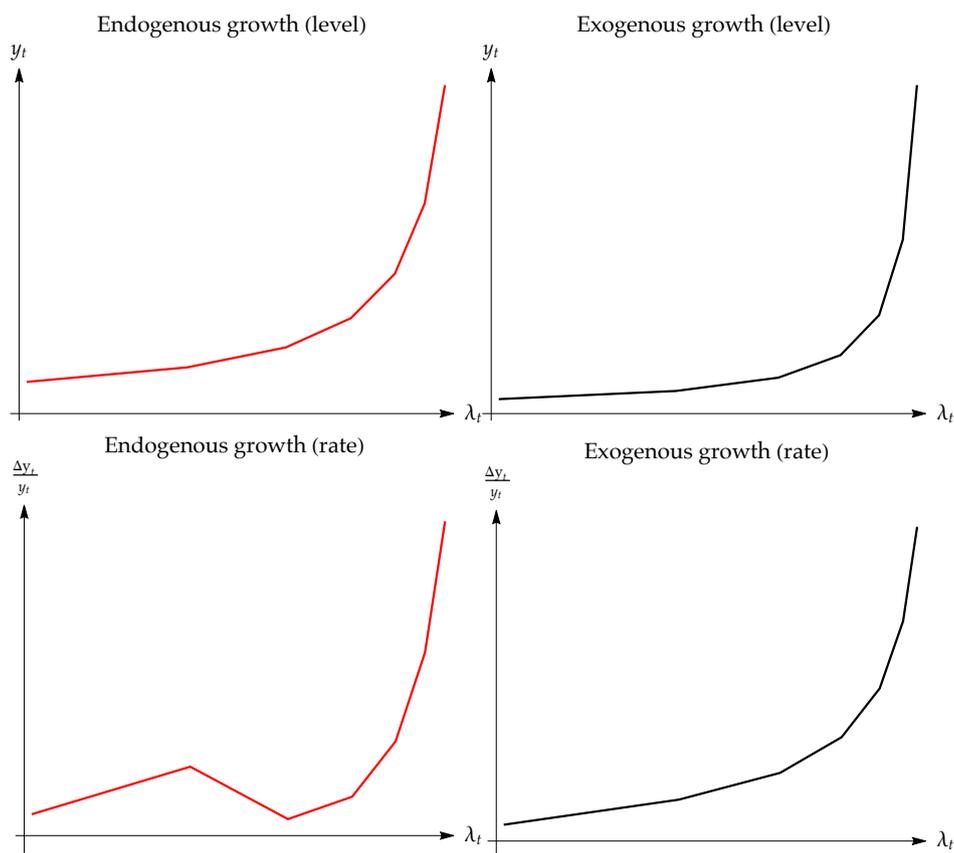


Figure 11: Co-movement between  $\lambda$  and GDP

them with a reproductive advantage driving 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 then 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.<sup>37</sup> The SHARE data thus

<sup>37</sup>The countries in the sample are: Austria, Belgium, Denmark, France, Germany, Greece, Israel, Italy, the Netherlands, Spain, Sweden, and Switzerland.

Table 2: Completed fertility by cohort.

	(1)	(2)	(3)	(4)	(5)
<i>Birth year</i>	$\leq 1922$	1923 – 1932	1933 – 1942	1943 – 1952	$\geq 1953$
<i>Panel (a)</i>					
LH	0.488** (0.179)	-0.153 (0.502)	-0.158 (0.159)	-0.152 (0.131)	-0.312 (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
<i>Panel (b)</i>					
LH	0.698*** (0.151)	-0.0516 (0.421)	-0.180 (0.155)	-0.196 (0.144)	-0.163 (0.202)
Couple (dummy)	3.576*** (0.197)	3.515*** (0.194)	3.201*** (0.279)	2.863*** (0.190)	2.672*** (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. \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

cannot help us to describe the fertility of cohorts born in the 19th century, but they are helpful for investigating whether left-handers born after 1900 exhibit 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:

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

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  $\delta_c$  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.<sup>38</sup> 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.

<sup>38</sup>This is robust to regressions without controls, and to setting the cutoff year in 1922, 1924 or 1925 (earlier cutoffs shrink the number of observations in the first cohort too much to observe relevant results).

Table 3: Fertility by parental handedness in family studies.

	(1) country, parents' birth cohort <sup>a</sup>	(2) Both RH	(3) At least one LH	(4) Both LH <sup>b</sup>	(5) Nb of families
Chamberlain (1928)	U.S., 1875–85	3.56	3.32	3.03	2201
Rife (1940)	U.S., 1882–92	3.21	2.76		687
Annett (1973)	U.K., 1912–25	2.10	2.05	2.10	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

<sup>a</sup>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.

<sup>b</sup>Not displayed when the sample counts less than 30 couples of left-handers.

