Invention and Technological Leadership during the Industrial Revolution*

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This paper provides the first empirical cross-country evidence on inventive activity during the Industrial Revolution. Idiosyncrasies in the French historic patent law allow us to compare invention rates in Britain and France across sectors based on French patent data from 1791 to 1855. Our key result is a robust, positive association of invention rates in Britain and France at the sectoral level. Furthermore, we provide the first quantitative evidence on technological leadership in invention at the sectoral level. The evidence informs a debate about whether the acceleration of technological progress during the Industrial Revolution mainly was a British or a European achievement, which has implications for theories of growth and innovation.

Keywords: Innovation; idea flows; international technology diffusion; technological leadership; Industrial Revolution.

JEL-classification: N10, 13; O14, 31, 33, 41

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1. Introduction

The Industrial Revolution is the watershed in human history that unleashed exponential income growth driven by technological progress, ultimately resulting in today's standard of living (Galor and Weil, 2000; Mokyr, 2002; Galor, 2011; Clark, 2014). This technological progress was fueled by an acceleration in the rate of inventive activity, which multiplied during the Industrial Revolution relative to the slow rate of pre-industrial times (Ashton, 1948; Landes, 1969; Mokyr, 1990, 1999). Commonly, Britain is perceived as the technological leader during the Industrial Revolution (Broadberry, 1994; Crafts, 1998). However, there is no empirical evidence of how large the British *technological leadership in invention* was.[1] Moreover, there is no consensus whether British technological leadership in invention can explain the aggregate acceleration in the rate of invention, or whether the rate of invention accelerated simultaneously in Britain and other European countries as France (Crafts, 2021).

Existing evidence cannot empirically distinguish the hypotheses proposed in the literature. On the one hand, it has been argued that invention was primarily constrained by demand (market size). As it was more extensive in Britain than elsewhere in sectors like coal, cotton, or steam, invention accelerated first in Britain, making her the technological leader. Then, ideas diffused to the European continent, which became a technological follower that imitated Britain (Landes, 1969; Allen, 2009a, 2017; *leader–follower hypothesis*). On the other hand, it has been argued that invention was primarily constrained by the supply of knowledge. Once this knowledge became available across Europe, invention accelerated across Europe, in particular in sectors as chemistry or machines where Britain and the European continent were technologically neck-on-neck (Mokyr, 1990, 2002, 2009a; *simultaneity hypothesis*). Both hypotheses have first-order predictions on invention and technological leadership in a setting with two (or more) countries and multiple sectors.

This paper uses a unique setting to compare invention rates across countries and sectors during the Industrial Revolution by observing domestic invention and the imitation of foreign inventions in France. During the period of the (first) Industrial Revolution, France was the main economic rival of Britain. The large majority of foreign inventions that were imitated in France originated in Britain. Using data on the universe of French patents 1791–1855, we are able to distinguish between invention and imitation patents and calculate invention and imitation patenting rates for almost all sectors of the economy.[2] Given that most imitation patents came from Britain, imitation patenting plausibly reflects invention in Britain. When

[1] We define technological leadership as an absolute advantage in invention, following the literature economic growth (e. g., Barro and Sala-I-Martin, 1997; Acemoglu, 2009).

[2] The only sectors which are not covered by the patent data are finance and pharmaceuticals.

comparing invention and imitation patents across sectors within France, we can account for country fixed effects and analyze how invention in France and Britain covaried between and within sectors.

Based on the British and French invention measures, we document novel stylized facts on technological progress and leadership during the Industrial Revolution. First, we provide the evidence on the association between the invention rate in Britain and the European continent across sectors. We find that invention and imitation patenting rates exhibit a significant, quantitatively large, and robust positive correlation. Second, we construct a quantitative measure of technological leadership in Britain compared to the European continent. We find substantial variation in leadership across sectors in terms of how much France imitated from Britain relative to how much France invented domestically. The findings are consistent with the hypothesis that, on the aggregate, invention accelerated simultaneously in Britain and the European continent. Despite a sizable technological lead of Britain in some sectors and France in others, technological leadership mattered little for the aggregate acceleration in invention during the Industrial Revolution.

