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HUMAN CAPITAL AND INDUSTRIALIZATION: EVIDENCE FROM THE AGE OF ENLIGHTENMENT

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ABSTRACT

While human capital is a strong predictor of economic development today, its importance for the Industrial Revolution is typically assessed as minor. To resolve this puzzling contrast, we differentiate average human capital (worker skills) from upper tail knowledge both theoretically and empirically. We build a simple spatial model, where worker skills raise the local productivity in a given technology, while scientific knowledge enables local entrepreneurs to keep up with a rapidly advancing technological frontier. The model predicts that the local presence of knowledge elites is unimportant in the pre-industrial era, but drives growth thereafter; worker skills, in contrast, are not crucial for growth. To measure the historical presence of knowledge elites, we use city-level subscriptions to the famous *Encyclopédie* in mid-18th century France. We show that subscriber density is a strong predictor of city growth after 1750, but not before the onset of French industrialization. Alternative measures of development confirm this pattern: soldier height and industrial activity are strongly associated with subscriber density after, but not before, 1750. Literacy, on the other hand, does not predict growth. Finally, by joining data on British patents with a large French firm survey from 1837, we provide evidence for the mechanism: upper tail knowledge raised the productivity in innovative industrial technology.

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The genre of modern industrial production requires extended knowledge of mechanics, notion of calculus, great dexterity at work, and enlightenment in the underlying principles of the crafts. This combination of expertise ... has only been achieved in this [18th century] period, where the study of science has spread widely, accompanied by an intimate relationship between savants and artisans. (Chaptal, 1819, p.32)

1 Introduction

A rich literature documents an important role of human capital for economic development in the modern world. Schooling is a strong predictor of economic growth,[1] and of per-capita income at the national and regional level.[2] Both theory and evidence explain these findings by worker skills facilitating technology adoption and innovation.[3] In contrast, the role of human capital during the Industrial Revolution is typically described as minor. In Britain – the cradle of industrialization – education was low and inessential for economic growth (Mitch, 1993).[4] On the other hand, Scandinavia – which was fully literate as early as 1800 – fell behind and was one of the poorest regions in Europe. Galor (2005, p.205) points out that "in the first phase of the Industrial Revolution ... [h]uman capital had a limited role in the production process, and education served religious, social, and national goals." At a more systematic level, cross-country growth regressions for the period of industrialization lead to the conclusion that "literacy was generally unimportant for growth" (Allen, 2003, p.433). The stark contrast to the findings in modern data is puzzling: did the escape from millennia of stagnation really occur without a role for one of the most important determinants of modern growth – human capital?

The previous non-results are based on education or literacy as skill measures of the *average* worker. This may veil the role of scientifically savvy engineers and entrepreneurs at the top of the skill distribution. Mokyr (2005a) stresses the importance of this "density in the upper tail", and Mokyr and Voth (2009, p.35) conclude that "the Industrial Revolution was carried not by the skills of the average or modal worker, but by the ingenuity and technical ability of a minority." Recent research on contemporaneous economies chimes in, underlining the importance of math

[1]See Barro (1991) and Mankiw, Romer, and Weil (1992) for early empirical growth studies, and Krueger and Lindahl (2001), Barro (2001), Cohen and Soto (2007), and Hanushek and Woessmann (2008) for more recent confirmations based on richer data.

[2]Gennaioli, La Porta, Lopez-de-Silanes, and Shleifer (2013). While the role of human capital as a fundamental determinant of growth and development has been debated, its importance as a proximate cause, i.e., an essential input in the production function, is undisputed (Hall and Jones, 1999; Glaeser, Porta, de Silanes, and Shleifer, 2004; Acemoglu, Gallego, and Robinson, 2014).

[3]C.f. Nelson and Phelps (1966), Benhabib and Spiegel (1994), Caselli and Coleman (2006), and Ciccone and Papaioannou (2009).

[4]As late as 1855, at the end of the first Industrial Revolution, primary schooling enrollment in Britain was only 11% (Flora, Kraus, and Pfenning, 1983). Also, modern technology typically replaced skilled craftsmen, and the skill premium remained unchanged until 1900 (Clark, 2005).

and science skills, or of entrepreneurial ability (Hanushek and Kimko, 2000; Bloom and Reenen, 2007; Gennaioli et al., 2013).

In this paper, we ask whether distinguishing between upper-tail and average skills may reinstate the importance of human capital during the transition from stagnation to growth. Answering this question hinges on a historical proxy for the thickness of the upper tail, i.e., the presence of knowledge elites.[5] We use a novel measure from the eve of industrialization in mid-18th century France: subscriptions to the *Encyclopédie* – the cornerstone of the Enlightenment, representing the most important collection of scientific and technological knowledge at the time. This period saw the emergence of the knowledge economy, and the encyclopedia was at its forefront (Mokyr, 2002). One of the publishers kept a list of all (more than 8,000) subscriptions to the most prominent edition.[6] Based on this information, we calculate subscriber density for almost 200 French cities and use it as a proxy for the local concentration of knowledge elites. Figure 1 shows that regions with high and low values are relatively evenly distributed and often immediately adjacent. In addition, subscriber density is uncorrelated with literacy rates in the same period, allowing us to differentiate between average and upper tail skills.[7]

We present a simple model of spatial technology diffusion to illustrate the different roles of average worker skills and upper tail knowledge during industrialization. Building on rich historical evidence, we assume that upper tail knowledge enabled entrepreneurs in manufacturing to keep up with advances at the technology frontier.[8] Thus, in the spirit of Nelson and Phelps (1966), advanced skills are particularly useful when technological progress is rapid. The model predicts that income and industrial employment grow faster in regions with a thick knowledge elite. However, this local effect becomes important only when the aggregate technology frontier expands rapidly; in pre-industrial times, upper tail knowledge is inessential for economic development. In contrast, average worker skills enter production in the standard labor-augmenting way. They thus affect income in the cross-section, but not growth over time. In other words, while worker skills raise

[5]Following Mokyr (2005a), we use a broad definition of "upper tail knowledge": it reflects an interest in scientific advances, motivated by the Baconian notion that knowledge is at the heart of material progress. This concept comprises innovative and entrepreneurial capabilities in adopting and improving new technology, but also lower access costs to modern techniques; it is thus compatible with Mokyr's notion of (economically) 'useful knowledge'. When referring to the local presence of people *embodying* such knowledge, we use the term "knowledge elite".

[6]The names of individual subscribers survived only in a few cases – where they did, a substantial share of subscribers were progressively minded and scientifically interested noblemen, administrative elites, and entrepreneurs.

[7]The fact that the two measures are uncorrelated is not astonishing, given that the knowledge elite was a tiny proportion of the overall population.

[8]This reflects that an interest in science helped entrepreneurs both to learn about new techniques in the first place, and to understand the underlying principles needed to implement and run them. A precondition for this assumption is that knowledge about scientific advances and new technologies was not kept secret. This 'open science' emerged during the period of Enlightenment, accompanied by the appearance of scientific and technical publications. In line with our argument, these "were without doubt of interest to only a small minority" (Mokyr, 2005b, p.300).

labor productivity for a *given* technology, upper tail entrepreneurial skills drive growth by *changing* technology.

We collect a host of outcome variables to test the model predictions. First, our main analysis uses city size in France between 1400 and 1850. We find that subscriber density was strongly associated with city growth after 1750 – when French industrial growth began – but not before that date. Figure 2 illustrates this finding, using a consistent set of cities that are observed over our full sample period. The coefficient on subscriber density is almost six times larger after 1750 – it rises from 0.037 to 0.218, and the difference is highly significant. Second, we use soldier height as a proxy for income at the French department level. We find that after 1820, soldier height is significantly associated with encyclopedia subscriptions, while this relationship disappears before 1750. Third, mid-19th century census data for almost 90 French departments reveal that those with higher subscriber density had significantly higher disposable income, industrial wages, and industrial employment. For all outcome variables, we also confirm the model prediction that literacy or schooling (proxying for average worker skills) are positively associated with development in the cross-section, but do not explain growth.

When interpreting our results, we do not argue that the encyclopedia *caused* scientific knowledge at the local level. In fact, knowledge elites were present prior to 1750, and their spatial distribution was stable over time. We show that early scientific societies are a strong predictor of subscriber density. The same is true for the share of Huguenots in 1670 – the suppressed Protestant minority that is typically associated with the French knowledge elite (Scoville, 1953; Hornung, 2014). In addition, locations with higher subscriber density brought up a larger proportion of famous people in scientific professions between the 11th and 19th centuries, and they also presented more innovations (per capita) at the 1851 London World Fair. In sum, there is compelling evidence that subscriber density reflects a stable spatial distribution of knowledge elites.[9] Our argument is that these elites began to foster growth when knowledge became economically 'useful', and technological progress became rapid. This follows Mokyr's (2002; 2005b) seminal work on the rising importance of upper tail knowledge during the period of Industrial Enlightenment.

To support our interpretation, we discuss detailed historical evidence that connects scientific knowledge to entrepreneurship and technological improvements, both via innovation and via the adoption of modern techniques. We further support our argument by providing systematic evidence for the mechanism from a survey of more than 14,000 French firms in 1837. Based on

[9]In this dimension, our empirical analysis is similar in spirit to Voigtländer and Voth (2012), who take the spatial pattern of anti-Semitism as given and use historical persecution of Jews to measure it. The spatial dispersion of scientific activity in early modern Europe is well-documented (Livingstone, 2003). We take this pattern as given, and argue that subscriber density is a powerful proxy to capture it.

sector-specific British patent data, we split these firms into 'modern' (innovative) and 'old'. We show that firms in 'modern' (but not in 'old') sectors were much more productive in regions with higher subscriber density, even after controlling for sector and location fixed effects. This suggests that upper tail knowledge favored the adoption and efficient operation of innovative industrial technology.

Importantly, we do not claim that upper tail knowledge was necessarily a *fundamental* driver of economic growth during industrialization.[10] The spatial variation in scientific knowledge may be due to deeper determinants such as culture, institutions, or geography that could also affect growth via channels other than human capital. Correspondingly, we interpret upper tail knowledge as a *proximate* driver of industrial growth, i.e., as a factor that influences the production function – possibly in combination with other proximate determinants. Among the latter, physical capital is probably the most relevant in the context of our study: encyclopedia subscribers typically came from the progressive bourgeoisie and nobility, who were not only part of the knowledge elite, but also had access to finance. A critical challenge for our interpretation is thus: could financial means have been the dominant factor, while upper tail knowledge was only a sideshow without economic relevance? Our results suggest that this is unlikely: subscriber density is not associated with growth before modern technology became available, and even thereafter, the presence of noble families (as a proxy for wealth) alone does not explain growth – it only does where noble families overlap with high subscriber density. In addition, the manufacturing sectors in which subscriber density had the strongest effect depended less on costly power engines, and firm size in these sectors was not important for productivity. These points, in combination with the rich historical evidence on the importance of advanced knowledge suggests that deep pockets alone were not enough. Rather than being a 'competing' factor, physical capital was complementary to upper tail knowledge.

We also control for other potential confounding factors. For example, total book sales per capita at the city level in the 18th century are strongly correlated with subscriber density, but they do not affect growth. To shed light on the role of institutions, we use the fact that the French Revolution occurred approximately at the mid-point of our main period of analysis (1750-1850). We find that subscriber density was strongly associated with city growth under both regimes, despite their radically different institutions.[11] Our results are also robust to controlling for geographic

[10]The distinction of fundamental vs. proximate determinants of growth goes back to North and Thomas (1973). As discussed above, evidence abounds that human capital is a proximate driver of *modern* development, but whether it is also fundamental is debated (see the references cited in footnote 2).

[11]In addition, after the 17th century France was a centralized absolutist state, allowing for relatively little local variation in institutions (Braudel, 1982; DeLong and Shleifer, 1993, see also Appendix B). Our analysis is thus less affected by the typical limitations of cross-country studies. We also control for regions where the king exerted particularly strong control – the *pays d'élection* – and find that these differed neither in subscriber density nor growth.

characteristics, pre-industrial activity, possible effects of the 'Reign of Terror', and the early presence of a printing press. In sum, the historical evidence in combination with our empirical findings renders it difficult to imagine that (upper tail) human capital did not play a major role during industrialization.

Our paper is related to a large literature on the transition from stagnation to growth (for an overview see Galor, 2011), and in particular to the role of human capital during industrialization. For England – the technological leader – the predominant view is that formal education did not contribute to economic growth (Mokyr, 1990; Mitch, 1993; Crafts, 1996; Clark, 2005). For the follower countries, the evidence is mixed. O'Rourke and Williamson (1995) and Taylor (1999) conclude from country-level cross-sectional and panel analyses that human capital was not a crucial driver of catch-up in the 19th century. In contrast, Becker, Hornung, and Woessmann (2011) document that elementary education predicts employment in metals and other industries, but not in textiles in 19C Prussia. This is in line with O'Rourke, Rahman, and Taylor (2008), who emphasize that industrial innovation in sectors such as textiles was initially unskill-biased, reducing the demand for skilled workers.[12] We shed new light on this debate by distinguishing between average and upper-tail skills, following Mokyr's (2005b) argument that the expansion and accessibility of 'useful knowledge' during the period of Enlightenment was a cornerstone of industrial development.[13] Our paper also relates to a literature showing that book production had a positive impact on pre-industrial economic development (Baten and van Zanden, 2008; Dittmar, 2011).[14] Our main explanatory variable, encyclopedia subscriber density, offers two advantages over printing locations or local book production. First, it is a more precise measure, identifying readers within the narrow category of scientific publications.[15] Second, subscriptions measure the local *demand* for knowledge, rather than the supply of books from printing locations.

Relative to this literature we make several contributions. To the best of our knowledge this paper is the first to empirically differentiate between average worker skills (literacy/schooling) and

[12] This led to the famous incident of the *Luddites* – skilled textile workers – wrecking modern machinery that was operated by unskilled labor.

[13] Kelly, Mokyr, and Ó Grada (2014) also emphasize the importance of highly skilled, technically capable individuals. In the contemporaneous context, Hanushek and Woessman (2012) show that the share of cognitively high-performing students is strongly associated with growth, independent of basic literacy.

[14] Baten and van Zanden show for a panel of 8 European countries over the period 1450-1850 that wage growth was more rapid where book printing was more pronounced. Remarkably, however, after 1750 countries with particularly high book printing, such as Sweden or the Netherlands, saw a decline in real wages. This suggests that the observed pattern is driven by variation before the onset of industrialization. Cantoni and Yuchtman (2014) also document early effects, showing that universities fostered commercial activity in medieval times.

[15] Total book production, in contrast, contains books from cooking manuals to religious works. For example, books about natural science, math, and engineering account for less than 5% of overall book sales by the large publishing house STN in the late 18th century, while 70% of all sales occurred in *Belles lettres* (e.g., romans and poetry), history, and religion.

upper tail knowledge during the early days of industrialization. Along this dimension, our study is the first to provide systematic evidence for Mokyr's (2005b) hypothesis about the importance of 'useful knowledge' for industrialization. We also shed light on the mechanism, showing that upper tail knowledge probably fostered growth by raising firm productivity in modern, innovative industries. Finally, we show that basic education was related to economic development in the cross-section, but – in contrast to upper tail knowledge – not to growth.