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 the extensive margin of fertility is theoretically explored in Appendix A.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, where at least one spouse is left-handed, and where both spouses are left-handed (columns (2) to (4)). 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, Rife 1940 and Annett 1973). 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 a fertility surplus (first half of the 20th century), before converging to the same fertility as right-handers from the mid-20th century.

## 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 causal 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 – the correlation between left-handedness and growth should switch from negative to positive. As long as the share of left-handers is relatively low, the negative effect 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 restore a positive correlation. In accordance with our theory, a change in the sign of the empirical correlation between left-handedness rate and growth rate over time could thus be interpreted as evidence of a possible impact of left-handedness on economic growth.

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 data (presented in Section 2), we compute the left-handedness rate of the working-age population of each U.S. state in 1960, 1970, 1980 and 1990. Specifically, we calculate the prevalence of left-handedness observed the first year of the decade among individuals aged 15 to 45, who represent the most productive or creative age-class of the population.<sup>39</sup> Second, we take advantage of 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).<sup>40</sup>

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

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<sup>39</sup>Our results are robust to considering alternative lower (namely, 20 or 25) and upper (namely, 50 or 60) bounds for the working-age population.

<sup>40</sup>Output per worker is also used by 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).

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 for which we have a small number of observations, we focus on the cohorts of 1960, 1970, 1980 and 1990 (which respectively gather 547,396, 736,983, 737,815 and 625,998 respondents), and exclude data before 1960. Second, we observe the respondents' state of residence at the time of the survey (1986), rather than when they are part of the working-age population. Our estimates of state-level left-handedness rates are thus based on the implicit assumption that respondents are still living in 1986 in the state where they worked when aged 15 to 45. To mitigate the risk that migration biases our measurement of left-handedness, we start our empirical exercise by focusing only on the youngest cohort of our data, *i.e.* individuals born between 1945 and 1975 who, according to our definition, form the core of the working-age population in 1990.

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

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

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 in the working-age population, 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

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

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 percentage point increase in the share of left-handers is associated, on average, with a 2.7% faster growth (the state-level average growth over the period being close to 17.5%). 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.<sup>41</sup> 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 non-significant. This loss of statistical significance 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

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<sup>41</sup>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 2.5% higher growth rate over the following decade, which corresponds to around 0.4 s.d. and to +0.25% per annum.

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

<i>Dependent variable:</i>	(1)	(2)	(3)	(4)
$\Delta \ln(\text{real output per worker})$	OLS, 1990-2000		FE	
Initial real output	-0.0489	-0.533***	-0.538***	-0.545***
per worker (ln)	(0.100)	(0.0693)	(0.0717)	(0.101)
LH (%)	0.0270***	-0.0162	-0.0175	-0.267***
	(0.00994)	(0.0169)	(0.0163)	(0.0918)
LH (%) x Post-1980 (dummy)			0.0300***	
			(0.0103)	
LH (%) x Schooling (ln)				0.105***
				(0.0380)
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	0.243	0.770	0.787	0.781

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 45, 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 labor force.

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 also 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 non-monotonic link between left-handedness and growth, with a positive association emerging only in recent times, *i.e.* when the level of economic 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 the labor force (from Turner et al. 2006), measured at the beginning of each decade. 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 average education is low, the correlation between the share of left-handers and growth becomes positive once the average years of schooling in the labor force exceeds, approximately, 12.7 years – a threshold that the

U.S. on average, as well as most of the states, reached during the 1980s.<sup>42</sup>

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 be detrimental to growth in unskilled economies, where manual ability (and possibly conformism) are key determinants of economic success.

The results presented 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 working-age population (aged 15 to 45) with the share of left-handers in the previous generation (aged more than 45).<sup>43</sup> 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.<sup>44</sup> 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 4% 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 literature, 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.<sup>45</sup> 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

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<sup>42</sup>In 1990, 17 states still exhibited an average level of education lower than the threshold (Alabama, Arkansas, Florida, Georgia, Indiana, Kentucky, Louisiana, Mississippi, Missouri, New Mexico, North Carolina, Pennsylvania, Rhode Island, South Carolina, Tennessee, Texas and West Virginia). In 2000, only one state (West Virginia) was below the threshold.

<sup>43</sup>Using the alternative cutoff ages of 50 and 60 yields similar results.

<sup>44</sup>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 0.727, 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.

<sup>45</sup>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).

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

<i>Dependent variable:</i>	(1)	(2)	(3)	(4)
$\Delta \ln(\text{real output per worker})$	2SLS, 1990-2000		sGMM	
Initial real output	-0.0605	-0.223***	-0.202***	-0.0874
per worker (ln)	(0.0817)	(0.0493)	(0.0480)	(0.0768)
LH (%)	0.0403***	0.00472	-0.00118	-0.250**
	(0.0114)	(0.00671)	(0.00608)	(0.0990)
LH (%) x Post-1980 (dummy)			0.0332***	
			(0.0116)	
LH (%) x Schooling (ln)				0.108***
				(0.0374)
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	0.285			
First stage F-test	52.32			
Number of instruments		58	58	51
AR1 test (p-values)		0.001	0.001	0.001
AR2 test (p-values)		0.225	0.180	0.296
Hansen test of joint instrument validity (p-values)		0.174	0.136	0.116
Difference-in-Hansen test of instrument subsets (p-values)				
Instruments for levels		0.651	0.860	0.793
Instruments for initial output		0.943	0.777	0.705

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 45, 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 labor force.