The first stylized fact is a significant, large, and robust positive association of invention and imitation across sectors. We document it at all three different levels of aggregation: Industries, sub-industries, and technologies. At the industry level, for example, the pairwise correlation of log imitation and log invention is 0.832 (p-value < 0.000) and the regression coefficient is 0.998 (std. err. $= 0.139$, $R^2 = 0.69$), implying that a one percent increase in invention is associated with a one percent increase in imitation. The positive association is robust to including fixed effects for industry or sub-industry, which rule out (sub-)industry composition effects as an explanation. Furthermore, the (sub-)industry fixed effects rule out alternative explanations that vary at the (sub-)industry level, for example, secrecy instead of patenting (Moser, 2012, 2013). The positive association also holds within sub-periods and before the acceleration of GDP per capita growth ("take-off") around 1830.

The second stylized fact is a pronounced variation of technological leadership across sectors, with Britain leading in some sectors, France leading in others, and Britain and France being neck-on-neck in yet others. The key metric is the revealed relative technological lead, which we calculate as the sectors' imitation intensity relative to the average imitation intensity. As we do not observe total invention in France and Britain directly, the measure does not by itself inform about absolute differences in inventiveness across countries. Nevertheless, we can quantify the absolute technological lead between France and Britain by combining the measure with historical case studies. First, we validate the leadership ranking with available case studies of absolute technological lead in France or Britain and rule out that one country was absolute leader in every sector. Second, we back out the absolute lead for all sectors based on a case study evidence on technological equality between France and Britain in applied sciences and applied mathematics. For example, at the technology level, we estimate Britain was about three times as inventive as France in spinning and steam engines, France was about twice as inventive as Britain in hydraulic pumps and watches, while they were equally inventive in chemical products and motors other than steam engines.

In sum, the evidence supports predictions of both hypotheses yet clearly distinguishes which hypothesis can explain what. As we explain in section 3.1, the simultaneity hypothesis predicts a positive association of the invention rate in Britain and France but no technological leadership. In contrast, the leader–follower hypothesis predicts a negative association of invention rates and significant technological leadership. Hence, the first stylized fact speaks clearly in favor of the simultaneity hypothesis as an explanation for the aggregate acceleration of the invention rate. In contrast, the second stylized fact of variation in technological leadership confirms a prediction of the leader–follower hypothesis, suggesting that both hypotheses are necessary to explain all data features.

The key feature of our setting that makes it possible to distinguish invention and imitation patents is distinct patent categories. The baseline category for invention is the "patent of innovation," which could be obtained by the French inventor, whose priority was protected, for an idea that was novel and related to production. The baseline category for imitation is the "patent of importation," which could be obtained by anyone who first patented a foreign idea in France, irrespective of priority or whether it was already patented abroad. In all other regards, the "innovation" and "importation" patents were the same. This idiosyncratic setting with imitation patents makes the French patent data a registry of domestic and foreign ideas present in France because it (a) documented stealing of ideas by imitators, which might otherwise have taken place clandestinely, and (b) incentivized the actual foreign inventors to register their ideas in France despite relatively high patent prices.

Beyond the patent categories, we adjust the invention and imitation measures with additional information to obtain more accurate measures of French invention and British invention. We define invention as the set of (technological) ideas invented in France, and imitation as the set of ideas invented abroad and transmitted to France.[3] We classify "patents of innovation" as imitation if they have a foreign (British) connection, which we see as an indication that the idea was potentially invented abroad and transmitted to France. In particular, we identify the country location of all addresses given by the patentee and classify patents as imitations if they had a foreign (primarily British) address. Moreover, we predict the nationality of all patentees based on their last names (British vs. French last name) and classify

[3]The definition follows the literature on international technology diffusion (Keller, 2004; Comin and Mestieri, 2014).

patents as imitations if they had a British last name. Finally, we measure invention and imitation as total patenting expenditure to capture systematic variation in the economic value of patents. The expenditure variation resulted from a mix of ex-ante patent duration choice (longer patents were more expensive than shorter ones) and ex-post patent renewal choice, both of which reflect the patentees' private information about their patent's (expected) economic value.