The paper is organized as follows: Section 2 discusses the historical background of industrialization in France with particular emphasis on the intersection of science and entrepreneurship. We also discuss encyclopedia subscriptions as a proxy for the presence of knowledge elites. Section 3 presents a model of industrialization that illustrates our main argument. In Section 4 we describe the data, and Section 5 presents our empirical results. Section 6 concludes by discussing the implications of our findings for the literature on human capital and development.

2 The Age of Enlightenment: Industrialization and Upper Tail Knowledge

The Enlightenment was a period of intellectual and cultural revolution in Western history that many consider a corner stone for the onset of modern economic growth (c.f. Jacob, 1997). The Age of Enlightenment stretched from the late 17th throughout the 18th century, stressing the importance of reason and science, as opposed to faith and tradition. Despite its efforts to popularize and spread knowledge, the Enlightenment never became a mass movement; it remained confined to a small elite. Nevertheless, it played a crucial role in fostering industrial development and economic growth, both through the expansion of propositional knowledge with practical applications, and through a reduction of access costs to existing knowledge. In this context, Mokyr (2005a, p.22) refers to the 'Industrial Enlightenment', which "bridged between the Scientific and Industrial Revolution." In the following, we describe the importance of upper tail knowledge for industrial growth during this period. We also provide background on the *Encyclopédie*, and discuss why its subscriptions are a good proxy for the local presence of knowledge elites.

2.1 Industrialization in France

France had its own path to industrialization, which was different, but not inferior to the British one (Crouzet, 2003). For example, French firms were smaller than their English counterparts, and most of them were family owned.[16] However, the small size of French firms was not necessarily due to a lack of entrepreneurial skills; instead, firm size suited the economic conditions of the time (such as the unstable political environment making investments risky), and firms "would not have

[16]As late as 1865, French firms had 9.5 workers on average (Verley, 1985), and in 1901, 71 percent had no hired employees (Nye, 1987).

stood to gain much in efficiency by being larger" (Nye, 1987, p. 668). Similarly, Horn (2006, p.10) argues that "[i]n an astonishing number of sectors, French entrepreneurs of the 1780s competed successfully with their English counterparts." Focusing on the demand side, Daudin (2010) shows that French domestic markets were already relatively integrated in the 18th century, allowing for specialization in production and thus efficiency gains.

French Economic growth began to accelerate in the mid-18th century; its industrial output more than doubled until 1800 (Rostow, 1975), and mechanization slowly began in the main industrial sectors – textiles and metallurgy (Daudin, 2005). During the early stages of industrialization, France depended largely on the adoption of British technology. Later on, it became an important source of innovations itself: "Technological progress became indigenous, built in to the economy, so that ... France became at mid-[19]century a centre of invention and diffusion for modern technologies" (Crouzet, 2003, p.234).[17]

British know-how reached France via several channels. Scientific reports published and studied by learned societies played an important role, in combination with an intense correspondence between "industrially minded" people in the two countries. In addition, industrial spies sent regular reports on English technology (Mokyr, 2005b; Horn, 2006). Progressive French producers imported English machines – often illegally, to avoid British export restrictions; they also hired thousands of British workers with the specific aim to gain access to technical knowledge (Horn, 2006). Finally, the state and provincial governments supported scientific institutions, bringing together entrepreneurs and scientists; they also fostered the adoption of machines and expertise from abroad. These policies were put into practice at the national and local level by a commercial, industrial, and scientific elite (Chaussinand-Nogaret, 1985; Horn, 2006).

2.2 The Encyclopédie and Upper Tail Knowledge

In the culturally vibrant atmosphere of 18th century France, Diderot and d'Alembert launched the ambitious project of the *Great Encyclopédie* – the "most paradigmatic Enlightenment triumph" (Mokyr, 2005b, p.285). Following Lord Francis Bacon's conceptual framework, Diderot's objective was to classify all domains of human knowledge in one single source, easily accessible to everybody. The focus was on knowledge derived from empirical observation, as opposed to su-

[17] Figure A.1 in the appendix shows that GDP per capita was relatively stable until approximately 1750, and then started to grow steadily. France lagged behind England, where incomes started to rise steadily after 1670 (Broadberry, 2013). Timing the French industrial takeoff is difficult, as it lacks a clear structural break (Roehl, 1976); the predominant "moderate revisionist" view describes steady growth starting around 1750 until the mid-19th century, only interrupted during the two decades after the revolution in 1789 (Crouzet, 2003). Growth was particularly strong between 1815 and the 1840s, then slowed down during a depression around 1875-95, which was followed by another period of rapid growth (*Belle époque*). On average, French GDP per capita grew as fast as its British counterpart over the period 1820-1913, although French population grew at a markedly slower rate (Maddison, 2001).

perstition. While mercantilistic ideas were still widespread, and artisans and guilds kept secrecy over knowledge, a small elite believed that scientific knowledge should not be a private good, but disseminated as widely as possible (Mokyr, 2005a).

The *Encyclopédie* went through several editions and reprints. The government initially refused to allow official sales, and most copies went to customers outside France.[18] Correspondingly, the first and the second editions sold together only 3,000 copies in France. Moreover, the first two editions were luxury items that did not penetrate far beyond the restricted circle of *courtiers*, *salon lions*, and progressive *parlementaires*. This changed radically with the Quarto (1777-1780) and the Octavo editions (1778-1782).[19] These became wide-spread throughout the country and largely reached middle class budgets (Darnton, 1973). Since our proxy for local knowledge elites is based on subscriptions to the Quarto, we discuss this edition in more detail.[20]

The Quarto edition

The Quarto edition of the *Encyclopédie* is particularly useful as a proxy for local knowledge elites for several reasons. It represents the turning point when the *Encyclopédie* moved to a phase of diffusion of Enlightenment on a massive scale. The Quarto was designed to be affordable for middle class readers. Correspondingly, its format was smaller than the luxurious Folio of Diderot, the quality of the paper poorer, and the price lower. The publishers described their price discrimination strategy as follows: "The in-folio format will be for ‘grands seigneurs’ and libraries, while the in-quarto will be within the reach of men of letters and interested readers ["amateurs"] whose fortune is less considerable."[21] This strategy proved extremely successful: scientific interest rather than deep pockets determined subscriptions, and the Quarto had the highest sales in France among all editions.

Crucially for our study, one of the publishers, Duplain, secretly kept a list of subscriptions, which survived in the archives of the Société Tipographique de Neuchâtel (STN). This list contains

[18] The articles of the Encyclopédie often resulted provocative to authorities. For example, in the engraving of the *Tree of Knowledge*, theology is considered a simple branch of Philosophy. This led to the imprisonment of the editor and the publishers; the Pope condemned the *Encyclopédie*, and it was suppressed by a royal decree (Vogt, 1982).

[19] The names Quarto and Octavo refer to the printing format: A Quarto sheet is folded twice, creating four leaves; an Octavo is folded three times, creating eight leaves. The central figure behind the Quarto edition was the French entrepreneur Charles-Joseph Panckoucke (1736-1798), who had bought the plates of the *Encyclopédie* from the original publishers, together with the rights to future editions. Administrative obstacles in selling the Quarto appear to have been minor. While the *Encyclopédie* was officially illegal until 1789, the government had relaxed its censorship. In addition, Panckoucke had good connections with the government, and did not hesitate to lobby and bribe public officials (Vogt, 1982).

[20] The Quarto edition comprised 36 volumes of text and 3 volumes of illustrative plates. Since these were typically not delivered in one chunk, readers of the *Encyclopédie* are commonly referred to as "subscribers".

[21] Société Tipographique de Neuchâtel (the publisher) in a letter to Rudiger of Moscow, May 31, 1777; cited after Darnton (1973, p.1349). The Quarto cost only one fifth of the first original folio. While unaffordable to lower social classes and workers, the Quarto was well within the reach of the middle class.

the name of booksellers (but not subscribers), their city, and the number of sets they purchased for retail among their local clients. Darnton (1973) provides this list, which comprises a total of 8,011 subscriptions, out of which 7,081 were sold in France – in 118 cities.[22]

Subscriptions to the Quarto edition and local knowledge elites

Does a higher frequency of subscriptions at a given location reflect a broader interest in upper tail knowledge?[23] While Duplain's list does not allow for a systematic analysis of individual subscribers to answer this question, some information is available. For Besançon, a list of 137 subscribers has survived. Darnton (1973, p.1350) summarizes these by profession and social status: 11% belonged to the first estate (clergy) and 39% to the second estate (nobility); the remaining 50% belonged to lower social ranks, including the bourgeoisie.[24] For example, professionals, merchants, and manufacturers account for 17% of the total. Thus, an important share of subscribers can be directly identified as economic agents (from lower ranks) involved in the French industrialization. Their share is likely a lower bound for the importance of the encyclopedia in the business community, because many subscribers in the upper class (nobility) were also active businessmen (Horn, 2006).[25] For example, Chaussinand-Nogaret (1985, p.87) argues that

> *Over a whole range of activities and enterprises nobles, either alone or in association with members of the greater business bourgeoisie, showed their dynamism, their taste for invention and innovation, and their ability as economic leaders: ... their ability to direct capital..., to choose investments according to their productiveness and their modernity, and ... to transmute the forms of production into an industrial revolution.*

It is, however, important to note that only a progressive subset of the nobility was involved in industrial activities.[26] The same subset was also heavily engaged in the Enlightenment (Chaussinand-Nogaret, 1985, p.73).

[22]Lyon with 1,078 and Paris with 487 subscriptions are at the top of this list; at the opposite end of the spectrum, there are 22 towns with fewer than 5 subscriptions. Subscriptions were not confined to major cities; instead, they were distributed across the whole French territory (see Figure 1).

[23]For example, it is possible that wealthy people merely bought the encyclopedia to decorate their bookshelves. However, according to Darnton (1973, p.1352), if anything, the opposite was probably the case: "far more people must have read the *Encyclopédie* than owned it, as would be common in an era when books were liberally loaned and when 'cabinets litteraires' were booming."

[24]This may be a lower bound for other locations. The second estate is probably over-represented in this sample – Besançon was a garrison town, and almost half of the subscriptions in this category went to noblemen in the army.

[25]This reflects the revisionist view that replaced earlier – often Marxist – interpretations of the nobility exemplifying an aristocratic tyranny of arrogance and decadence. An impartial reading of the historical account shows that "nobles of the eighteenth century had been as modern and progressive as anyone" (Smith, 2006a, p.2).

[26]As Chaussinand-Nogaret (1985, p.90) puts it: "In the economic sphere, ...it is clear that the whole of nobility was not involved, but only the part that can be considered its natural elite, ... because of its ... openness to the progressive tendencies of the age."

In addition, many subscriptions went to high public officials and *parlementaires* – about 28% of the total in Besançon. Enlightened elites in the provincial administration were often involved in fostering local industrialization. For example, in Rouen and Amiens, they established the *Bureau of Encouragement* that gathered businessmen, manufacturers, local savants, and provincial authorities in an effort to assist technological advance (Horn, 2006, p.81). Finally, the *Encyclopédie* – and especially the Quarto – also reached non-subscribers in the lower ranks of society, via indirect access (Roche, 1998). Organized lectures, symposia, and public experiments were booming in France during the Enlightenment, and public readings of the *Encyclopédie* were organized by scientific societies, libraries, lodges, and coffeehouses (Darnton, 1979; Mokyr, 2005b).

In sum, the encyclopedia had a broad spectrum of readers from the knowledge elite that were directly and indirectly involved in industrialization. This supports both our use of subscriber density as a proxy for local upper tail knowledge, and the hypothesis that this knowledge was crucial in fostering economic growth.[27] Next, we discuss a number of concrete examples for how scientific knowledge affected entrepreneurial activity and technological growth in France during its industrialization.

2.3 Scientific Knowledge and Entrepreneurship

There are many prominent examples for the link between upper tail knowledge and entrepreneurship 18th and 19th century France. The father of the chemical revolution of the 18th century, Antoine Lavoisier (1743-1794), was educated in the spirit of Enlightenment, and fascinated by the *Dictionnaire de Chymie* (published in 1766). He worked on several applied problems such as the role of oxygen in combustion, street lighting, and he predicted the existence of silicon. Alexandre Vandermonde (1735-1796), a mathematician attracted to machinery and technology, fostered the first major industrial application of Lavoisier's chemistry in iron production (Mokyr, 2005b). Similarly, the chemist Claude Louis Berthollet (1748-1822) experimented with chlorine, discovering new methods for bleaching. His results were both published in scientific journals and applied in most of the leading textile-manufacturing firms of France. These discoveries led the contemporaneous observer Robert O'Reilly (an Irishman living in Paris) to declare in 1801: "a complete revolution in the art of bleaching...we have finally arrived in an époque where science

[27] Certainly, reading or hearing about a new technology was not sufficient to be able to adopt and operate it. However, scientific publications and lectures made technological know-how available on a large scale, breaking the exclusive transmission from master to apprentice (Mokyr, 2005b). The details needed for actual adoption of new technologies were then often found elsewhere, such as embodied in 'imported' British experts. For example, Fox (1984, p.143) describes the case of the engineer Job Dixon from Manchester, who was hired in 1820 by the Risler brothers. These had just founded the first machine-building firm in southern Alsace and wanted to implement advanced British technology. The firm subsequently became the main supplier of the latest spinning and weaving machinery for the region, serving also as a training ground for French engineers.

and industrial arts, reinforcing each other, rapidly spill indefinite improvements" (cited after Musson and Robinson, 1969, p.253; our translation). Another example is the Duke d'Orléans, who set up a soda-making facility together with the chemist Nicolas Leblanc (1742-1806). He invested in several textile firms, adopting modern machinery from Britain, and introduced steam-engines into cotton spinning in France (Horn, 2006; Chaussinand-Nogaret, 1985).

In other cases, the same person or family was involved in both scientific research and industrial activities. For instance, Jean-Antoine Chaptal, a famous chemist, successful entrepreneur, and political figure considered science to be inseparable from technology, and the key to foster industrial development. He was well-connected in the French network of savants, which entertained an intensive exchange with international scientists such as James Watt, and stimulated the application of science to industry in France. Chaptal pursued this cause both as a public figure and as a private entrepreneur. As a public official, he created favorable economic and bureaucratic conditions for entrepreneurs, for example by founding the *Conseils d'Agriculture, des Arts et Commerce*, and the *Société d'Encouragement pour l'Industrie National*, where scientists, industrialists, and bureaucrats were brought together. He also subsidized promising artisans, engineers, and industrialists, and gave public lectures on chemistry and experimental physics. As a private entrepreneur, Chaptal built the largest factory for chemical products in France (Horn and Jacob, 1998).