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

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.<sup>46</sup> The findings are very much in line with the fixed-effects estimates. In

<sup>46</sup>In columns (2) and (3), we use the second to sixth lags (both in differences and in levels) as instruments. In column (4), we use the second and further collapsed lags. Using the second to sixth lags, as in the previous two columns, yields very similar results but generates 87 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

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)). Note also that the coefficients of the interaction terms in columns (3) and (4) of Table 5 are very close to those reported in columns (3) and (4) of Table 4, thus attesting to the robustness of our findings across estimation methods.

Overall, our empirical results are compatible with the existence of a non-monotonic correlation between left-handedness prevalence and economic growth. In Appendix F, 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.

## 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 technological progress, 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.

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tests for the validity of instrument subsets confirm that the stationarity restrictions on the initial conditions process required for the validity of sGMM are satisfied (see Roodman 2009).

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# Appendices

## A 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 in 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.

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.

### A.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).<sup>47</sup>

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 (rather than non-industrial) areas of the four localities of Prussia that he studies in 1894–96. In addition, Haines (1976) observes that, in the Prussian Upper Silesia (Oppeln) between 1831 and 1913, fertility was

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<sup>47</sup>Clark and Cummins (2015) suggest, however, that the inversion of the income-fertility relationship in Britain may have happened before the 19th century.

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 6. Since our theory 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 6 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.

## A.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

$$e_{ij,t} = \begin{cases} 0 & \text{if } w_{ij,t} \leq \frac{1}{\beta\phi} \\ \frac{\beta\phi w_{ij,t} - 1}{1 - \beta} & \text{if } w_{ij,t} > \frac{1}{\beta\phi} \end{cases}, \quad (52)$$

and

$$n_{ij,t} = \begin{cases} \frac{\gamma}{(1 + \gamma)\phi} & \text{if } w_{ij,t} \leq \frac{1}{\beta\phi} \\ \frac{\gamma(1 - \beta)w_{ij,t}}{(1 + \gamma)(\phi w_{ij,t} - 1)} & \text{if } w_{ij,t} > \frac{1}{\beta\phi} \end{cases}. \quad (53)$$

Fertility, as a function of wages, is now described by Figure 12. The Malthusian, upward-sloping portion of the fertility curve represented in Figure 5 is replaced by a horizontal segment: as long as agents do not invest in education, wage differentials 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, 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  $v_{ij,t}$ , which

Table 6: 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
		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 pages 135–36) and Haines (1976) (Table 1 page 337).

depends on relative income. In particular,

$$v_{ij,t} = \left( \frac{w_{ij,t}}{w_{S,t}} \right)^\psi, \quad (54)$$

with  $\psi > 0$ .

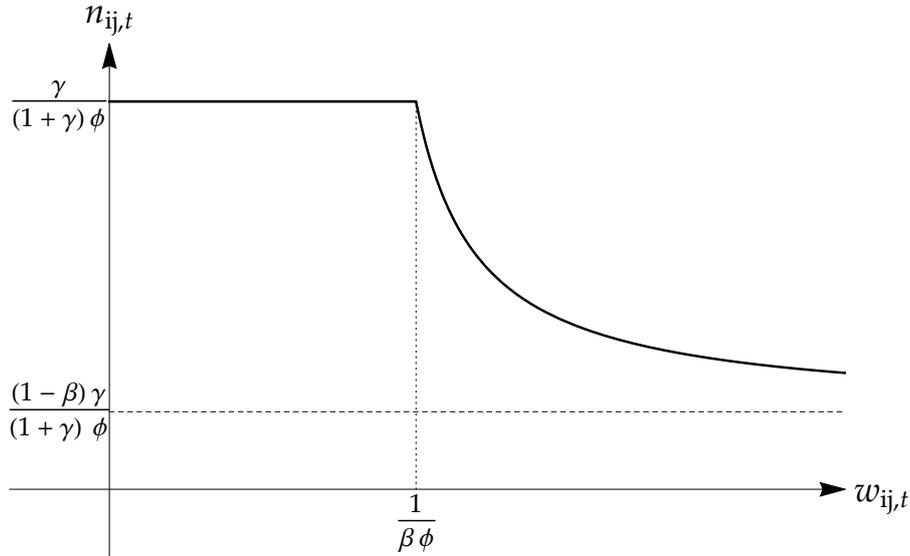


Figure 12: Endogenous fertility, when  $\tau = 0$

This means that, while skilled agents are certain to find a marriage partner, 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 income *per se* does not affect the fertility of married people, *i.e.* the intensive margin.<sup>48</sup> Formally, average fertility rates by type can be written as

$$\bar{n}_{ij,t} = v_{ij,t} n_{ij,t}. \quad (55)$$

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 to 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 13. 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 14 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.<sup>49</sup>

<sup>48</sup>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).