The paper relates to several literatures that span the fields of economic history, macroeconomics, and innovation. The paper contributes to studies of the rate of invention and technological progress in Britain and the European continent during the Industrial Revolution by providing the first quantitative comparison of British to continental—here, French—invention rates. The empirical evidence on invention in Britain is relatively abundant. The first contributions which evaluated patent data were by Dutton (1984), MacLeod (1988). Sullivan (1989) showed that patenting in Britain accelerated in all major sectors of the British economy. Temin (1997) showed that technological progress must have accelerated in all (manufacturing) sectors of the British economy. Meisenzahl and Mokyr (2012) analyzed the determinants and characteristics of inventors, and Hanlon (2020b) showed how engineers became the dominant group of inventors over time. However, this evidence is isolated from the (comparatively scarce) evidence on invention in other countries. Among the few studies for France, Khan (2016) studies the role of female inventors, Galvez-Behar (2019) presents several statistics on French patents, and Nuvolari et al. (2020) study the connections of French to British patents.[4] Our paper connects this literature by documenting the rate of invention in France and Britain within the same legal and economic environment. By observing British invention indirectly in terms of imitation patents in France, which can readily be compared with invention patents in France, we overcome problems associated with direct comparisons of national invention registers, including selection—which ideas are included—and quality—how valuable are included ideas.

Furthermore, the paper contributes to studies of international technology diffusion and of technological leadership during the Industrial Revolution by providing the first systematic, quantitative evidence on idea diffusion from Britain to the European continent and technological leadership of Britain relative to the continent across almost all industries and technologies. There exist case studies for some sectors that document anecdotal evidence on idea diffusion, imitation by France, and British technological leadership (Landes, 1969; Harris, 1998; Allen, 2009b). Several recent papers study the diffusion and adoption to the

[4]For invention in other countries as Germany, see Donges and Selgert (2019) who study patent data from Württemberg and Dittmar and Meisenzahl (2020) who provide quantitative evidence based on a scholarly catalog of important inventions. Sáiz (2014) studies importation patents for Spain.

production of British technologies within France, notably of spinning machines and steam engines (Juhász, 2018; Franck and Galor, 2021, 2022).[5] Our quantitative evidence on imitation and technological leadership puts these case studies into context by providing the first quantitative evidence on how imitation varied across industry and technology and the first quantitative evidence on the size of technological leadership based on invention measures. Indeed, we confirm that spinning and steam engines were among the technologies Britain was most technologically ahead of France, but the finding also implies that these sectors are different regarding technological lead and do not represent the aggregate. There is one previous study that documented industry-level specialization and leadership in terms of output per worker (O'Brien and Keyder, 1978). Here, we provide evidence on specialization and leadership in terms of technological creativity (invention), which is closer to the definition of technological leadership in the growth literature (Barro and i Martin, 2003; Acemoglu, 2009), and disaggregate industries into sub-industries and technologies. Furthermore, our results are affected by limited data availability and questionable data quality of sectoral output and labor force in Britain and France before 1840.

We follow the macroeconomic literature in distinguishing between invention or idea growth (e. g., Romer, 1990; Jones, 2005; Jones and Romer, 2010; Jones, 2016), imitation or idea diffusion (e. g., Eaton and Kortum, 1999; Lucas Jr, 2009; Buera and Lucas, 2018), and adoption or idea implementation (e. g., Benhabib and Spiegel, 2005; Comin and Mestieri, 2014, 2018). In this paper, we focus on invention and imitation. Technological leadership has been analyzed, among others, by Grossman and Helpman (1991); Barro and Sala-I-Martin (1997); Acemoglu et al. (2006); Benhabib et al. (2014); König et al. (2016); Buera and Oberfield (2020); Benhabib et al. (2021). That idea diffusion results from imbalances in invention among economies close to the technology frontier has been documented by Eaton and Kortum (1999) and Peri (2005) based on data of cross-national patent registration or patent citations, respectively.