In many cases, entrepreneurial dynasties with scientific spirit came from the Protestant minority – the Huguenots. For example, the Koechlin and Dollfus families in Mulhouse were closely related by intermarriage and descended directly from the famous mathematician Bernouilli. They ran prosperous firms in cotton and wool spinning, and founded the first cloth-printing firm in France. Some members also entered other industrial businesses, such as the manufacturing of textile machineries, locomotives, and railroad equipment. Their dynasties kept marrying other scientific families (such as the Curies and the Friedels), and produced successful scientists themselves: for instance, Daniel Dollfus-Ausset (1797-1879) was a chemist who made major innovations in bleaching and simultaneously ran his own textile firm. The Koechlin and Dollfus families were also co-founders of the *Société industrielle de Mulhouse*, which promoted technological progress via conferences and publications (Hau, 2012; Smith, 2006b).

Even in raw material production such as silk growing, scientific studies played an important role. The silkworm is extremely sensitive to cold, heat, and drafts, which rendered its adoption in France difficult. The entrepreneur Camille Beauvais ran a silk farm near Paris with the support of distinguished chemist d'Arcet. Their methods raised worm productivity enormously, more than doubling output per egg, and allowing for four harvests per year (Barbour and Blydenburgh, 1844, p.39). Beauvais trained young growers at his farm, who spread his methods throughout France and eventually to the United States. His work was promoted and advertised by scientific organizations, such as the *Société d'Encouragement pour l'Industrie Nationale*.

Our argument also applies contrariwise: the absence of advanced knowledge typically came along with the use of backward technology. The French iron industry is one example – Dunham (1955, p.119) observes that "a typical ironmaster knew little or nothing about science... He was as ignorant of planning, routing, and economics as of metallurgy, and carried on his business in the manner of his fathers, with little knowledge of what went on outside his own district." Correspondingly, when puddling – a crucial process to produce high-grade bar iron – was invented in England in 1784, the vast majority of French iron producers ignored it until well into the 19th century. However, there were some exceptions, and the evidence suggests that upper tail knowledge played a crucial role: a small minority of "the ablest metallurgists in France ... [brought] the puddling process...successfully from England to France and introduced [it] almost simultaneously at several widely separated establishments run by metallurgists of outstanding ability" (Dunham, 1955, p.128).

These examples illustrate that the effect of knowledge elites on local industrial development could go via the dialogue between scientists and entrepreneurs, via scientifically savvy public officials supporting entrepreneurship, and via members of the elite themselves operating businesses.

3 Model

In this section, we provide a simple model of spatial technology diffusion that connects the historical evidence discussed above with the empirical analysis that follows below. The model distinguishes between worker skills and upper tail knowledge of entrepreneurs. We present a mechanism where upper tail knowledge enables local entrepreneurs to *improve* their technology, while worker skills raise the productivity for a *given* technology. This yields differential predictions for how the two types of human capital affect income and economic growth before and after industrialization.

The model features $n = 1, ..., N$ regions with given land endowment. In each region, there is a mass $L >> 1$ of workers who supply one unit of labor inelastically in each period. Worker skills h_n vary across regions. In addition, there are $i \in [0, 1]$ entrepreneurs who produce intermediate goods in manufacturing. A share s_n of entrepreneurs in region n disposes of upper tail (scientific) knowledge.[28]

There is no saving, so that all income is consumed in each period. In any given period, workers optimally choose between working in two sectors: agriculture (A) and manufacturing (M). The latter is performed in cities, so that the manufacturing labor share also reflects urbanization.

[28]To distinguish between their effects on development, we assume that h_n and s_n are independently distributed across regions. This also reflects the observation that our historical proxies for the two types of human capital, literacy and subscriber density, are uncorrelated across French departments.

We keep the model tractable by following Hansen and Prescott (2002) in assuming that agricultural and manufacturing goods are perfect substitutes. In addition, we assume that workers and entrepreneurs are immobile, operating within their region of origin.

Sector-specific wages in each region depend on both types of knowledge. First, average worker skills affect the efficiency of production in both sectors, but to a lesser degree in agriculture. Second, highly skilled entrepreneurs can raise productivity in manufacturing. Because we focus on differential development in the cross-section, we take the aggregate technology frontier $\bar{A}$ as given. We then study the effects when $\bar{A}$ grows (exogenously) over time. Growing $\bar{A}$ has two interpretations that are both in line with the historical evidence: i) that France was a follower country, with most technological progress coming from Britain; and ii) more broadly, that the frontier of useful knowledge expanded during the period of Industrial Enlightenment and that this knowledge became more accessible due to the emergence of 'open science' (Kelly et al., 2014). The latter interpretation allows for the possibility that France also innovated (as suggested by the historical evidence in Section 2.1), instead of merely adopting existing technology.[29] Finally, all relevant cross-sectional predictions of our model can be derived in partial equilibrium, taking the price of output (in both sectors) as given and using it as the numeraire.

3.1 Production

Each worker supplies one unit of labor and chooses a sector of employment at the beginning of each period. Technology in all sectors exhibits constant returns, so that the scale of production is not important. We denote total labor in sector $j \in \{A, M\}$ in region n by $L_{j,n}$. In the following, we characterize the production technologies used by the two sectors. Agricultural output in region n is given by

$$Y_{A,n} = A_A h_n^{\beta_A} X_n^{\alpha_A} L_{A,n}^{1-\alpha_A} \; , \tag{1}$$

where X is land endowment, α_A is the share of land in production, and β_A reflects the sensitivity of agricultural productivity with respect to worker skills.[30] We assume that there are no property rights to land, so that wages in agriculture are given by the average product $y_{A,n} = Y_{A,n}/L_{A,n}$:

$$w_{A,n} = A_A h_n^{\beta_A} \left(\frac{X_n}{L_{A,n}} \right)^{\alpha_A} = A_A h_n^{\beta_A} \left(\frac{x_n}{l_{A,n}} \right)^{\alpha_A} \; , \tag{2}$$

[29] The second, broader, interpretation also reflects the historical account that upper tail knowledge was crucial for both innovation and adoption. Consequently, distinguishing between these two dimensions (as for example in Vandenbussche, Aghion, and Meghir, 2006) is not crucial for our results.

[30] In growth models and development accounting, h typically multiplies L directly, reflecting the average impact of schooling on productivity via Mincerian returns (c.f. Bils and Klenow, 2000). By using different β_j for $j \in \{A, M\}$, we allow these returns to vary across sectors, i.e., we allow for sector-specific returns to worker skills.

where $l_{A,n} = L_{A,n}/L$ is the agricultural labor share, and x_n is land per worker in region n. Note that agricultural wages increase if the labor share in agriculture declines, because this leaves more land for each remaining peasant. Thus, growth in manufacturing indirectly raises wages in agriculture.

Our modeling of the manufacturing sector builds on Acemoglu, Aghion, and Zilibotti (2006). The setup embeds a role for entrepreneurial skills in the manufacturing production process; it also has the advantage that it reduces to a simple aggregate production function. The final manufacturing good is produced under perfect competition by firms that use labor and a continuum of intermediates as inputs. The technology exhibits constant returns, so that we can focus on aggregate output in manufacturing, produced by a representative firm in the final sector:

$$Y_{M,n} = \xi \cdot \left(\int_0^1 A_{M,n}(i)^{1-\alpha_M} z_n(i)^{\alpha_M} di \right) \left(h_n^{\beta_M} L_{M,n} \right)^{1-\alpha_M} \tag{3}$$

where ξ is a constant, $z_n(i)$ is the flow of intermediate good i in final production, $L_{M,n}$ is total labor in manufacturing, β_M is the sensitivity of manufacturing production with respect to worker skills, and α_M denotes the share of intermediates in final production. Intermediates are produced by entrepreneurs under monopolistic competition. Each entrepreneur $i \in [0, 1]$ produces a specific intermediate i by transforming one unit of the final good into one unit of the intermediate. Thus, the marginal cost is identical for all entrepreneurs. However, the productivity with which intermediates enter final production, $A_{M,n}(i)$, differs across entrepreneurs i.[31] We study the evolution of productivity as a function of entrepreneurial skills below.

Solving the entrepreneurs' optimization problem yields a simple expression for aggregate manufacturing output (see Appendix C.1 for detail):

$$Y_{M,n} = A_{M,n} h_n^{\beta_M} L_{M,n}, \quad \text{with} \quad A_{M,n} = \int_0^1 A_{M,n}(i) di \tag{4}$$

Thus, aggregate manufacturing productivity $A_{M,n}$ is a simple linear combination of individual entrepreneurial efficiencies $A_{M,n}(i)$. The first order condition of (3) with respect to $L_{M,n}$ implies that a share $1 - \alpha$ of final output is paid to labor. Combining this with (4) yields the wage rate in

[31] Effectively, higher $A_{M,n}(i)$ raises the demand for intermediate i in final production, but it does not affect the unit cost of i. This approach ensures tractability. It can be motivated, for example, by interpreting $A_{M,n}(i)$ as the quality of intermediate i, so that more productive entrepreneurs produce higher quality intermediates at the same marginal cost. Note, however, that productivity can still be interpreted as the standard quantity-related concept: in equilibrium, entrepreneurs with high $A_{M,n}(i)$ sell more and make higher profits, so that our setup is akin to an alternative that loads productivity differences on marginal costs.

manufacturing:

$$w_{M,n} = (1-\alpha_M) A_{M,n} h_n^{\beta_M} \tag{5}$$

Finally, we assume $\beta_M > \beta_A$, i.e., that manufacturing production is relatively more sensitive with respect to worker skills. This assumption matters for cross-sectional predictions in our model, but it does not affect growth. In the following, we study the evolution of productivity, where entrepreneurial skills play a central role.

3.2 The Evolution of Productivity

The technological frontier at time t is given by $\bar{A}_t$, and it grows at an exogenous rate $\gamma_{\bar{A},t}$.[32] The frontier affects the productivity of individual entrepreneurs i at locations n, as represented by the productivity process

$$A_{M,n,t}(i) = \eta \bar{A}_t \;+\; (1-\eta) \left(1 + \tau(i)\, \gamma_{\bar{A},t}\right) A_{M,n,t-1} \tag{6}$$

where $\eta \in (0,1)$, and $\tau(i)$ reflects two types of entrepreneurs: $\tau(i) = 1$ for those with upper tail (scientific) knowledge, and $\tau(i) = 0$ for the remainder. $A_{M,n,t-1}$ is aggregate manufacturing productivity at location n in the previous period (described in more detail below). To interpret (6), consider first an entrepreneur with $\tau(i) = 0$. In this case, $\eta > 0$ guarantees that at least some innovation trickles through, and entrepreneurial productivity is the closer to the frontier the larger is η. We refer to this mechanism as (passive) catchup.

Next, consider highly skilled entrepreneurs with $\tau(i) = 1$. These also experience catchup, but in addition they actively improve their productivity, by the rate $\gamma_{\bar{A},t}$ relative to the initial local productivity $A_{M,n,t-1}$. We refer to this process as 'knowledge effect' – highly skilled entrepreneurs improve local technology by keeping up with technical progress at the frontier. This reflects several dimensions of the historical evidence discussed in Section 2. First, more scientifically savvy entrepreneurs were more likely to know about the existence of new technologies, which reduced their search costs and raised the likelihood of *adoption*.[33] Second, they could *operate* modern technology more efficiently because of a better understanding of the underlying processes. Third, scientific knowledge made further *innovative* improvements more likely.[34] Importantly, the 'knowledge

[32]By taking the evolution of $\bar{A}_t$ as given, we abstract from the feedback mechanism in Unified Growth Theory whereby human capital drives *aggregate* technological progress (Galor, 2011). At the *local* level, however, our approach allows for upper tail skills to accelerate productivity growth.

[33]As Mokyr (2000, p.30) put it: "Of course I do not argue that one could learn a craft just from reading an encyclopedia article (though some of the articles in the *Encyclopédie* read much like cookbook entries). But ... once the reader knew what was known, he or she could look for details elsewhere."

[34]This interpretation is in line with Kelly et al. (2014), who argue that the Industrial Enlightenment generated ideas that were then implemented by entrepreneurs and scientists in the upper tail of the skill distribution. Similarly, Mokyr

effect' is the stronger the higher is $\gamma_{\bar{A},t}$. This reflects the argument by Nelson and Phelps (1966) that human capital – here in the form of its upper tail – is particularly useful in periods of rapid technological change.

We now turn to the evolution of aggregate manufacturing productivity at location n, $A_{M,n,t}$. This term corresponds to the average entrepreneurial productivities, as given by (4). Recall that at each location n, there is a share s_n of highly skilled entrepreneurs. Thus, integrating (6) over all entrepreneurs $i \in [0, 1]$ yields:

$$A_{M,n,t} = \eta \bar{A}_t + (1-\eta) A_{M,n,t-1} \left(1 + s_n \cdot \gamma_{\bar{A},t}\right) \tag{7}$$

This equation illustrates three forces that drive manufacturing productivity at location n: First, passive catchup with the frontier, which depends on η. Second, the 'knowledge effect', which is larger for regions with higher s_n, and larger when technological progress $\gamma_{\bar{A},t}$ is rapid. Third, there is also a spillover effect of entrepreneurs with upper tail knowledge: they raise $A_{M,n,t}$, which is then reflected as $A_{M,n,t-1}$ in (6) in the following period, benefiting both entrepreneurs with and without scientific knowledge. Our setup also ensures that $A_{M,n,t} \leq \bar{A}_t$, which holds with equality in regions with $s_n = 1$. In other words, a region where all entrepreneurs have scientific knowledge will always be at the technological frontier.

Finally, we specify the productivity process in agriculture. We assume that upper tail knowledge is not important in this sector.[35] However, some technologies from the frontier 'trickle through' to agriculture, as well.[36] We model this process in the same fashion as for manufacturing, so that agricultural productivity in region n evolves according to

$$A_{A,n,t} = \eta \bar{A}_t + (1-\eta) A_{A,n,t-1} \tag{8}$$

Note that this equation corresponds to (7) with $s_n = 0$. Thus, in regions without upper tail knowledge, productivity in agriculture and manufacturing are the same. This delivers a useful benchmark

(2005a) argues that technological progress often came in the form of micro-inventions by implementation of broader technological concepts.

[35]Compared to manufacturing, agriculture saw much less innovation that required advanced knowledge to be adopted. This pattern is clearly borne out by innovations exhibited at world fairs: Among the 6,377 exhibits at the 1851 Crystal Palace fair in London, only 261 (or 4.1%) were agricultural machinery. At the other end of the spectrum, modern manufacturing sectors made up the large majority of innovations: textiles alone accounted for more than 26%, and engines and scientific instruments for another 15% (Moser, 2012, Table 3).

[36]This reflects the historical evidence that agricultural productivity also grew significantly during the industrial revolution (Crafts, 1985). We note in passing that differential growth in agriculture and manufacturing is not essential for our results. Alternatively, the same productivity process in the two sectors, combined with non-homothetic demand, yields similar predictions due to high income translating into disproportionately more manufacturing demand.

case for our analysis.

3.3 Equilibrium and Predictions

We now analyze how worker skills and upper tail knowledge affect income, growth, and the sectoral allocation of labor. Importantly, we assume that (exogenous) technological progress at the frontier, $\gamma_{\bar{A},t}$, is initially slow and then accelerates. Growth in total factor productivity (TFP) was minuscule prior to industrialization – probably in the range of 0.1% per year (Galor, 2005) – and it then accelerated to approximately 1% in the mid-19th century (Crafts and Harley, 1992; Antràs and Voth, 2003). With low $\gamma_{\bar{A},t}$, equation (7) implies that upper tail knowledge does not have important effects on regional productivity; it only matters when technology advances more quickly. This difference is crucial for our predictions before versus during industrialization.