<sup>49</sup>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

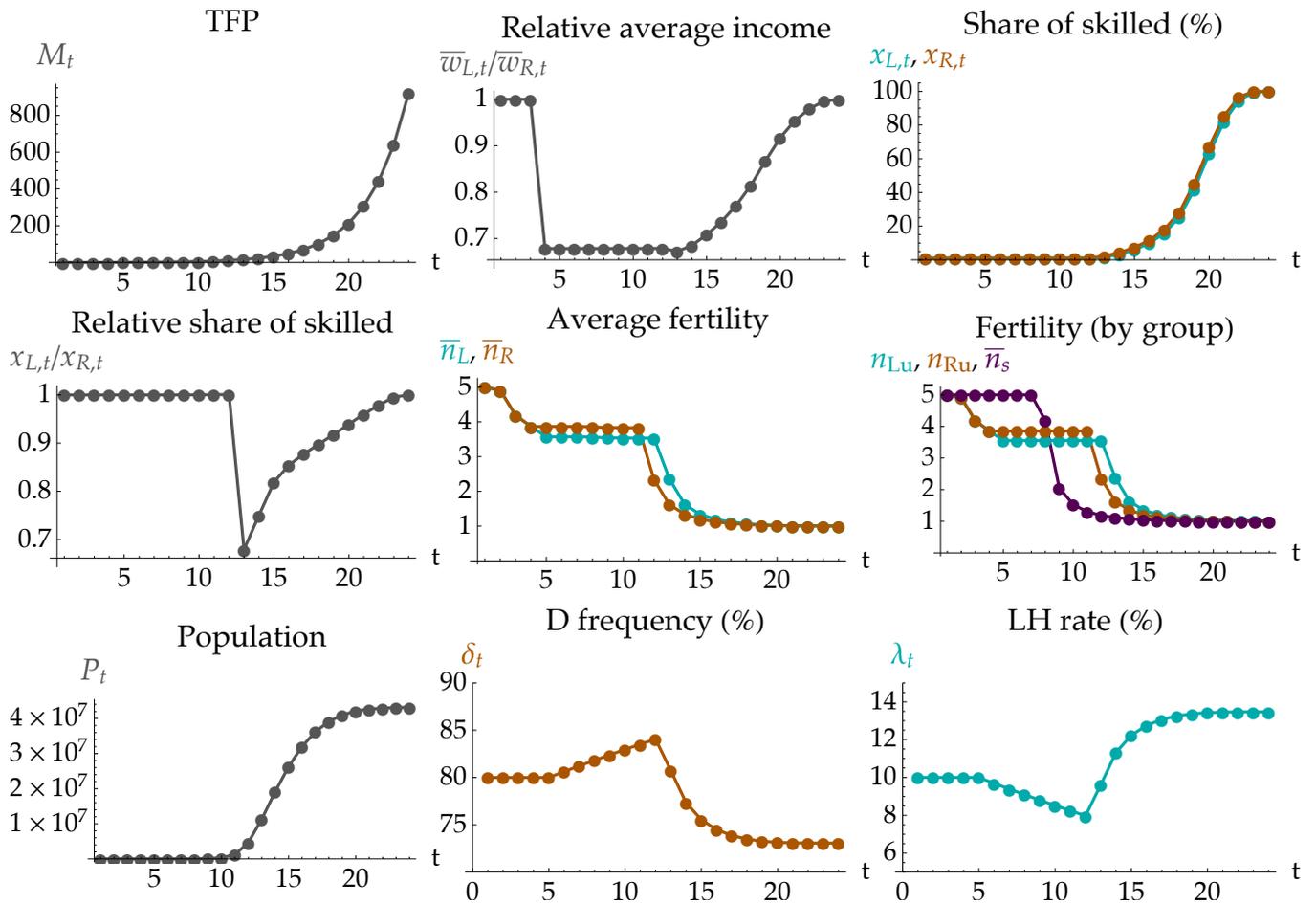


Figure 13: Simulations of the model with extensive margin of fertility

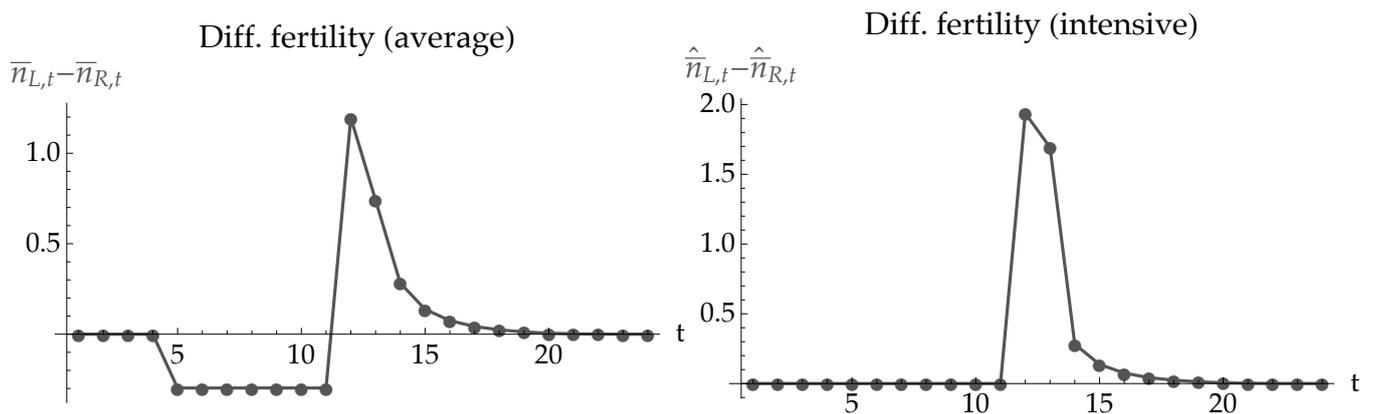


Figure 14: Simulations of the model with extensive margin of fertility: intensive vs average fertility differentials

Overall, this alternative version of the model accommodates our theory to the possibility that 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).

the decrease in left-handedness rates might have lasted beyond the tipping point of the income-fertility relationship in the United States. In fact, it can generate a decline in the prevalence of left-handedness without relying on an explicit Malthusian mechanism. If unskilled left-handers, being on average poorer, were discriminated against on the marriage market during the 19th century, this could have caused the frequency of  $D$  genes to increase, even in the absence of a positive correlation between income and fertility.<sup>50</sup>

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.<sup>51</sup> The decline of  $\lambda_t$  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).

## B 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 also consistent with our description of optimal choices as emanating from single-parent households. In this Appendix, we show that our theoretical 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.<sup>52</sup>

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  $CC$ .<sup>53</sup> We further assume that individ-

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<sup>50</sup>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.

<sup>51</sup>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).

<sup>52</sup>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).

<sup>53</sup>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.

uals 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 probability  $p(L|DC) = p(L|CD) = 1/4$ .<sup>54</sup>

We denote by  $\delta_t$  the proportion of  $D$ -alleles at time  $t$ .<sup>55</sup> If  $\sigma \in [0, 1]$  is the degree of ex-ante genotypic assortative mating, the frequency  $f$  of the different genotypes is given by the following equations:

$$f_{DD} = \delta_t(\sigma + (1 - \sigma)\delta_t), \quad (56)$$

$$f_{CC} = (1 - \delta_t)(\sigma + (1 - \sigma)(1 - \delta_t)), \quad (57)$$

and

$$f_{CD} = f_{DC} = 2(1 - \delta_t)(1 - \sigma)\delta_t. \quad (58)$$

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  $f_{DD} = \delta$ .<sup>56</sup>

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

$$1 - \lambda_t = p(R|DD)f_{DD} + p(R|CC)f_{CC} + p(R|DC)f_{DC} + p(R|CD)f_{CD}. \quad (59)$$

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

$$\lambda_t = \frac{1 - \delta_t}{2}. \quad (60)$$

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 the right- and left-handers as  $\bar{n}_{R,t}$  and  $\bar{n}_{L,t}$ , respectively, we have that

$$\delta_{t+1} = \frac{\delta_t((1 - \delta_t)(1 - \sigma)\bar{n}_{L,t} + (3 + \delta_t + \sigma(1 - \delta_t))\bar{n}_{R,t})}{2((1 - \delta_t)\bar{n}_{L,t} + (1 + \delta_t)\bar{n}_{R,t})}. \quad (61)$$

<sup>54</sup>Such probabilities may be re-parameterized, but we prefer to stick to these simple values and remain fully consistent with McManus (1985).

<sup>55</sup>In Section 3.4,  $\delta_t$  was used to denote the proportions of  $D$ -genotypes.

<sup>56</sup>On the importance of assortative mating by genotype, see Conley et al. (2016) and Hugh-Jones et al. (2016). Our numerical simulations show that the dynamic behavior of the whole model is not very sensitive to the value assigned to  $\sigma$ .

We can therefore write

$$\Delta\delta_t = -\frac{(1 - \delta_t)\delta_t(1 + \sigma)(\bar{n}_{L,t} - \bar{n}_{R,t})}{2(1 - \delta_t)\bar{n}_{L,t} + 2(1 + \delta_t)\bar{n}_{R,t}}, \quad (62)$$

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

**Lemma 2** *The frequency of D-alleles increases (decreases), and the proportion of left-handed individuals decreases (increases), when the average fertility of right-handed individuals is higher (lower) than that of the left-handed individuals. If reproductive success is the same across different agents, allele frequency stabilizes.*

**Proof.** Follows directly from Equations (60) and (62). ■

Note that Equations (60), (61) and (62) are the counterparts of Equations (22), (23) and (24) in the benchmark model. Similarly, Lemma 2 is the diploid version of Lemma 1. Overall, 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.