Our finding of the invention rate's simultaneous acceleration in France and Britain is consistent with several economic mechanisms. One group of mechanisms highlights complementarities and knowledge spillovers between ideas, for example due to sequential innovation (Scotchmer, 1991; Bessen and Maskin, 2009), general purpose technologies (Helpman and Trajtenberg, 1996; Helpman, 1998), or combinatorial growth (Weitzman, 1998). Another group of mechanisms highlights that invention and imitation arise simultaneously in a given sector because they require the same knowledge or human capital as inputs (Cohen and Levinthal, 1989; Griffith et al., 2003, 2004; Aghion and Jaravel, 2015), in the sense that "good innovators make good imitators" (Landes, 1969, 28). Either group of mechanisms points to

[5]Juhász et al. (2020) study within France firm-level dynamics in the spinning industry as compared to paper and metal industry.

idea diffusion among countries as critical, either for the realization of knowledge spillovers or for sharing a joint knowledge base as input. As a result, the invention rate would accelerate jointly in Britain and France in the same industries and technologies.

Our finding that there was variation in technological leadership at the sectoral level but that it mattered relatively little for the aggregate acceleration in the rate of invention during the Industrial Revolution relates to a debate whether relative prices explain both rate and direction of technological change. Differences in relative factor prices influence the direction of invention (Acemoglu, 2002; Hanlon, 2015), yet it is theoretically ambiguous whether they also cause a higher aggregate rate of invention (Acemoglu, 2007). In the context of the Industrial Revolution, Allen (2009a,b, 2017) argues that relative prices of energy—coal—varied between Britain and France (and the rest of the world), causing Britain to invent more in coal intensive technologies.[6] Reversely, Mokyr (2009a) argues that in France, water power was relatively cheaper than coal, causing France to invent more water-power intensive rather than coal intensive technologies. Indeed, the pattern of technological leadership we find is consistent with these arguments, as coal-intensive sectors are among those with the largest lead of Britain, and water-intensive sectors are among those with the largest lead of France. The finding of a positive association of invention in France and Britain does not preclude that directed technical change contributed to accelerating invention in some sectors. However, it clearly shows that directed technological change cannot explain the aggregate acceleration—unless it simultaneously affected both Britain *and* France compared to the rest of the world, contrary to the argument by Allen (2009a, 2017) that it explained why Britain would industrialize earlier than France.

2. Historical evidence

2.1. Invention and technological leadership

Anecdotal evidence on breakthrough inventions suggests a pattern that technological leadership varied between Britain and France across sectors. The famous British breakthrough inventions came from the industries of machines, textiles/spinning, and metals. In machines, the breakthroughs were Newcomen's atmospheric engine in 1712 and Watt's separate condenser and other improvements during 1780s (Mokyr, 1990, 85-7).[7] In spinning, they were

[6] Allen (2009a,b, 2017) also argues that labor was more expensive in Britain due to high wages, yet the factual basis of this argument has recently been questioned (Humphries and Weisdorf, 2019).

[7] Newcomen's atmospheric engine was the first functioning steam engine and based on the concept of a fire engine developed by the French scientist Denis Papin Cohen (2004). Watt's improvements allowed the application of the steam engine outside of coal mining.

Hargreaves' spinning jenny in 1764; Arkwright's water frame during the 1770s; and Crompton's mule in 1779 (Mokyr, 1990, 96-7). In metals, they were Darby's coke smelting process in 1709 and Cort's puddling iron making process in 1784 (Mokyr, 1990, 93). The famous French breakthrough inventions came from the industries of chemicals, textiles/weaving, food, and paper. In chemicals, the breakthroughs were Berthollet's invention of chlorine bleaching (bleaching water) in 1784 and Leblanc's artificial soda making in 1787 (Mokyr, 1990, 107); in weaving, the Jacquard loom in the 1800s (Mokyr, 1990, 100);[8] in food, the invention of food canning by Appert in 1795 (Mokyr, 1990, 140); and in paper, the continuous paper-making machine by Robert in 1798 (Mokyr, 1990, 106). These examples are consistent with economic mechanisms that predict British inventors specialize in some sectors and French inventors in others.