Within each region n, labor mobility ensures that wages in agriculture and manufacturing are equalized: $w_{A,n} = w_{M,n} = w_n$. Using (2) and (5), this yields the employment share in agriculture:

$$l_{A,n} = \left(\frac{A_A}{(1-\alpha_M)A_M} h_n^{\beta_A - \beta_M} \right)^{\frac{1}{\alpha_A}} x_n \tag{9}$$

More land-abundant regions (higher x_n) have higher employment shares in agriculture. Since we assume that manufacturing production occurs in cities, the urbanization rate is given by $l_{M,n} = 1 - l_{A,M}$. In addition, equation (5) implies that wages grow at the same rate as local manufacturing productivity $A_{M,n}$.[37] The growth rate is thus given by

$$\gamma_{w,n,t} = \eta \left(\frac{\bar{A}_t}{A_{M,n,t-1}} - 1 \right) + (1-\eta)\, s_n \cdot \gamma_{\bar{A},t} \tag{10}$$

where the first term reflects the catchup effect, and the second term, the 'knowledge effect'.

We now present three predictions of the model. The first two analyze the cross-sectional effect of knowledge elites for the cases of relatively low $\gamma_{\bar{A}}$ (before the Industrial Revolution), and for high $\gamma_{\bar{A}}$ (in the industrial period). The third prediction highlights the role of worker skills. We discuss the intuition behind each prediction in the text.

Prediction 1. <u>Pre-industrialization:</u> *If the technological frontier expands slowly (low $\gamma_{\bar{A}}$), labor shares in manufacturing, wages, and economic growth are only weakly affected by local upper tail knowledge.*

Intuitively, if technological progress is slow, entrepreneurs with upper tail knowledge enjoy only a tiny productivity advantage (or none at all, if $\gamma_{\bar{A}} = 0$). Thus, (7) implies that productivity

[37] Total income in region n also comprises entrepreneurial profits given by $\alpha_M(1-\alpha_M)Y_{M,n}$ (see Appendix C.1). Since profits are directly proportional to wages, we focus on the latter when discussing the model predictions.

is similar or identical in regions with high and low s_n. Consequently, wages and labor shares – given by (5) and (9) – are also similar in the cross-section. The same is true for income growth, given by (10). The left panel of Figure 3 provides an illustration of Prediction 1. Under reasonable parameter choices, the percentage of entrepreneurs with scientific knowledge has only minuscule effects on development.[38]

Next, we turn to the industrialization period, when technological knowledge grew rapidly. The following prediction shows that, despite production knowledge being non-rival and available to all regions, it can have differential effects on economic development.

Prediction 2. During and after industrialization: *As the technological frontier expands more rapidly (high $\gamma_{\bar{A}}$), a larger local knowledge elite leads to higher wages, higher manufacturing employment, and faster economic growth.*

The intuition for this prediction follows the same logic as above, but now with rapid technological growth at the frontier, so that upper tail knowledge has sizeable effects on regional productivity. The right panel of Figure 3 illustrates the prediction in the simple calibrated version of our model: both wages and manufacturing employment now grow hand-in-hand with the local density of scientific knowledge.

Finally, we describe the effect of worker skills on income and employment.

Prediction 3. Effect of worker skills: *Higher average worker skills h_n in region n lead to higher employment shares in manufacturing and higher regional wages, but not to faster growth. This holds irrespective of the rate of technological progress at the frontier.*

Figure 4 illustrates this prediction. Regional wages in both sectors grow in worker skills, as given by (2) and (5). In addition, worker skills are more important in manufacturing than in agriculture ($\beta_M > \beta_A$). Thus, following equation (9), higher h_n leads to a concentration of employment in manufacturing – and thus in cities. Since these effects are independent of scientific knowledge, we can plot the pre-industrial and industrial periods together. Finally, wage growth as given by (10) is independent of worker skills. Intuitively, worker skills affect how productively a *given* technology is operated, but not which technology is used.

Summing up, as compared to the previous theoretical literature, our model provides a more differentiated view on the role of human capital during industrialization. Distinguishing between worker skills and upper tail (scientific) knowledge allows us to derive predictions that differ importantly for the two types of human capital. To test the model's predictions, we collect a rich dataset covering industrialization in France.

[38] The model calibration serves mainly illustrative purposes – we do not intend to precisely predict actual magnitudes of effects. Appendix C.3 explains our parameter choices in detail. We simulate the model for 250 periods, corresponding to 1600-1850.

4 Data

In this section we describe our data. We begin with our main city-level dataset and then turn to department-level variables that reflect French development before, during, and after industrialization. Finally, we analyze whether our main explanatory variable – subscriber density – varies systematically with other local characteristics.

4.1 City Dataset and Subcriber Density

Our main dataset is constructed from the city population data by Bairoch, Batou, and Chèvre (1988). This panel includes cities that reached (at least once) 5,000 inhabitants between 1000 and 1800; it reports city size for every 100 years until 1700, and for every 50 years thereafter until 1850. We use those 193 French cities for which Bairoch et al. report population in 1750 – the period when French industrial growth began. To these, we match the 7,081 subscriptions to the *Encyclopédie*'s Quarto Edition in France from Darnton (1973). We identify 85 cities with recorded subscriptions.[39] Since our data covers the universe of subscriptions, we can safely assume that the remaining 108 cities in Bairoch et al., had zero subscribers. In the following, we use $Subs_n$ to denote overall subscribers in city n. Because larger cities will mechanically tend to have more subscribers, we normalize subscriptions by population in 1750. Subscriptions per capita (among cities with above-zero entries) varied substantially, from 0.5 per 1,000 in Strasbourg to 16.3 in Valence; Paris belonged to the lower tercile of this distribution, with 0.85 subscriptions per 1,000. To reduce the influence of extreme values, we use log-subscriber density as our baseline variable: $lnSubDens_n = \ln(Subs_n/pop_n^{1750} + 1)$, where pop_n^{1750} is city population in 1750.[40] Since all subscriptions to the Quarto were sold at the same price including shipment (Darnton, 1979, p.264), $lnSubDens_n$ is arguably a comparable measure for the local demand for the *Encyclopédie*, and thus for upper tail knowledge.

4.2 Additional Outcome Variables

To test the model predictions on income *levels*, we need a proxy that is observed before and after industrialization. Following a rich literature in economic history, we use soldier height (c.f. Steckel, 1983; Brinkman, Drukker, and Slot, 1988; Komlos and Baten, 1998).[41] We obtain con-

[39] In total there are 118 cities with subscriptions listed in Darnton (1973); 12 of these are not reported in Bairoch et al. (1988), and the remaining 21 can be matched to Bairoch et al., but population data are not available in 1750.

[40] Adding the number 1 ensures that the measure is also defined for cities with zero subscriptions. Appendix A.2 provides further detail and distribution plots.

[41] Cross-sectional analyses typically document a strong positive correlation between height and per capita income (see Steckel, 2008, for a recent survey of the literature and empirical evidence). In longitudinal studies, the relationship is less clear, since it can also be affected by income inequality, volatility, and food prices (Komlos, 1998). We thus only exploit the variation in height across French regions, but not within regions over time.

script height before 1750 at the department level from almost 30,000 individual records collected by Komlos (2005). These reflect conscriptions over the first half of the 18th century. We filter out cohort- and age-specific patterns in recruitment as described in Appendix A.3. As our first proxy for income *after* industrialization, we use department level soldier height from Aron, Dumont, and Le Roy Ladurie (1972) for the period 1819-1826. In addition, we use disposable income in 1864 from Delefortrie and Morice (1959).

Next, we use wages in industry and agriculture (measured in 1852) from Goreaux (1956), as well as employment shares in industry and agriculture (in 1876) from Service de la Statistique Général de France (1878). Finally, we perform a detailed within-sector analysis, using local wages as a proxy for productivity. The underlying data are from Chanut, Heffer, Mairesse, and Postel-Vinay (2000), who cleaned and digitalized a survey of 14,238 firms over the period 1839-1847. The data were collected by the *Statistique de la France* at the arrondissement (sub-county) level, and categorize firms into 16 industrial sectors.

4.3 Control Variables

In the following, we briefly describe our control variables. Appendix A.4 provides more detailed descriptions and sources. Our baseline set of controls includes various geographic characteristics of cities, such as dummies for ports on the Atlantic Ocean and on the Mediterranean Sea, as well as for cities located on navigable rivers. Following Dittmar (2011), we also include a dummy for cities that had a university before 1750, a printing press between 1450 and 1500, and the log number of editions printed before 1501. To control for cultural and language differences, we construct a dummy for cities located in non-French speaking departments.[42]

To proxy for worker skills, we use literacy rates in 1686 and 1786 from Furet and Ozouf (1977). These reflect the percentage of men able to sign their wedding certificate. For 1837, department-level schooling data are available from Murphy (2010), computed as the ratio of students to school-age population (5 to 15 years).[43]

We also control for a number of potential confounding factors. These include total book sales at the French city level over the period 1769-1794 from the Swiss publishing house STN (which

[42]There were a number of regions in 18C France that spoke different languages such as Alsacien and Basque. The corresponding 6 departments comprise 24 cities in our sample, out of which 6 had above-zero subscriptions.

[43]These proxies have the same limitation as schooling in the modern context: the tacit worker skills needed to install and operate industrial machines were typically not learned in school. Entrepreneurs – and even inventors such as Boulton and Watt – would train workers themselves in the skills needed to handle industrial machinery. French entrepreneurs also hired English mechanics to install machines and to train local workers (Kelly et al., 2014). However, schooling or literacy of workers facilitated the training process: for example, Dunham (1955, p.184) describes how the *lack* of education affected French iron manufacturing: "Workers were ignorant, frequently illiterate, and consequently most reluctant to learn new methods." Conversely, this suggests that literacy and schooling are reasonable empirical proxies for worker skills.

also published the *Encyclopédie*). We match more than 140,000 sold copies to the cities in our dataset. We obtain the number of noble families in each department from the Almanach de Saxe Gotha, the most important classification of European royalty and nobility. Altogether, our sample contains more than 1,000 noble families in 1750, in 88 French departments. We also control for early industrial activity in France, following Abramson and Boix (2013). These data provide the number of mines, forges, iron trading locations, and textile manufactures prior to 1500 for each department. To proxy for the reach of centralized institutions, we include a dummy for cities located in *pays d'élection*, where the king exerted particularly strong power in fiscal and financial matters. Finally, we control for executions during the 'Reign of Terror' in 1792-94, when alleged counter-revolutionaries were murdered on a massive scale. This addresses the concern that mass executions may have hampered economic development in reactionary areas (where subscriber density may also have been low). We process data on approximately 13,000 executions, assigning them to each department.

In order to guarantee consistency with our main explanatory variable, we calculate the local density of scientific society members, total book sales, noble families in 1750, pre-industrial locations, and executions during the 'Reign of Terror' in the same way as for subscriptions: $\ln(1 + x/pop_{n,1750})$. Appendix A.6 describes how we aggregate city-level variables to the arrondissement and department level. At the end of the appendix, we include a table that lists all variables together with a brief description.

4.4 Balancedness

Do other town characteristics vary systematically with encyclopedia subscriptions? In Table 1 we regress our main explanatory variable $lnSubDens$ on a variety of controls (one-by-one). We begin with our baseline controls in the first two columns. Column 1 uses all cities, while column 2 uses only those with above-zero subscriptions. Few control variables show a consistent pattern. City size is significantly positively correlated with $lnSubDens$ in col 1, but significantly negatively in col 2.[44] Seaports are essentially uncorrelated with subscriber density. The coefficient on navigable rivers is significant in col 1, but switches signs and becomes insignificant in col 2. Cities in non-French speaking areas have a smaller proportion of subscribers, which is to be expected given that the encyclopedia was published in French. The correlation with university and printing press dummies, as well as with books printed before 1500, are all positive (and significant in col 1), as one should expect since they also reflect local access to knowledge.

Next, columns 3-5 in Table 1 report the coefficients of regressing subscriber density on our

[44] Below, we confirm that our results hold in both samples. Note that this implicitly addresses potential unobserved factors that are associated with both city size and $lnSubDens$, because the correlation with city size changes signs between the two samples.

proxies for average worker skills, as well as a variety of potentially confounding variables.[45] Literacy rates in both 1686 and 1786, as well as schooling rates in 1837, are not significantly correlated with subscriber density in any specification. On the other hand, overall (STN) book purchases are strongly and positively associated with encyclopedia subscriptions. This suggests that locations with a greater interest in reading also host more people with scientific interests. Next, there is no systematic relationship between subscriber density and the reach of centralized institutions as reflect by *pay d'élection*. The correlation between $lnSubDens$ and pre-industrial activity is small, negative, and insignificant. This makes it unlikely that our results are driven by early industrial centers. Finally, the local densities of noble families and of executions during the Reign of Terror are positively associated with subscriber density, with a significant coefficient in one of the three specifications. Appendix A.7 provides further tests of balancedness, comparing cities with and without subscriptions, as well as those with above- and below-median subscriber density. These additional tests confirm the pattern described above: the few city characteristics that vary systematically with subscriber density are those that one should expect if subscriptions reflect the size of the local knowledge elite.

5 Empirical Results

In this section we present our empirical results. We test the predictions of the model by estimating equations of the form

$$y_n = \beta \cdot S_n + \gamma \cdot h_n + \delta \mathbf{X}_n + \varepsilon_n \ , \tag{11}$$

where S_n represents our proxy for scientific elites in location n – subscriber density; h_n denotes proxies for average human capital, such as literacy and schooling; $\mathbf{X_n}$ is a vector of control variables, and ε_n represents the error term. We use a variety of outcome variables y_n, depending on the prediction that we analyze. When analyzing growth, we expect $\beta = 0$ prior to 1750 (Prediction 1) and $\beta > 0$ thereafter (Prediction 2), as well as $\gamma = 0$ throughout (Prediction 3). For level variables such as income proxies or manufacturing labor shares, we again expect $\beta = 0$ prior to 1750 and $\beta > 0$ afterwards, but $\gamma > 0$ in both periods.

5.1 City Growth

Because detailed regional income data are not available for early modern Europe, city population is a widely used proxy for economic development (DeLong and Shleifer, 1993; Acemoglu, Johnson, and Robinson, 2005; Dittmar, 2011). In economies with mobile labor, city growth reflects tech-

[45] For those variables that are observed at the department level, we aggregate city-level subscriber density to departments (see Appendix A.6). The department-level data comprise 88 observations in the cross-section, and 66 out of these had above-zero subscriptions. Col 3 reports coefficients for all departments without controls, col 4 adds controls, and col 5 restricts the sample to departments with above-zero subscriptions.

nological progress, since a productive urban sector attracts migrants (Glaeser, Scheinkman, and Shleifer, 1995). Following this approach, we use the outcome variable $gpop_{nt}$, the log difference in city population between two periods t and $t-1$ (mostly 100-year intervals). Figure 5 shows the distribution of $gpop_{nt}$ for different subscriber densities. During industrialization in France, cities with encyclopedia subscriptions grew substantially faster: the city growth distribution is markedly shifted to the right. In addition, this shift is more pronounced for cities with above-median subscriptions per capita. In the following, we analyze this pattern in more detail.