## C 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.<sup>57</sup>

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

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<sup>57</sup>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).

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  $\eta$ ) and the scarcity-related advantage of left-handers (through  $\kappa$ ).

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

$$w_{L,t} = (\lambda_t + (1 - \lambda_t)(1 + (1 - \lambda_t)\kappa - \eta))P^{-\alpha}. \quad (63)$$

Symmetrically,

$$w_{R,t} = ((1 - \lambda_t) + \lambda_t(1 - (1 - \lambda_t)\kappa + \eta))P^{-\alpha}. \quad (64)$$

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

$$\lambda^* = 1 - \eta/\kappa, \quad (65)$$

thus depending on the two parameters,  $\kappa$  and  $\eta$ , which determine the outcome of fighting.

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).

## D Proofs

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

### D.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.

### D.1.1 Stage (1)

In our economy, all unskilled workers are employed in agriculture at time  $t$  if,  $\forall i, w_i^T > w_{iU,t}^M$ . 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

$$P_{U,t}^{-\alpha} > \rho M_t. \quad (66)$$

In this case, all workers earn the same wage

$$w_{LU,t} = w_{RU,t} = P_{U,t}^{-\alpha}. \quad (67)$$

The situation is depicted in panel (1) of Figure 6.

### D.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

$$\left(P_{U,t}^T\right)^{-\alpha} \leq \rho M_t. \quad (68)$$

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.*

$$\left(P_{LU,t}^T\right)^{-\alpha} > \rho M_t. \quad (69)$$

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

$$\left(P_{U,t}^T\right)^{-\alpha} = \left(P_{LU,t} + P_{RU,t}^T\right)^{-\alpha} = \rho M_t. \quad (70)$$

This gives

$$P_{RU,t}^T = (\rho M_t)^{-\frac{1}{\alpha}} - P_{LU,t}. \quad (71)$$

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:

$$w_{LU,t} = w_{RU,t} = \rho M_t. \quad (72)$$

Stage (2) is illustrated in panel (2) of Figure 6.

### D.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  $w_{LU,t}^M < w_{LU,t}^T \leq w_{RU,t}^M$ . This is the case if

$$M_t < \left(P_{LU,t}^T\right)^{-\alpha} \leq \rho M_t. \quad (73)$$

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

$$w_{RU,t} = w_{RU,t}^M. \quad (74)$$

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

$$w_{RU,t} \geq w_{LU,t} = w_{LU,t}^T. \quad (75)$$

This case with perfect segregation by handedness is represented in panel (3) of Figure 6.

### D.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

$$\left(P_{LU,t}^T\right)^{-\alpha} \leq M_t, \quad (76)$$

which implies that

$$w_{LU,t}^T \leq w_{LU,t}^M. \quad (77)$$

In particular, the number of unskilled, left-handed workers who are still employed in the traditional sector can be retrieved from Equation (76), and is given by

$$P_{LU,t}^T = M_t^{-1/\alpha}. \quad (78)$$

Accordingly,

$$P_{LU,t}^M = P_{LU,t} - M_t^{-1/\alpha}, \quad (79)$$

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 6.

## D.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.

### D.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

$$P_{U,t} > \left( \frac{\theta - \beta\tau}{\beta\phi} \right)^{-1/\alpha}, \quad (80)$$

we have

$$e_{RU,t} = e_{LU,t} = 0 \quad (81)$$

and

$$n_{RU,t} = n_{LU,t}. \quad (82)$$

We are then in a Malthusian regime, corresponding to region (1a) in Figure 7. Notice that in this case the probability of having a skilled child,  $\pi_{ij,t}$ , is equal to  $\tilde{\zeta}\theta^\beta$  – as can be inferred from Equation (5).

If instead

$$P_{U,t} \leq \left( \frac{\theta - \beta\tau}{\beta\phi} \right)^{-1/\alpha}, \quad (83)$$

then

$$e_{RU,t} = e_{LU,t} = \frac{\beta(\tau + \phi P_{U,t}^{-\alpha}) - \theta}{1 - \beta} > 0, \quad (84)$$

and

$$n_{RU,t} = n_{LU,t}. \quad (85)$$

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

$$P_{U,t} > \left( \frac{(1 - \beta)\tilde{\zeta}^{-1/\beta} + \beta(\theta - \tau)}{\beta\phi} \right)^{-1/\alpha}, \quad (86)$$

which – together with Equation (83) – defines region (1b) in Figure 7. We will instead have  $\pi_{ij} = 1$  as soon as

$$P_{U,t} \leq \left( \frac{(1 - \beta)\tilde{\zeta}^{-1/\beta} + \beta(\theta - \tau)}{\beta\phi} \right)^{-1/\alpha}. \quad (87)$$

The above condition identifies region (1c) in Figure 7, 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  $M_t$ .