While this contraposition of examples suggests clear technological leadership in invention of either Britain or France in a given sector, the actual size of leadership is unclear because British and French inventors also contributed to sectors where the first breakthroughs originated in the respective other country. In textiles/spinning, the spinning machine of Hargreaves was anticipated by two French machines (McCloy, 1952, 91-2).[9] Also, another breakthrough in spinning, the wet spinning of flax, was invented in France by de Girard in 1810 (Mokyr, 1990, 103). In machines, some of the earliest applications of steam engines to transportation originated in France, including the first steam tractor in 1770 and the first (successful) steamboat in 1783 (McCloy, 1952, 28-9, 36-7).[10] Reversely, bleaching powder, which had superior industrial qualities to the original French invention, was invented in Britain by the Scot Tennant in 1799 (99 Mokyr, 1990). Also, the continuous paper-making machine was improved and made practical and economical by in London (Mokyr, 1990, 106). These anecdotes suggest that both countries could have contributed to invention in many sectors, independent of the question of which country was leading and how large the technological

[8]The Jacquard loom was a programmable loom that used punch cards to store information, "one of the most sophisticated technological breakthroughs of the time." Bouchon and Falcon pioneered the use of punch cards to store information in the 1720s, and de Vaucaçcon improved the punch card reader in 1775 (Mokyr, 1990, 100-1).

[9]One machine the French Academy of Sciences approved of as novel and useful in 1745 (it spun three threads simultaneously, Hargreaves' spinning jenny spun eight). For the other machine invented in 1755, the Academy awarded the inventor a grant of 5000 Francs.

[10]The steam truck was invented by Cugnot and is said to have inspired Trevithick's locomotive. The steamboat by Jouffroy d'Abbans was the first successful one because angry boatmen scuppered an earlier steamboat by D'Auxiron before the first test boating. Jouffroy d'Abbans applied for a royal privilege (proto-patent) but was required to transport the steamboat from Lyon to Paris that it would be evaluated there. However, without covering the expenses, he was effectively denied the proto-patent as there was no river or canal connection of Rhône and Seine rivers, and the boat was unsuitable for high sea circumnavigation of the Iberian peninsula (McCloy, 1952, 31-36). The first commercially successful steamboat was operated by the American Fulton in 1807 (Mokyr, 1990, 88).

lead was.

Indeed, anecdotal evidence suggests that invention in Britain and France could have been positively related due to knowledge spillovers and complementarities between ideas. Instead of specialization of British inventors in some sectors and French inventors in others, ideas could have been combined across borders to create new and better ideas. For example, the invention of gas lighting resulted from an international collaboration among German, French, and Anglo-Saxon inventors. The potential use of gas as a light source was first pointed out in the late 1780s by the Belgian Minkelers and the German Pickel. The first lamp which used gas was invented by Lebon in 1799 (so-called thermolamp), based on a lamp invented by the French Argand in the early 1780s.This invention used gas derived from wood, which was unpopular because burning wood gas created an unpleasant smell. Thus, coal gas, first derived by the Scot Murdock in 1798, was superior because it did not smell disagreeable. Later, the English Clegg and Malam respectively perfected gas distribution and invented the gas meter, which allowed substantially better commercial operation of the technology.

The notion that ideas diffused across borders to cross-fertilize invention is embedded in several statements of contemporaries. For example, a Swiss printer observed upon visiting Britain in 1766 that "[the English] cannot boast of many inventions but only of having perfected the inventions of others …for a thing to be perfect it must be invented in France and worked out in England" (cited after Mokyr, 1990, 240). To the same effect reported in 1829 "an eminent engineering consultant of London" to a parliamentary committee that

> "we have derived almost as many good inventions from foreigners, as we have originated among ourselves. The prevailing talent of English and Scotch people is to apply new ideas to use, and to bring such applications to perfection, but they do not imagine so much as foreigners; …" (cited after Musson and Robinson, 1969, 63-4).

In sum, the anecdotal evidence suggests that national specialization and technological leadership could be less relevant for a high rate of invention. Instead, it could be the case that the larger the available stock of knowledge and ideas, and the more inventors in both countries working on the same problems, the larger the total rate of invention. In this interpretation, the diffusion of ideas across borders would make ideas available everywhere, cross-fertilizing inventiveness and preventing double research efforts. Our empirical evidence will show whether the rate of invention was higher in industries and technologies where both countries contributed inventions and where the technological lead was small.