Cities with vs. without subscriptions: matching estimation

Between 1750 and 1850, cities with above-zero subscriptions to the encyclopedia grew at approximately double the rate as compared to those without subscribers (0.51 vs. 0.26 log points). However, merely comparing the two subsets is problematic, because larger cities are more likely to have at least one subscriber. As a first pass at this issue, we use propensity score matching, comparing cities with and without subscriptions of similar size. The results are reported in Table 2.[46] Panel A shows results for a variety of specifications for the period 1750-1850. In col 1, we use the full sample and match by initial population; col 2 excludes the 10% smallest and largest cities in 1750. In cols 3 and 4 we introduce geographic latitude and longitude as additional matching variables.[47] We thus compare *nearby* cities with similar population size, accounting for regional unobservables. The results are stable and economically significant throughout: French cities with subscriptions grew approximately 0.15 log points faster (relative to an average city growth rate of 0.37 log points) than those of comparable size without subscriptions.

In Panel B of Table 2, we repeat the analysis for the pre-industrial period. The difference in growth is now substantially smaller and statistically insignificant, and for 1400-1500, the coefficient is even negative and significant. The matching results support our model prediction that knowledge elites fostered economic growth during, but not before industrialization.

Subscriber density

We now turn to our main explanatory variable, subscriber density $lnSubDens$, using OLS regressions. This offers several advantages over the previous matching exercise: it exploits the full

[46]Following Abadie, Drukker, Herr, and Imbens (2004), we use the three nearest neighbors. Our results are robust to alternative numbers of neighbors. We define 'treatment' as cities with above-zero subscriptions and report average treatment of the treated (ATT) effects. We exclude the top and bottom 1-percentile of city growth rates for each respective period. This avoids that extreme outliers due to population changes of very small towns (for example, from 1,000 to 4,000 or vice-versa) drive our results. In the OLS analysis below, we address this issue by using population weights; in propensity score matching, weighting by city size is not feasible.

[47]The average population difference between matched cities with and without subscriptions is 6,500 inhabitants in col 1, and 500 inhabitants in col 2. When matching by geographic location (col 3), matched cities are on average less than 30 miles apart.

variation in subscriber density (instead of only a dummy), we can examine the coefficient on controls to see how they affect city growth, and we can use population-based weights to reduce the noise in growth rates due to population changes in small cities – there is more reliable information in a city growing from 100,000 to 200,000 inhabitants, than in one growing from 1,000 to 2,000.

Table 3, Panel A, presents our main OLS results for city growth. Subscriber density is strongly and positively associated with city growth over the period 1750-1850 (cols 1-4). Atlantic and Mediterranean ports have a similar effect; the former is in line with Acemoglu et al. (2005). The negative coefficient on initial population (after controlling for other characteristics) provides some evidence for conditional convergence (Barro and Sala-i-Martin, 1992). Both Paris and cities in non-French speaking areas grew faster than average between 1750 and 1850.[48] Finally, we include a dummy for cities that had a printing press in 1500 and control for the log number of editions printed by that date. This replicates the specification in Dittmar (2011), who shows that early adoption of printing had a strong positive effect on city growth in Europe overall, long before industrialization. Within France, this pattern holds in the century after the introduction of the printing press (col 7), but is not stable thereafter. A similar pattern holds for early universities. In sum, including a rich set of control variables does not affect the size or statistical significance of the coefficient on $lnSubDens$. A one standard deviation increase in subscriber density is associated with a city growth rate that is higher by 8.2-16.9 percentage points (0.17-0.35 standard deviations).

Columns 5-8 repeat the analysis for the pre-industrial period. The coefficients on $lnSubDens$ are now small and insignificant. In addition, where sample size and specification are comparable, the difference between the post- and pre-1750 coefficients is strongly significant: the 95% confidence intervals of the estimate for $lnSubDens$ in cols 3 and 5 do not overlap. In Panel B of Table 3 we repeat all city growth regressions for the subset of cities with above-zero subscriptions. The results closely resemble those of Panel A: subscriber density is strongly and significantly associated with city growth after 1750, but not before – in fact, in Panel B the coefficients for the two periods prior to industrialization are now negative (and insignificant).

Literacy and additional controls

Table 4 reports our results for average worker skills (measured by literacy) and a variety of additional controls.[49] The coefficients on literacy are mostly insignificant, in line with Prediction 3. In fact, the coefficients are small and negative throughout. While this should not be over-interpreted

[48]The latter is mostly due to 6 Alsacien-speaking cities in the Rhine area, which saw rapid growth during industrialization. When including a separate Rhine-area dummy, the coefficient of non-French speaking falls to less than one half its original size, while the coefficient on $lnSubDens$ is unchanged.

[49]Standard errors are now clustered at the department level, since this is the geographical unit at which literacy and most additional controls are observed.

due to the low statistical significance, one possible explanation for the negative sign is that traditional artisan manufacturing was more worker skill intensive than modern production. Thus, areas with higher worker skills may have had a comparative advantage in traditional technology, resulting in slower industrialization. Next, while overall book purchases are strongly correlated with $lnSubDens$ (see Table 1), they do not affect city growth (col 2 in Table 4). This provides important support for our argument that upper tail knowledge, but not general literacy, affected growth. In addition, the non-finding for overall book sales also serves as a 'placebo', making it unlikely that our results are driven by reverse causation, i.e., affluent individuals staffing their libraries.

Among the remaining controls in Table 4, only pre-industrial activity is positively and significantly associated with city growth. This confirms the findings in Abramson and Boix (2013). Note that controlling for early industrial centers does not alter the coefficient on subscriber density, suggesting the two are parallel, rather than competing, explanations (recall also the weak negative correlation between the two measures in Table 1). The standardized beta coefficient on pre-industrial activity is 0.17, and thus half the one on subscriber density. The reach of central institutions (*pays d'élection*), executions during the 'Reign of Terror', and nobility density are not associated with city growth. The latter is in line with the historical evidence discussed in Section 2.2 that only a progressive subset of the nobility (which was more likely to read the *Encyclopédie*) was involved in industrial activity. Finally, column 7 includes all potential confounding factors together, confirming the previous results. Importantly, in all regressions the coefficient on $lnSubDens$ remains highly significant and quantitatively similar to our baseline results in Table 3. In sum, the results in Table 4 strongly support our argument that there was a crucial difference between *average* worker skills and upper tail knowledge during industrialization.

Panel estimation

So far, we have shown that the association between subscriber density and city growth was strong after 1750, and weak before that date. Next, we analyze systematically whether the observed increase in the coefficient was statistically significant. Table 5 replicates the specification from Nunn and Qian (2011), using log population as dependent variable in a panel setting. This specification also includes city fixed effects, absorbing all unobserved city characteristics that do not vary over time. We find that the interaction of $lnSubDens$ with a post-1750 dummy is highly significant and positive, with a magnitude that is very similar to the above growth regressions. This finding is robust to including interactions of the post-1750 dummy with our baseline controls (col 2), as well as with our additional controls (col 3). The baseline result also holds in the balanced samples in cols 4 and 5, which include only the 45 (148) French cities where population is observed in every sample year between 1500 and 1850 (1700 and 1850).[50] Finally, cols 6 and 7 report the results for placebo cutoffs in 1600 or 1700. Both yield small, negative, and insignificant coefficients.

City growth before and after the French Revolution

The French Revolution occurred approximately in the middle of our main period of analysis, followed by a radical change in institutions. In Table 6 we show that our results hold for both sub-periods, 1750-1800 (col 1) and 1800-1850 (cols 2 and 3). In column 3, we also control for growth in the earlier period and find a negative and significant coefficient.[51] This suggests that unobserved factors that determined city growth prior to 1800 did not foster growth thereafter, which is in line with a structural break after the French Revolution. Nevertheless, cities with higher subscriber density grew faster under both regimes. This makes it unlikely that subscriber density reflects unobserved institutions that in turn drive growth, complementing our results for *pays d'élection*.

Alternative specifications

We perform a number of additional checks in Appendix A.8. First, we run our city growth regressions for the period 1750-1850, using four different sub-samples, each including those cities for which population data are available in the years 1400, 1500, 1600, and 1700 respectively. The coefficients on $lnSubDens$ are very similar to our baseline results and are always significant at the 1% level. Next, our results are almost identical when pooling growth over the period 1400-1750 and comparing it with growth in 1750-1850 (as visualized in Figure 2). In addition, we use two alternative measures of subscriber density: one that is not log-based, and another one that allows for variation in subscriber density across cities without subscription, assigning lower densities to larger cities. All our results continue to hold. Finally, in line with the model predictions, we find no clear relationship between early literacy (recorded in 1686) and city growth prior to 1750.

5.2 Local Persistence and Roots of Scientific Knowledge

We argue that encyclopedia subscriber density reflects the presence of scientific elites. In the following, we provide evidence that this pattern was locally stable, i.e., that locations with higher subscriber density saw more scientific activity both before and after the mid-18th century. In addition, we shed light on one possible historical root of the observed spatial pattern – the presence of Huguenot minorities.

[50] The results in col 5 are particularly useful to address the concern that cities with high subscriber density in the mid-18th century may already have been richer and on a different growth path: any initial income differences in 1700 are absorbed by city fixed effects. In addition, there is no association between subscriber density and city growth in 1700-50 (as shown above). Thus, it is unlikely that (unobserved) income in 1750 is correlated with $lnSubDens$ and confounds our results.

[51] This is unlikely to be driven by reversion to the mean, i.e., by fast initial growth being mechanically followed by slower subsequent growth, because the regression separately controls for initial log population in 1800.

Scientific societies

Scientific societies are a prime example for the emergence of scientific activity during the Age of Enlightenment (Mokyr, 2005b). In France, there were 22 cities with scientific societies founded before 1750 (see Appendix A.5 for detail). These cities were over three times more likely to be the home to encyclopedia subscribers, and they had almost four times more subscribers per capita than cities without scientific societies (Table A.2 in the appendix). In other words, subscriber density is high were scientific elites were present already before 1750.

The data on pre-1750 scientific societies also allow us to address the possibility of reverse causality: since subscriptions are measures in 1777-80, initial industrial growth between 1750-80 may have raised the demand for the encyclopedia. In Table 7 we repeat our city growth regressions, using scientific societies as explanatory variable. Both propensity score matching (panel A) and OLS estimation using member density (panel B), confirm our main results: cities with pre-1750 scientific societies grew significantly faster during French industrialization, but not before.[52]

'Famous' people in scientific professions, and exhibitions of local innovations

Next, we present two additional variables that point towards a persistent spatial distribution of scientific elites. First, we use data on 'famous' people in 1000-1887 from the *Index Bio-Bibliographicus Notorum Hominum* (IBN), as coded by de la Croix and Licandro (2012). We match these to our sample by city of birth and identify 574 individuals who worked in scientific professions (science, mathematics, chemistry, and physics). Columns 1 and 2 in Table 8 show that doubling subscriber density is associated with a (statistically highly significant) five percent increase in the local density of 'famous scientists'.[53] Second, columns 3 and 4 show that cities with higher subscriber density also presented significantly more innovations (relative to total industrial employment) at the London world fair in 1851.[54] Altogether, a consistent pattern emerges where subscriber density reflects more scientific activity both before and after the time period when the encyclopedia's Quarto edition was printed.

Huguenots and upper tail knowledge

So far, we have taken the spatial dispersion of scientific elites – proxied by $lnSubDens$ – as given. Historians of science have pointed to a variety of local factors that attracted scientific activity in

[52]Member density ($lnMembDens$) in panel B is calculated in the same way as $lnSubDens$ (see Section 4.1). The two measures are strongly correlated, with a coefficient of 0.313 (p-value 0.0001).

[53]The dependent variable is defined as ln(1+'famous scientists'/pop$_{1750}$), where we divide by city population in 1750 because this is closest to the mean year of birth of the 'famous' individuals.

[54]The dependent variable is based on 1,261 exhibits from France, coded by Moser (2005), that we matched to our city dataset. We calculate the dependent variable as ln(1+number of exhibits/pop$_{1850}$). See Appendix A.5 for further detail.

early modern times, but have not analyzed these systematically.[55] In the following we shed light on one historical root of advanced knowledge in France. The Huguenots – the protestant minority – represented an important part of the entrepreneurial and knowledge elite (Scoville, 1953; Hornung, 2014). Contemporaneous observers around 1700 point out that Huguenots "were determined to acquire an education so they could read, write, and master arithmetic", and that they were "skillful in trade and daring in enterprise, apply themselves well to commerce and have all the genius which is needed to succeed in their profession" (cited after Scoville, 1953, pp. 429, 444). One explanation for this focus on entrepreneurship in combination with knowledge is the status of Huguenots as a 'penalized minority'.[56] Employment opportunities for Huguenots were restricted, confining them to professions in the private industry, trade, and finance, where they had a comparative advantage due to the Protestant emphasis on education.[57] In addition, while successful Catholic merchants and craftsmen would often seek pass into public office or into the nobility (via marriage), this path was closed to Huguenots. This reinforced their specialization on entrepreneurship and education. As a result, "there were a large number of individuals among them who were powerful and very intelligent in business affairs" (Scoville, 1953, p.442). Summarizing this argument, Scoville cites the Frenchman Beaumelle, who characterized Huguenots in the mid-18th century as "enlightened and capable of grasping all new ideas, and of borrowing new technical processes from abroad which will help them gain success" (ibid., p.444).

In Table 9 we examine the relationship between Huguenots, subscriber density, and city growth systematically. Column 1 shows that the Huguenot population share in 1670 is a strong predictor of subscriber density a century later.[58] Of course, this does not mean that the majority of Huguenots were highly educated. Instead, it indicates that they had a higher probability of ascending to the knowledge elite.[59] On the other hand, Huguenot presence does not predict literacy (col 2). This

[55] For example, Livingstone (2003, p.181) observes that "the Scientific Revolution bore the stamp of ... local arenas of engagement. In some cases a maritime culture was the chief engine power behind the cultivation of scientific pursuits; in some a courtly culture predominated; in others religious conviction was the molding agent; in yet others economic ambitions provided both impetus and constraint."

[56] Huguenots were persecuted after they converted to Protestantism in the 16th century. The Edict of Nantes in 1598 temporarily granted religious freedom, but it was revoked in 1685, and Protestantism was declared illegal in France. As a result, about 10% of the approximately 1.5-2 million Huguenots left France. Hornung (2014) shows that Huguenot migrants brought technological know-how to their destinations, raising the productivity of local firms.

[57] The latter part of this argument is similar to Botticini and Eckstein (2012) that the Jewish religion's emphasis on education provided a comparative advantage in commerce and trade, resulting in the choice of prosperous urban professions (even in the absence of occupational discrimination).

[58] See Appendix A.5 for details on the Huguenot population share. We also show that the spatial distributions of Huguenots remained relatively stable between 1670 and 1815, i.e., that emigration after the revocation of the Edict of Nantes was not disproportionately stronger in some regions than in others.