### D.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 7, corresponding to threshold values of  $M_t$ .

### D.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.*

$$n_{LU,t} = \frac{\gamma w_{LU,t}}{(1 + \gamma)(\tau + \phi w_{LU,t})} \quad (88)$$

and

$$n_{RU,t} = \frac{\gamma(1 - \beta)w_{RU,t}}{(1 + \gamma)(\tau + \phi w_{RU,t} - \theta)}, \quad (89)$$

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

$$\tilde{M}_t = \frac{(\theta - \tau)}{\beta\rho\phi - P_{LU,t}^{-\alpha}(1 - \beta)\rho\tau}. \quad (90)$$

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  $\lambda$  increases (decreases) from  $t$  to  $t + 1$ .

Within region (3b), the threshold function  $\tilde{M}_t$  turns out to be increasing and concave in  $P_{LU,t}$ . It is represented by a dashed line in Figure 15, which zooms in Figure 7 on 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 7). This can be verified by substituting the

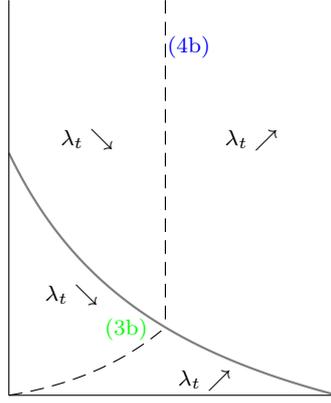


Figure 15: The dynamics of  $\lambda$ : the reversal of the fertility differential in regions (3b) and (4b)

coordinates of this point, *i.e.*

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

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

into Equation (90).

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

$$P_{LU,t} = \left( \frac{\theta - (1 - \rho(1 - \beta))\tau}{\beta\rho\phi} \right)^{-\frac{1}{\alpha}}. \quad (91)$$

#### D.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

$$\hat{M}_t = \frac{\theta - (1 - \rho(1 - \beta))\tau}{\beta\rho\phi}. \quad (92)$$

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 (91). This is illustrated in Figure 15.

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  $\lambda$  increases (decreases) from  $t$  to  $t + 1$ .

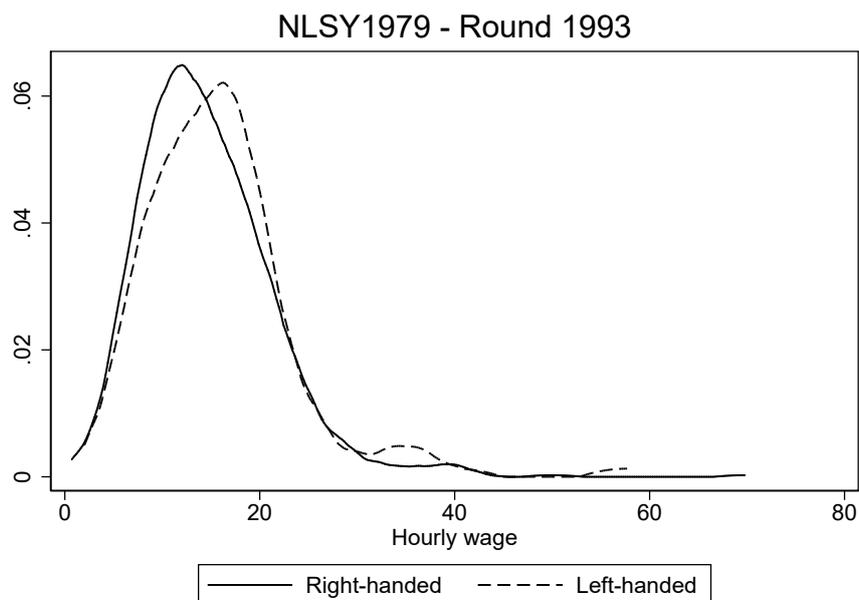


Figure 16: Distribution of earnings by handedness (education >16 years)

Table 7: 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. \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$

## E Additional stylized facts

### E.1 Left- vs right-handers

Here, 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, we plot in Figure 16 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 highly educated people – left-handers earn higher wages, which could reflect higher productivity levels. This difference in earnings is statistically significant, as reported in Table 7.

### E.2 Left-handedness and income

In Figure 17, we plot left-handedness rates by state and decade of birth (obtained from the NGSS) against data on 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.