2.2. International diffusion of inventions

Through which routes did inventions diffuse among countries? Among the multitude of routes were periodicals and journals (Mokyr, 2005), private and business correspondences (e.g., Musson and Robinson, 1969, 216-31), the bilateral migration of inventors to Britain (e.g., Musson and Robinson, 1969, 61-4) and to France (e.g., Buchanan, 1986, 509-10), or travels for industrial espionage (e.g., Crouzet, 1996, 39). Before the French revolution, the French state supported the systematic imitation of British technology. Masters, skilled workers, and engineers were poached to relocate to France, introduce new machinery and other state-of-the-art production processes, and train French workers. Even whole factories were copied and installed in France, as was the case with Arkwright's spinning factory, which used water-powered machinery to card cotton fibers and spin cotton yarn (Harris, 1998, ch. 15). After the French revolution, "[g]overnment had given up industrial espionage, but private enterprise stepped in: there were agencies which obtained from England machines which it was prohibited to export and also procured English workmen" (Crouzet, 1996, 39).

As for the diffusion of inventions from France to Britain, one illuminating example of the multitude of channels of diffusion is the case of chlorine bleaching of textiles. Chlorine bleaching of textiles was invented by the French Berthollet, who shared his discoveries with others both through personal contact and communication and through publications in scientific journals. One of Berthollet's direct contacts was James Watt, to whom he demonstrated his bleaching experiments when Watt visited Paris in 1786 and who had an interest in applying the invention as his father-in-law McGrigor was a bleacher. Subsequently, Watt and McGrigor set out to experiment with industrial-scale textile bleaching while Watt and Berthollet kept up their correspondence and exchanged information about experiences and subsequent improvements (Musson and Robinson, 1969, 262-98). Berthollet had also demonstrated the process to the Frenchmen Alban and Vallet, who ran the Javel chemicals firm. They set up company in Liverpool around 1787 to produce and manufacture bleaching water (Musson and Robinson, 1969, 273-85). Berthollet's invention also diffused to Britain through other private and public channels. For example, the French inventor Argand, a common friend of Berthollet and Watt, shared information directly with British entrepreneurs in London (Musson and Robinson, 1969, 264). Further, as Berthollet published his experiments and results in scientific journals, readers in Britain who were familiar with foreign and especially French scientific publications also knew about it (Musson and Robinson, 1969, 287-88). Finally, earlier experiments by the Swedish chemist Scheele, which had already suggested the potential of applying chlorine to bleaching, were known to scientists in Britain who passed it on to entrepreneurs (Musson and Robinson, 1969, 289).

The main barrier to idea flows was the war between Britain and France, which started with the French Revolution in 1792 and continued basically through the end of Napoleon's reign in 1815.[11] For British technologies that were already present in France at the outbreak of the war, like cotton spinning machines, the disruption of trade and protection from British competition, particularly during the Continental Blockade in 1806–13, provided incentives for widespread adoption of British technology (Juhász, 2018). For other technologies and new ideas generated between 1791 and 1815, the war obstructed idea flows across country. It became more difficult for French entrepreneurs to transfer tacit knowledge and hire British workers (cf Crouzet, 1996, 38). Likewise, it became more difficult for British industrialists to acquire new ideas despite being "well equipped to profit from international friendships" (Musson and Robinson, 1969, 230).

In sum, there is much anecdotal historical evidence for idea flows *in both directions* between Britain and France during the Industrial Revolution. Certainly after the removal of the diffusion barrier in 1815, the diffusion of invention from Britain to France, which we define as imitation, will represent inventions in Britain that had not yet been discovered in France (reversely for the diffusion of invention from France to Britain). Our empirical analysis will use patent data to document the diffusion of invention to France and indirectly measure invention in Britain.

3. Empirical framework

3.1. Predictions

In a two-country, two-sector setting, the simultaneity and leader–follower hypotheses can be illustrated as follows. Denote countries by B (Britain) and F (France), and suppose there are two sectors, one dynamic with a large acceleration of the rate of invention (e. g., steam engines), the other traditional with a small acceleration of the rate of invention (e. g., ceramics/glass). Figure 1, panel (b) illustrates the simultaneity hypothesis. Invention in both countries B and F are roughly balanced and, as a result, imitation and idea flows between them. In the dynamic sector, invention and imitation are large, while in the traditional sector, invention and imitation are small. Neither country is a technological leader in any sector. Figure 1, panel (a) illustrates the specialization hypothesis. In the dynamic sector, B has a high invention rate, leading to large idea flows and imitation of B in F. In the traditional

[11] The French Revolution and subsequent wars also negatively affected invention in France, which is observable in the patent data, where patenting drops to zero in the years of terror 1793-4. The effect probably worked both through economic channels (price controls and occasional expropriation of businesses) and the execution of influential scientists and inventors, among which the most famous was the chemist Lavoisier.

sector, F has a somewhat lower invention rate, leading to a somewhat lower imitation of F in B. There will be reverse idea flows in any empirical application, but if they are smaller than the main flow, then B is the technological leader in the dynamic sector and F leader in the traditional one.