[59] In fact, this is similar to the pattern that emerges for another highly educated minority today: while Jews account only for about 1 percent of the total European and U.S. population, they have an important impact in the scientific world, having received more than 20 percent of Nobel Prizes.

is not astonishing: despite their individual education, the Huguenot share in the population overall was too small to systematically affect average literacy.[60]

The remaining results in Table 9 show that areas with higher Huguenot density in 1670 saw significantly faster city growth after 1750 (col 3). Interestingly, this effect becomes small and insignificant once we control for subscriber density (col 4). This suggests that an important part of the relationship between Huguenot presence and city growth worked via upper tail knowledge, while effects of religion (such as a Protestant work ethic) were probably less crucial. In other words, it is unlikely that Huguenots purchased the *Encyclopédie* for religious reasons; a more plausible interpretation is that they formed part of the knowledge elite who became important for growth during industrialization.[61] Finally, in line with our argument, the association between Huguenot presence and growth only emerged after 1750 (cols 5 and 6).

5.3 Income and Industrialization

We now turn to the cross-sectional predictions of our model, analyzing a variety of outcome variables at the department level.

Soldier height

We begin by using a common proxy for income – soldier height, as discussed in Section 4.2. This variable is available in France before and after 1750, allowing us to test the income effects that our model predicts for worker skills and knowledge elites before and after the onset of industrialization. Columns 1-4 in Table 10 show that conscript height in 1819-26 is strongly positively associated with both subscriber density and literacy. This holds even when we control for historical height (cols 3-4). The point estimates imply that a one standard deviation increase in $lnSubDens$ is associated with an increase in average soldier height by 0.3cm (or 0.25 standard deviations). Columns 5 and 6 show that soldier height prior to 1750 is also positively associated with literacy, but not with $lnSubDens$.[62] In sum, the results on soldier height lend support to Predictions 1-3.

Disposable income, employment shares and wages

In column 1 of Table 11 we show that encyclopedia subscriptions in the mid-18th century predict disposable income in 1864, i.e., about a century later. The point estimate implies that a one stan-

[60] In contrast, where Protestants account for the majority of the local population, their impact on literacy can be substantial (Becker and Woessmann, 2009).

[61] Note that part of the observed pattern may also reflect access to financial means: Huguenots were not only more educated but also often affluent entrepreneurs. This is compatible with our interpretation that upper tail knowledge was a proximate driver of industrialization, and investment in physical capital a complementary factor.

[62] While noise in the early height data is an obvious concern, the significant correlation with early literacy is comforting. Table A.10 in the appendix reports further robustness checks, showing that all results hold when regressing conscript height separately on $lnSubDens$ and $Literacy$, and when weighting regressions by the number of soldiers for which height is observed in each department.

dard deviation increase in $lnSubDens$ is associated with 5.6 percent (0.25 standard deviations) higher income. To proxy for average worker skills, we can now use department-level schooling rates, which are available for 1837. This variable is positively and significantly associated with income. Next, we use employment shares in 1876 as dependent variables. In line with Prediction 2, subscriber density predicts lower employment shares in agriculture (col 2) and higher industrial employment (col 3). Finally, we use department-level wages from 1852. Subscriber density is not significantly associated with wages in agriculture (col 4), but it is a positive and significant predictor of overall industrial wages (col 5). In line with Prediction 3, schooling is strongly positively associated with income in the cross-section, with higher manufacturing employment, and with wages in both sectors.

5.4 Knowledge Elites, Innovation, and Productivity

In the following, we provide evidence for the mechanism outlined in the model. If upper tail knowledge helped entrepreneurs to keep up with technological progress, the effect of knowledge elites on local productivity should be particularly strong in sectors that saw rapid innovation.[63] To test this, we implement a two-step argument. We first show that our proxy $lnSubDens$ predominantly reflects modern technology: the majority of technologies that it described and illustrated where innovative.[64] Second, we show that subscriber density predicts firm productivity in modern (innovative), but not in traditional sectors.

From English patents to plates in the Encyclopedia

Nuvolari and Tartari (2011) provide data on the share of "inventive output" of 21 British industrial sectors for the period 1617-1841. This measure is based on reference-weighted patents, adjusted for the sector-specific frequency of patenting rates and citations. For example, *textiles* have the highest score, accounting for 16.6% of total inventive output; and *pottery, bricks and stones* are at the lower end with a share of 1.4%. As a first step, we use the British patent data to analyze whether 'modern' innovative sectors were prominently represented in the encyclopedia. We obtain detailed information on 2,575 plates that the encyclopedia used to illustrate crafts, processes, and inventions (see Appendix A.11 for sources and further detail). About half of these describe manufacturing technologies, and they include examples such as "cloth cutting and figuring" or "machines to evacuate water from a mine". We match plates to the 21 British industrial sectors,

[63] This would also be reflected by a simple model extension with two manufacturing sectors, a 'modern' one where the technological frontier expands quickly (high $\gamma_{\bar{A}}$), and a 'traditional' one with low $\gamma_{\bar{A}}$. According to (10), the effect of scientific elites on income would be stronger in the former.

[64] We do not argue that the encyclopedia was the only publication that illustrated recent innovations. However, its subscribers were also more likely to read other scientific publications, and to be involved in innovation. This underlines the character of our subscriber density measure as a *proxy* for local knowledge elites.

which allows us to split them into 'modern' and 'old' technologies, corresponding to above- and below-median share of total inventive output. We find that more than two thirds of all plates dedicated to manufacturing in the encyclopedia described 'modern' technologies (see Table A.12 in the appendix). Thus, there is strong evidence that the encyclopedia indeed spread predominantly knowledge on modern, innovative industrial technology.

Knowledge elites and productivity in modern vs. traditional manufacturing

We now analyze the relationship between subscriber density and firm productivity (proxied by wages) in 'modern' versus 'old' manufacturing sectors. This analysis builds on data from a French industrial survey of more than 14,000 firms in 1839-47, which reports the sector and firm location by arrondissement.[65] We run the following regression:

$$\ln\left(wage_{jn}\right) = \beta_1 S_n + \beta_2 S_n \times I_j^M + \gamma_1 h_n + \gamma_2 h_n \times I_j^M + \delta_1 \mathbf{X}_n + \delta_2 \mathbf{X}_n \times I_j^M + \alpha_j + \alpha_n + \varepsilon_{jn} \quad (12)$$

where $wage_{jn}$ is the average male wage paid by firms operating in sector j in arrondissement n. Our main explanatory variables are subscriber density S_n and schooling rates h_n. I_j^M is an indicator variable that takes on value one if sector j is 'modern'. The vector $\mathbf{X}_n$ includes the controls used above, as well as total population and the urbanization rate in order to control for agglomeration effects. In addition, we control for sector fixed effects (α_j), location fixed effects (α_n), and for average firm size ($size_{jn}$) to capture scale effects.

If upper tail knowledge affected development by raising the productivity in innovative technologies, we expect $\beta_2 > 0$, reflecting a stronger association between subscriber density and wages in 'modern' as compared to 'old' sectors. Table 12 presents compelling evidence in support of this hypothesis: β_2 is strongly positive. This holds after adding sector fixed effects (col 2), baseline and additional controls (cols 3 and 4), and also when including department or arrondissement fixed effects (cols 5 and 6). The base effect for 'old' sectors (reflected by β_1), is smaller and less robust. The point estimates can be interpreted as follows: suppose that we "move" two representative firms – one in a 'modern' sector and the other in an 'old'-sector – from an arrondissement without subscriptions to one in the 90th percentile of subscriber density (with $lnSubDens \approx 2$). Then productivity of the 'old' firm would increase by 2-8 percent.[66] For the 'modern' firm, productivity would increase by an *additional* 10-14 percent, on top of the base effect captured by β_1. Turning to average worker skills, as reflected by schooling, we find a strong base affect (γ_1), but no additional effect in 'modern' sectors. This is in line with our model, where schooling is positively associated

[65] French arrondissements correspond to the sub-county level – there were altogether 356 arrondissements in 86 departments in the mid-19th century. Appendix A.10 describes the firm survey in more detail and shows how we match French to British sectors. It also lists the resulting consistent 8 sectors and their share of 'inventive output'.

[66] This suggests that upper tail knowledge probably had some positive effects also in 'old' sectors, where innovation was below the median – but above zero.

with wages in the cross-section, but not with faster take-up of innovative technology. With respect to firm size, larger establishments are more productive in 'old' industries, but the net effect is essentially zero in 'modern' industries. This suggests that scale effects (and thus investment constraints) are probably not a major confounding factor for our results. Finally, on average modern sectors pay higher wages, as should be expected if they tend to use more productive technology.

In Table 13, we analyze the relationship between encyclopedia subscriptions and wages within *individual* sectors. We rank sectors by the size of the coefficient on $lnSubDens$. The top four sectors are all 'modern', and the bottom four are all 'old'. In particular, the coefficient on subscriber density is large within sectors that saw rapid innovation during industrialization, such as textiles or transportation (the first steamboat was built in France in 1783). For the least innovative sectors (leather; mining; ceramics and glass), subscriber density is only weakly related to wages.[67] Table 13 also revisits the concern that unobserved local wealth may drive our results, i.e., that the rich could afford the encyclopedia and also had the financial means to invest in industrial machines. We use two proxies for an industry's dependence on up-front investment: the number of steam engines (col 4), and the number of other engines such as wind and water mills (col 5). Interestingly, both measures for up-front investment tend to be higher in sectors where the effect of encyclopedia subscriptions is weaker (such as metal and leather). This makes financial abundance less likely as a confounding factor.[68] In sum, our analysis suggests that knowledge elites supported industrialization by raising the local productivity in innovative modern technology.

5.5 Discussion: Interpretation and Limitations of Results

We have documented a striking pattern: encyclopedia subscriptions are strongly associated with economic growth and income after 1750, but not before the onset of industrialization in France. Our interpretation is not that the encyclopedia turned its readers into entrepreneurs, or that it *caused* local upper tail knowledge. Instead, we use subscriber density as an indicator for the local presence of knowledge elites. The geographic pattern was likely persistent: we provided evidence that locations with higher subscriber density hosted more knowledge elites both before and after 1750. If scientific elites where present before industrialization, why did they not spur growth? In line with the historical account, our model suggests that local scientific elites started to matter when knowledge became economically 'useful' (Mokyr, 2005b), and when the aggregate technological frontier began to advance rapidly. The mechanism is not confined to inventors or scientists actively

[67] Column 3 shows that the number of observations and the R^2 are similar for 'modern' and 'old' sectors. Thus, overall fit or small samples do not drive the differences in coefficients.

[68] Verley (1985, p.103-104) observes that the metal industry was particularly capital intensive and often operated by the rich nobility, while textile production occurred at a smaller scale and required much less capital. Our finding that subscriber density is particularly strongly associated with productivity in the latter is thus compatible with a knowledge-based explanation.

improving technology, but it also comprises lower access costs (e.g., via information networks in the knowledge elite) and higher efficiency at adopting complex modern techniques. Thus, our interpretation emphasizes a broad concept of upper tail knowledge – but one that is clearly distinct from ordinary worker skills.

Our empirical analysis follows the common approach to regress growth rates on initial levels of human capital (Barro, 2001). It thus also shares the common limitation that skills are not assigned exogenously to different locations, which makes causal inference difficult. Correspondingly, we do not claim that upper tail knowledge was necessarily a fundamental driver of industrial growth. However, our results suggest that it was at least a proximate determinant. For this interpretation to be valid, we need to discuss potential confounding factors that also fit the observed empirical pattern, but work via channels unrelated to upper tail knowledge: such factors would have to be correlated with subscriber density, affect growth only after 1750, and do so particularly strongly in innovative modern sectors. We have discussed some alternative explanations that might fit this pattern – institutions, broader knowledge (overall book purchases), access to finance (presence of noble families), and the 'Reign of Terror' – and concluded that these are unlikely to fully account for our results.[69] Among these, access to finance is the most probable additional driver of industrial development. In modern economies, advanced education and income are strongly related; this was also true in the period that we analyze, where a substantial share of encyclopedia subscribers came from the progressive bourgeoisie and nobility. Nevertheless, deep pockets alone are unlikely to explain industrial growth – even the most affluent individuals could not invest in technology they did not know about. In this sense, physical capital is not a 'competing' factor, but rather another proximate driver that is *complementary* to upper tail human capital. In sum, the historical evidence in combination with our empirical results make it hard to imagine that knowledge elites did not play an important role during industrialization.

We also confirmed the model prediction that average worker skills were positively associated with development in the cross-section both before and after industrialization, but not with growth.[70] For the cross-sectional results, reverse causality is a concern: income may have led to more literacy, rather than the other way around. Nevertheless, this can hardly explain our finding that literacy was *not* associated with growth during industrialization.

In sum, by predicting when the two types of human capital will and will *not* affect economic development, our model allows us to run a number of consistency checks. These are confirmed

[69] We also demonstrated that subscriber density was unrelated to most observable local characteristics at the eve of French industrialization.

[70] This dimension of human capital also shows a relatively stable local pattern over time: the department-level literacy rate in 1686 has a correlation coefficients of 0.84 with literacy in 1786, and of 0.65 with schooling in 1837.

by the data. The empirical results thus strongly support our theoretical setup that differentiates between average and upper tail skills.

6 Conclusion

An ample literature has highlighted the importance of human capital for economic development in the modern world. However, its role during the Industrial Revolution has typically been described as minor. Hence, a crucial driver of modern growth appeared to be unrelated to the onset of growth itself, and thus to the greatest structural break in economic history. We resolved this puzzle by showing that not education of the masses, but upper tail human capital – the presence of knowledge elites – played an important role for industrial growth. To proxy for scientific elites, we use subscriber density to the encyclopedia and show that this measure is strongly associated with other indicators of local scientific activity both before and after the encyclopedia was printed in the mid-18th century. We also shed some light on one historical root of this spatial pattern – the presence of the suppressed Huguenot minority with a strong emphasis on educational attainment. A promising route for future research is to systematically examine the causes of the spatial dispersion of scientific elites at the eve of industrialization.

We provided a simple model to guide our empirical analysis and interpretation. While worker skills raise productivity for any *given* technology, upper tail knowledge allows entrepreneurs to adopt more productive techniques. Thus, the former raise income per capita in the cross-section, while the latter fosters growth. In the spirit of Nelson and Phelps (1966), advanced knowledge is more important when the technological frontier expands rapidly (which we take as given, since we focus on cross-sectional, rather than aggregate growth). Consequently, upper tail knowledge matters for development, but only after technological advances become rapid. Our data lend strong support to this prediction. Importantly, we do not argue that *average* worker skills were altogether unimportant; we show that they were strongly correlated with income *levels* before and after industrialization, but not with growth.

Our results have important implication for economic development: while improvements in basic schooling raise wages, greater worker skills alone are not sufficient for industrial growth. Instead, upper tail skills – even if confined to a small elite – are crucial, fostering growth via the innovation and diffusion of modern technology. In this respect, our findings resemble those in today's economies, where the existence of a social class with high education is crucial for development (Acemoglu, Hassan, and Robinson, 2011), entrepreneurial skills matter beyond those of workers (Gennaioli et al., 2013), and scientific education is key (Hanushek and Kimko, 2000).