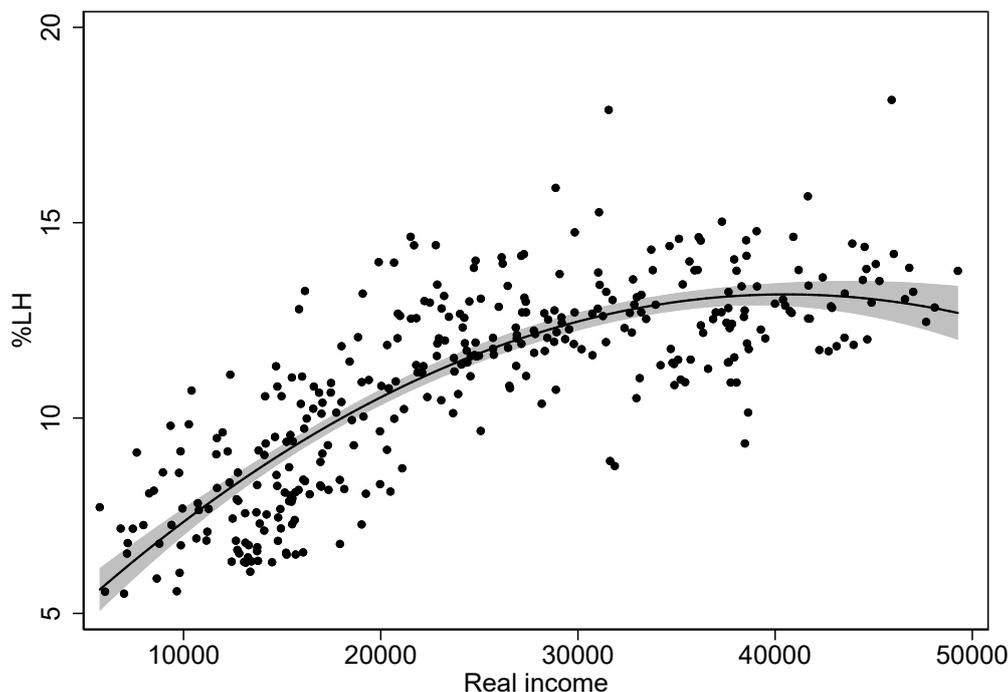


Figure 17: Left-handedness and income across the U.S. states, 1910 – 1980.

This concave relationship is in line with the prediction of our simulated model, as illustrated by Figure 11 that shows the correlation between income and left-handedness after the nadir of left-handedness.

## F 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 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. To measure TFP, we compute the ratio between output per worker and average years of schooling. 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 8 and 9, which are immediately comparable with Tables 4 and 5. Similar to what we found for output growth, we observe a positive 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 9. Overall, our results on TFP growth are com-

patible with the hypothesis that left-handedness influences economic development through the productivity channel.

Table 8: Left-handedness and TFP growth I.

<i>Dependent variable:</i>	(1)	(2)	(3)	(4)
$\Delta \ln(TFP)$	OLS, 1990-2000		FE	
Initial TFP (ln)	-0.108 (0.0926)	-0.624*** (0.0922)	-0.658*** (0.0832)	-0.615*** (0.0955)
LH (%)	0.0252** (0.00975)	-0.0127 (0.0170)	-0.0143 (0.0166)	-0.278*** (0.0841)
LH (%) x Post-1980 (dummy)			0.0291*** (0.0104)	
LH (%) x Schooling (ln)				0.110*** (0.0350)
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	0.227	0.819	0.832	0.831

Robust standard errors in parentheses. \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

*LH (%)* is the prevalence of left-handedness among the population aged 15 to 45, 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 labor force.

Table 9: Left-handedness and TFP growth II.

<i>Dependent variable:</i>	(1)	(2)	(3)	(4)
$\Delta \ln(TFP)$	2SLS, 1990-2000		sGMM	
Initial TFP (ln)	-0.104 (0.0829)	-0.159** (0.0627)	-0.138** (0.0606)	-0.187** (0.0761)
LH (%)	0.0375*** (0.0114)	0.00510 (0.00598)	0.00197 (0.00550)	-0.265*** (0.0714)
LH (%) x Post-1980 (dummy)			0.0340*** (0.00939)	
LH (%) x Schooling (ln)				0.111*** (0.0271)
Population (ln)	✓	✓	✓	✓
State fixed-effects		✓	✓	✓
Period dummies		✓	✓	✓
Lagged $\Delta \ln(TFP)$	✓			
Post-1980 (dummy)			✓	
Schooling (ln)				✓
Observations	51	204	204	204
Number of states	51	51	51	51
R-squared	0.239			
First stage F-test	49.76			
Number of instruments		58	58	51
AR1 test (p-values)		0.001	0.001	0.001
AR2 test (p-values)		0.133	0.113	0.273
Hansen test of joint instrument validity (p-values)		0.243	0.183	0.115
Difference-in-Hansen test of instrument subsets (p-values)				
Instruments for levels		0.990	0.977	0.631
Instruments for initial TFP		0.943	0.845	0.749

Robust standard errors in parentheses. \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

*LH (%)* is the prevalence of left-handedness among the population aged 15 to 45, 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 labor force.

In columns (2) and (3), we use the second to sixth lags (both in differences and in levels) as instruments. In column (4), we use the second and further collapsed lags. Using the second to sixth lags, as in the two previous columns, yields very similar results but generates 87 instruments which violates the standard rule of thumb.