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FIGURES

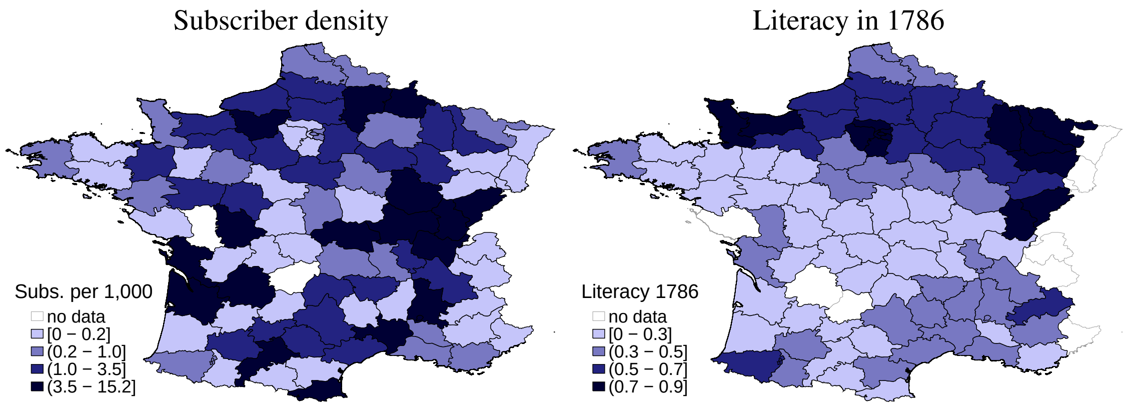

Figure 1: Encyclopedia subscriber density and literacy rates

Notes: The left panel shows the spatial distribution of encyclopedia subscribers per 1,000 city inhabitants in the second half of the 18th century. The right panel shows the distribution of literacy rates (percentage of males signing their marriage certificate) across French departments in 1786. Both variables are described in detail in Section 4.1. Figure A.2 in the appendix plots the two variables against each other, show that they are not correlated.

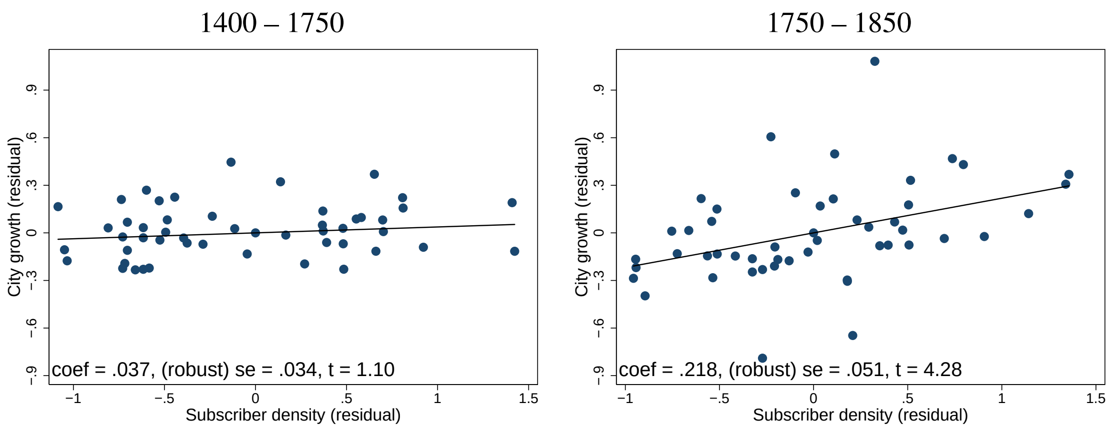

Figure 2: Encyclopedia subscriptions and city growth – before and after 1750

Notes: The figure plots average annual city growth in France against encyclopedia subscriber density ($lnSubDens$), after controlling for our baseline controls (listed in Table 1). The left panel uses the pre-industrial period 1400-1750. The right panel examines the same cities over the period of French industrialization, 1750-1850. Average annual city growth was 0.23% and 0.48% over the two periods, respectively.

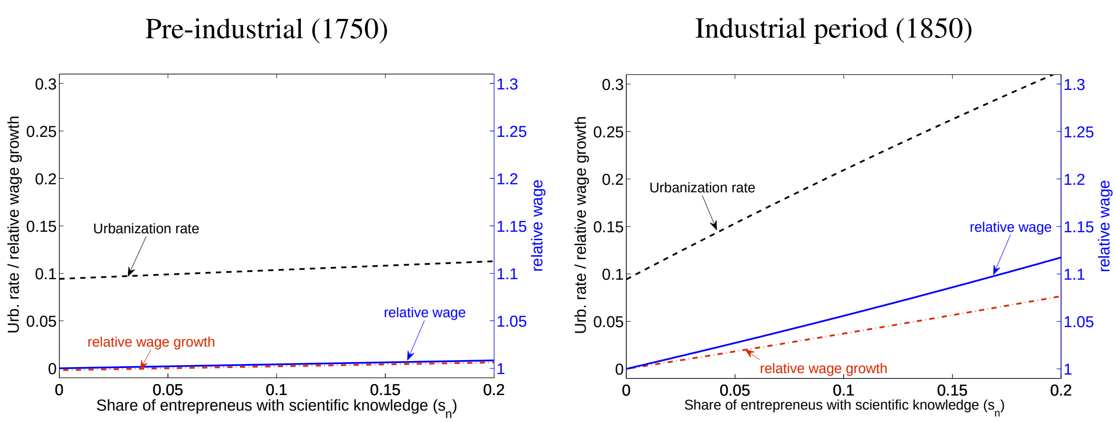

Figure 3: Scientific knowledge and economic development

Notes: The figure illustrates how the share of entrepreneurs with scientific knowledge in region n, s_n, affects urbanization, wages, and economic growth. The left panel refers to the pre-industrial period (illustrating model Prediction 1), and the right panel illustrates Prediction 2, referring to the industrial period. The urbanization rate corresponds to the labor share in manufacturing. Wages (right axis) are reported relative to regions without scientific knowledge ($s_n = 0$). Relative wage growth (left axis) is measured as annual percentage growth in region n, net of growth in regions with $s_n = 0$.

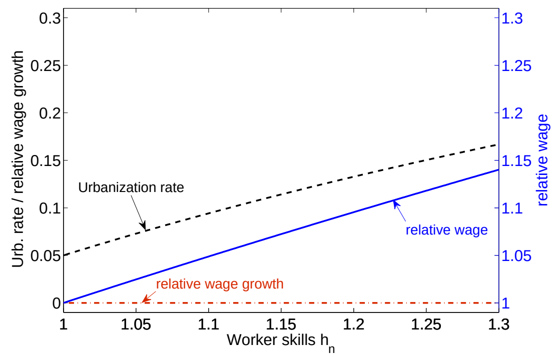

Figure 4: The role of worker skills

Notes: The figure illustrates model Prediction 3, showing how worker skills in region n, h_n, affect urbanization, wages, and economic growth. Since the effect of worker skills does not change over time, the figure illustrates both the pre-industrial period and the industrial period. See Figure 3 for a description of the three depicted variables.

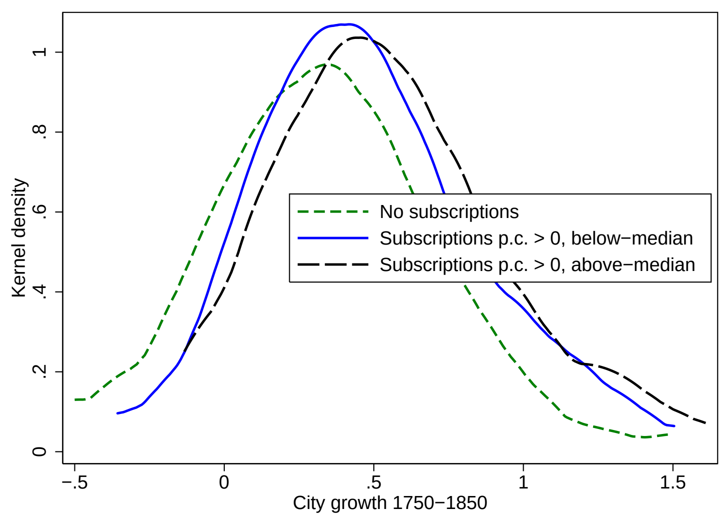

Figure 5: Subscriptions and city growth, 1750-1850

Notes: The figure shows the Kernel density of city growth over the period 1750-1850 for three subsets of French cities: 108 cities without encyclopedia subscriptions, as well as 43 (42) cities with subscriptions and below-median (above-median) subscriber density.

TABLES

Table 1: Correlations with subscriber density ($lnSubDens$)

	(1)	(2)		(3)	(4)‡	(5)‡
Cities included:	All	Subs>0	Cities/Dept. included:	All	All	Subs>0
Baseline Controls			Worker skills			
Population in 1750	0.374***	-0.234**	Literacy 1686†	0.551	0.905	0.026
	(0.073)	(0.110)		(0.593)	(0.650)	(0.777)
Atlantic Port	0.081	-0.222	Literacy 1786†	0.290	0.358	0.054
	(0.207)	(0.213)		(0.345)	(0.323)	(0.383)
Mediterranean Port	0.022	-0.129	School Rate 1837†	0.363	0.313	0.200
	(0.276)	(0.223)		(0.350)	(0.335)	(0.412)
Navigable River	0.422**	-0.167				
	(0.202)	(0.210)	Additional Controls			
Non French-Speaking	-0.376**	-0.719**	*lnSTNBooksDens*	0.242***	0.194***	0.062
	(0.146)	(0.297)		(0.041)	(0.050)	(0.056)
			Pays d'Eléction	0.046	0.137	0.048
Early Knowledge Controls				(0.129)	(0.128)	(0.205)
University	1.030***	0.316	*lnPreIndDens*†	-0.027	-0.033	-0.546
	(0.186)	(0.194)		(0.830)	(0.829)	(0.846)
Printing Press	0.712***	0.203	*lnNoblesDens*†	0.233	0.253	0.736***
	(0.170)	(0.182)		(0.278)	(0.301)	(0.249)
ln(Books Printed 1500)	0.171***	0.039	*lnExecuteDens*†	0.272**	0.210	0.247
	(0.061)	(0.066)		(0.117)	(0.138)	(0.148)

Notes: The table shows the coefficients of individual regressions of subscriber density, $lnSubDens$, on a variety of city characteristics. $lnSubDens$ is computed as described in Section 4.1. *Population in 1750* measures urban population (in thousands) for the cities in our sample. *Atlantic Port*, *Mediterranean Port* and *Navigable River* are dummies for cities with ports on the Atlantic Ocean or on the Mediterranean Sea, or located on a navigable river. *Non French Speaking* is a dummy for six French departments who spoke a language other than French. *University* is a dummy for cities that hosted a University before 1750. *Printing Press* is a dummy for cities where a printing press was established before 1500. *Ln(Books Printed 1500)* represents the log number of editions printed before 1501. *Literacy* in 1686 and 1786 measures the percentage of men signing their wedding certificate in the respective year. $SchoolRate$ in 1837 measures the ratio of students to school-age population (5 to 15 years) in 1836-37. $lnSTNBooksDens$ represents the (log) book purchases per capita from the Swiss publishing house *Société Typographique de Neuchâtel* (STN) over the period 1769-1794. *Pays d'élection* is a dummy for cities in regions where the French king exerted particularly strong control over tax collection. $lnPreIndDens$ is an index of pre-industrial activities in France that includes the number of mines, forges, iron trading locations, and textile manufactures before 1500. $lnNoblesDens$ reflects the density of noble families in each French department. $lnExecuteDens$ measures the density of executions during the reign of Terror. For sources and details, see Section A.4. Robust standard errors in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

† Variable observed at the department level, and corresponding regression also run at department level.

‡ Regressions include baseline and early knowledge controls.

Table 2: Matching estimation by city size and location

Dependent variable: log city growth over the indicated period

	(1)	(2)	(3)	(4)
	PANEL A: Period 1750-1850			
City size percentiles incl.:	All	10-90 pct	All	10-90 pct
$I_{Subs>0}$	0.146**	0.155**	0.267***	0.163**
	(0.07)	(0.07)	(0.07)	(0.07)
Matching variables				
Population	✓	✓	✓	✓
Location			✓	✓
Observations	177	154	167	144
	PANEL B: Pre-1750			
	1700-1750	1600-1700	1500-1600	1400-1500
$I_{Subs>0}$	0.087	0.034	0.181	-0.567***
	(0.06)	(0.17)	(0.17)	(0.21)
Matching variables				
Population	✓	✓	✓	✓
Location	✓	✓	✓	✓
Observations	129	58	43	37

Notes: All regressions are run by propensity score matching at the city level, excluding the 1% of log city growth outliers, and using the three (two) nearest neighbors when there are more (less) than 50 observations. Average treatment of the treated (ATT) effects are reported, where the treatment variable is the indicator $I_{Subs>0}$, which takes on value 1 if a city had above-zero subscriptions to the encyclopedia. Columns 1 and 2 in Panel A use city population as matching variable. Columns 3 and 4, as well as Panel B, add geographic longitude and latitude (*location*) as matching variables. Standard errors in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

Table 3: Encyclopedia subscriptions and city growth, before and after 1750

Dependent variable: log city growth over the indicated period

	Period 1750-1850				Pre-1750			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
				[unweighted]	1700-1750	1600-1700	1500-1600	1400-1500
PANEL A: All cities								
lnSubDens	0.100**	0.171***	0.169***	0.204***	0.008	0.060	0.056	0.115
	(0.039)	(0.036)	(0.033)	(0.036)	(0.037)	(0.119)	(0.087)	(0.167)
$lnPop_{initial}$	0.055***	-0.085**	-0.089*	-0.156***	-0.058	-0.456**	-0.376***	-0.287**
	(0.014)	(0.041)	(0.048)	(0.051)	(0.040)	(0.186)	(0.087)	(0.134)
Atlantic Port		0.221***	0.242**	0.349**	0.087	-0.124	0.372**	0.256
		(0.082)	(0.094)	(0.162)	(0.101)	(0.239)	(0.145)	(0.272)
Mediterranean Port		0.779***	0.794***	0.752***	-0.203**	0.784*	0.309*	0.716**
		(0.076)	(0.091)	(0.142)	(0.094)	(0.398)	(0.161)	(0.277)
Navigable River		0.095	0.068	0.134*	0.001	0.222	-0.017	0.221
		(0.068)	(0.072)	(0.069)	(0.076)	(0.191)	(0.131)	(0.291)
Paris		0.575***	0.610***	0.760***	-0.020	0.638	1.237***	0.402
		(0.136)	(0.132)	(0.171)	(0.135)	(0.478)	(0.321)	(0.582)
Non French Speaking		0.337***	0.330***	0.428***	0.100	-0.438	0.078	0.156
		(0.089)	(0.097)	(0.145)	(0.129)	(0.376)	(0.272)	(0.373)
University			-0.063	-0.123	0.122*	0.299*	-0.108	-0.049
			(0.067)	(0.084)	(0.069)	(0.173)	(0.117)	(0.271)
Printing Press in 1500			0.093	0.188*	-0.078	-0.628**	0.448**	-0.063
			(0.094)	(0.098)	(0.083)	(0.272)	(0.182)	(0.351)
ln(Books Printed 1500)			-0.001	0.006	0.029*	0.162**	-0.040	0.020
			(0.020)	(0.025)	(0.017)	(0.065)	(0.040)	(0.067)
R^2	0.12	0.36	0.36	0.27	0.17	0.55	0.53	0.31
Observations	193	193	193	193	148	56	45	39
PANEL B: Only cities with positive subscriptions								
lnSubDens	0.090	0.135***	0.117**	0.086*	-0.069	-0.061	0.018	0.175
	(0.063)	(0.051)	(0.045)	(0.044)	(0.053)	(0.129)	(0.094)	(0.213)
Controls	✓	✓	✓	✓	✓	✓	✓	✓
R^2	0.08	0.46	0.48	0.38	0.32	0.64	0.64	0.30
Observations	85	85	85	85	76	44	36	32

Notes: All regressions are run at the city level and are weighted (except for Column 4) by initial population of the respective period. The dependent variable is log city population growth over the period indicated in the header. 'Controls' in Panel B are the same as in the corresponding column of Panel A. For details on the explanatory variables see the notes to Table 1. Robust standard errors in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

Table 4: Literacy and additional controls

Dependent variable: log city growth, 1750-1850							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
lnSubDens	0.180***	0.198***	0.187***	0.176***	0.176***	0.179***	0.187***
	(0.040)	(0.042)	(0.040)	(0.038)	(0.041)	(0.040)	(0.042)
Literacy 1786	-0.209	-0.156	-0.190	-0.276**	-0.208	-0.185	-0.192
	(0.142)	(0.135)	(0.143)	(0.133)	(0.144)	(0.144)	(0.138)
lnSTNBooksDens		-0.025					-0.020
		(0.021)					(0.021)
Pays d'Eléction			-0.076				-0.043
			(0.065)				(0.069)
lnPreIndDens				1.107***			0.952**
				(0.363)			(0.391)
lnNoblesDens					0.085		0.129
					(0.135)		(0.119)
lnExecuteDens						0.037	0.030
						(0.037)	(0.039)
ln(Pop 1750)	-0.075*	-0.053	-0.086*	-0.067	-0.061	-0.072	-0.033
	(0.043)	(0.041)	(0.045)	(0.040)	(0.055)	(0.044)	(0.048)
Controls	✓	✓	✓	✓	✓	✓	✓
R^2	0.38	0.39	0.39	0.40	0.38	0.39	0.41
Observations	166	166	164	166	166	166	164

Notes: All regressions are run at the city level and are weighted by city population in 1750. The dependent variable is log city population growth in 1750-1850. 'Controls' include the baseline controls and early knowledge controls listed in Table 1; a dummy for Paris is also included. For details on the explanatory variables see notes to Table 1. Robust standard errors in parentheses (clustered at the department level). * p<0.1, ** p<0.05, *** p<0.01.

Table 5: Panel regressions with city population, 1500-1850

Dependent variable: log city population

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Full panel, 1500-1850			Balanced panel		Placebo periods	
				1500-1850	1700-1850	$y = 1600$	$y = 1700$
$lnSubDens \times Post_{1750}$	0.106***	0.136***	0.109**	0.164**	0.123***	0.146***	0.158***
	(0.029)	(0.031)	(0.042)	(0.070)	(0.026)	(0.029)	(0.033)
$lnSubDens \times Post_y$						-0.039	-0.043
						(0.077)	(0.044)
Controls		✓	✓	✓	✓	✓	✓
Additional Controls			✓				
City FE	✓	✓	✓	✓	✓	✓	✓
Time Period FE	✓	✓	✓	✓	✓	✓	✓
R^2	0.86	0.87	0.88	0.85	0.94	0.88	0.87
Observations	846	846	722	270	592	846	846

Notes: All regressions are run at the city level. The dependent variable is the log of city population in the years 1500, 1600, 1700, 1750, 1800, and 1850. The $Post_{1750}$ indicator variable takes value zero for the periods 1500-1750, and value one for 1800 and 1850. $Post_y$ is defined similarly, but with respect to the placebo period y indicated in cols 6 and 7. 'Controls' include a dummy for Paris as well as the baseline controls and early knowledge controls listed in Table 1, which also lists the 'Additional Controls'. All controls are interacted with $Post_{1750}$, and, where applicable, also with $Post_y$. Robust standard errors in parentheses (clustered at the department level in col 3). * p<0.1, ** p<0.05, *** p<0.01.

Table 6: City growth over the sub-periods 1750-1800 and 1800-1850

Dependent variable: log city growth over the indicated period

	(1)	(2)	(3)
Period	1750-1800	1800-1850	1800-1850 Control for prior growth
lnSubDens	0.108***	0.059**	0.073***
	(0.035)	(0.028)	(0.027)
Growth 1750-1800			-0.187***
			(0.069)
Controls	✓	✓	✓
R^2	0.29	0.39	0.42
Observations	192	192	192

Notes: All regressions are run at the city level over the period indicated in the table header. 'Controls' include the baseline controls and early knowledge controls listed in Table 1, as well as log city population at the beginning of each period and a dummy for Paris. For further detail see the notes to Table 1. Robust standard errors in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

Table 7: Scientific societies and city growth

Dependent variable: log city growth over the indicated period

	(1)	(2)	(3)
	Period 1750-1850		1700-1750
PANEL A: Matching Estimation			
$I_{Scient.Scociety>0}$	0.204**	0.193**	0.028
	(0.098)	(0.095)	(0.083)
Matching variables			
Population	✓	✓	✓
Location		✓	✓
Observations	185	175	136
PANEL B: OLS Estimation			
lnMembDens	0.171*	0.287***	0.069
	(0.088)	(0.080)	(0.105)
Controls		✓	✓
R^2	0.10	0.32	0.19
Observations	185	185	140

Notes: All regressions are run at the city level. The dependent variable is log city population growth over the period indicated in the header. In Panel A, all regressions are run by propensity score matching as described in Table 2. Treatment variable is the indicator $I_{Scient.Society>0}$, which takes on value 1 if a city hosted a scientific society before 1750. Column 1 uses city population as matching variable. Columns 2 and 3 add geographic longitude and latitude (*location*) as matching variables. In Panel B, all regressions are run by OLS and are weighted by initial population of the respective period. 'Controls' include the baseline controls and early knowledge controls listed in Table 1. In addition, all specifications include log city population at the beginning of each period and a dummy for Paris. For further detail see the notes to Table 1. Standard errors in parentheses.* p<0.1, ** p<0.05, *** p<0.01.

Table 8: Subscriber density, scientists and exhibits

	(1)	(2)	(3)	(4)
Dep. Var.:	'Famous' Scientists		Exhibits in 1851	
lnSubDens	0.044***	0.048***	0.023**	0.022*
	(0.014)	(0.013)	(0.011)	(0.012)
Baseline Controls		✓		✓
R^2	0.13	0.15	0.19	0.32
Observations	193	166	193	165

Notes: All regressions are run at the city level and include dummies for Paris. The dependent variable in cols 1-2 is (log) 'famous' scientists per capita. These are people listed in the *Index Bio-Bibliographicus Notorum Hominum* whose profession is related to science, mathematics, chemistry, or physics. These data are from de la Croix and Licandro (2012). In total, there 574 'famous' scientists listed for France over the period 1000–1887. The dependent variable in cols 3-4 is (log) innovations per capita from French cities exhibited at the London world fair in 1851. These data are from Moser (2005). 'Baseline Controls' are those listed in Table 1, which also provides further detail on the variables. Robust standard errors in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

Table 9: Huguenots, subscriber density, and city growth

	(1)	(2)	(3)	(4)	(5)	(6)
Dep. Var.:	$lnSubDens$	$Literacy_{1786}$	Log City Growth			
			1750-1850		1700-1750	
$lnHugDens_{1670}$	0.590***	-0.058	0.197**	0.070	-0.039	-0.060
	(0.168)	(0.060)	(0.077)	(0.089)	(0.074)	(0.069)
lnSubDens				0.216***		0.035
				(0.055)		(0.039)
Baseline Controls	✓	✓	✓	✓	✓	✓
R^2	0.20	0.06	0.15	0.25	0.04	0.04
Observations	163	150	163	163	132	132

Notes: All regressions are run at the city level and include a dummy for Paris. For $lnSubDens$, $Literacy_{1786}$, and 'Baseline Controls' see Table 1. $lnHugDens_{1670}$ is the (log) number of Huguenots in 1670 relative to population at the department level. Standard errors (clustered at the department level) in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

Table 10: Soldiers height before and after 1750

Dependent variable: Soldier height in cm

	(1)	(2)	(3)	(4)	(5)	(6)
	Period 1819-1826				Pre-1750	
lnSubDens	0.416***	0.450***	0.403***	0.443***	0.116	0.120
	(0.136)	(0.129)	(0.139)	(0.132)	(0.115)	(0.116)
Literacy	2.805***	3.056***	2.463***	2.849***	1.043*	0.982*
	(0.398)	(0.360)	(0.459)	(0.389)	(0.525)	(0.549)
Height pre-1750			0.303	0.172		
			(0.193)	(0.147)		
Baseline Controls		✓		✓		✓
R^2	0.42	0.60	0.46	0.61	0.06	0.16
Observations	77	77	77	77	74	74

Notes: All regressions are run at the department level and include a dummy for Paris (Department Seine). The dependent variable in cols 1-4 is soldier height as reported by Aron et al. (1972). In Columns 5-6, the dependent variable is average soldier height recorded over the period 1716-49 and collected by Komlos (2005). To account for variation in height and soldier age within this period, we control for age, age squared, and birth decade (see Appendix A.3 for detail). We exclude departments with data for less than 20 soldiers (Table A.10 reports results when using all departments and weighting by the number of soldiers). 'Baseline Controls' are those listed in Table 1; we use *Literacy* in 1786 in Colums 1-4 and in 1686 in Columns 5-6. For details on $lnSubDens$, Literacy and controls see the notes to Table 1. Robust standard errors in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

Table 11: Disposable income, employment shares and wages

	(1)	(2)	(3)	(4)	(5)
Dep. var.	ln(disposable income)	Employment shares		Wages	
		Agric.	Industry	Agric.	Industry
lnSubDens	0.068**	-0.033*	0.019*	0.040	0.055***
	(0.030)	(0.017)	(0.011)	(0.026)	(0.017)
School Rate 1837	0.225**	-0.205***	0.121***	0.413***	0.203***
	(0.111)	(0.063)	(0.038)	(0.084)	(0.056)
Baseline Controls	✓	✓	✓	✓	✓
R^2	0.33	0.47	0.34	0.51	0.48
Observations	87	85	85	79	79

Notes: All regressions are run at the French department level and include a dummy for Paris (Department Seine). 'Baseline Controls' are those listed in Table 1. For details on $lnSubDens$ and controls see the notes to Table 1. Robust standard errors in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

Table 12: Subscriber density and average local firm productivity in 1837

Dep. Var.: log wages (by sector and arrondissement)

	(1)	(2)	(3)	(4)	(5)	(6)
lnSubDens	0.041**	0.040**	0.031**	0.025	0.012	
	(0.016)	(0.015)	(0.014)	(0.015)	(0.021)	
$lnSubDens \times modern$	0.069***	0.056***	0.052***	0.062***	0.066***	0.060***
	(0.015)	(0.015)	(0.017)	(0.018)	(0.019)	(0.021)
School Rate 1837	0.248***	0.234***	0.242***	0.205***		
	(0.071)	(0.072)	(0.072)	(0.066)		
$School \times modern$	-0.002	-0.015	-0.016	0.017	0.040	0.047
	(0.069)	(0.067)	(0.072)	(0.082)	(0.087)	(0.094)
Establishment Size	0.055***	0.045***	0.043***	0.044***	0.044***	0.038***
	(0.008)	(0.009)	(0.010)	(0.011)	(0.010)	(0.010)
$Size \times modern$	-0.074***	-0.036***	-0.035***	-0.034**	-0.039***	-0.034**
	(0.012)	(0.011)	(0.013)	(0.015)	(0.015)	(0.016)
Modern Sector	0.129***					
	(0.035)					
Sector FE		✓	✓	✓	✓	✓
Baseline Controls			✓	✓	✓	✓
Additional Controls				✓	✓	✓
Department FE					✓	(✓)
Arrondissement FE						✓
R^2	0.14	0.23	0.35	0.37	0.48	0.58
Observations	1,480	1,480	969	879	879	879

Notes: All regressions are run at the arrondissement level and include a dummy for Paris (Department Seine). The dependent variable is the log of average male wages across all firms in a sector j in arrondissement n. There are more than 14,000 firms in the sample (see Appendix A.10). Firms a classified into 8 sectors, and the 4 most innovative ones are categorized as 'modern' (see Appendix Section A.10 and Table A.11 for detail). *Establishment size* is the (log) average number of workers across all firms in j and n. 'Baseline Controls' and 'Additional Controls' are those listed in Table 1; we also control for (log) total department-level population and urbanization rates (both in 1831) to capture agglomeration effects. For each control variable, both its level and its interaction with 'modern' is included. For details on $lnSubDens$ and controls see the notes to Table 1. Original city-level variables are aggregated to the arrondissement level as described in Appendix A.6. Standard errors (clustered at the department level) in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

Table 13: Subscriber density and firm productivity within individual industries

Sector Name	(1) Sector type	(2) Coefficient $lnSubDens$	(3) R^2 Obs.	(4) Engines per 1,000 Steam	(5) Others
Transportation Equipment	modern	0.114*** (0.026)	0.63 39	2	9
Printing Technology, and Scientific Instruments	modern	0.103*** (0.021)	0.20 221	1	26
Textile and Clothing	modern	0.067*** (0.018)	0.28 298	3	8
Furniture and Lighting	modern	0.056* (0.033)	0.54 75	13	1
Metal and Metal Products	old	0.042* (0.024)	0.16 273	6	34
Leather	old	0.041* (0.022)	0.19 165	3	46
Mining	old	0.038** (0.018)	0.31 188	3	15
Ceramics and Glass	old	0.003 (0.020)	0.27 168	4	5

Notes: For each sector, column 1 specifies whether the sector belongs to the ‘modern’ or ‘old’ manufacturing classification (see Section 5.4 for detail). Sectors are ranked by the size of the coefficient on *lnSubDens*, reported in column 2; this coefficient is obtained by regressing – within each sector – log male wages (the dependent variable in Table 12) on *lnSubDens*, average establishment size, the urbanization rate, and the baseline controls listed in Table A.4. For each regression, column 3 reports the R^2 and the number of observations. For details on the firm data see Appendix A.10. Standard errors (clustered at the department level) in parentheses. * p<0.1, ** p<0.05, *** p<0.01. Columns 4-5 show the sector-specific average number of steam engines and of other engines per 1,000 workers (see Appendix A.10 for detail).