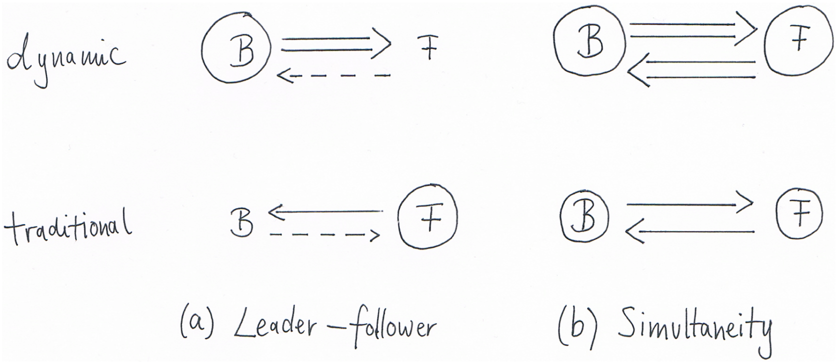

Figure 1: Hypotheses in two country, two sector setting. Circle size proportional to invention rate. Arrows denote idea flows (international technology diffusion), with arrow size proportional to rate of imitation.

The hypotheses differ in their predictions regarding the covariance of invention across sectors and regarding technological lead. Our empirical approach is to take the perspective of one country in which we can observe local invention and foreign invention indirectly through incoming idea diffusion (imitation). In this setting, the simultaneity hypothesis predicts that domestic invention and imitation covary positively across sectors. Within sectors, it predicts that the ratio of imitation to invention does not significantly differ from the average ratio of imitation to invention, implying no technological leadership. In contrast, the simultaneity hypothesis predicts that domestic invention and imitation covary negatively across sectors. Within sectors, it predicts that the ratio of imitation to invention will differ significantly from the average ratio of invention to imitation, implying large variation in technological leadership.

3.2. Ideas and patents

We define ideas as productivity improvements of technologies.[12] We posit the following reduced form idea production function, which is symmetric for France and Britain $c \in \{F, B\}$

$$N_{c,i} = A_c \, A_i \, \eta_{c,i} \tag{1}$$

[12]For our empirical setting, it does not matter whether the productivity improvements result from quality ladders or expanding varieties. In fact, it could be a mix of both.

where A_c are country shifters, A_i are sector shifters, and $\eta_{c,i}$ are "inventiveness" parameters for France and Britain in sector i.[13] Each idea is represented by one patent, and can be patented only once. In our data, we observe French invention patents $N_{F,i}$ and imitation patents M_i for sectors i. Imitation patents represent a share $\alpha \in (0, 1)$ of British inventions,

$$M_i = \alpha N_{B,i} \,. \tag{2}$$

In appendix A.2.1, we justify this assumption and explain further implications, which do not affect our empirical strategy.

3.3. Association of invention and imitation

The core prediction that we test is whether invention in France and Britain covary positively or negatively across sectors, that is, whether $\mathrm{Cov}(N_F, N_B) > 0$ or $\mathrm{Cov}(N_F, N_B) < 0$. To implement the hypothesis test, we rewrite it as the following linear regression,

$$\ln M_i = \beta_0 + \beta_1 N_{F,i} + \epsilon \tag{3}$$

where the prediction is $\beta_1 > 0$ if the simultaneity hypothesis is more important and $\beta_1 < 0$ if the specialization hypothesis is more important. [14] The reduced form idea production function tells us that equation (3) estimates

$$\ln A_i \eta_{B,i} = \widehat{\beta_0} + \beta_1 \ln A_i \eta_{F,i} + \epsilon \,, \tag{4}$$

where $\widehat{\beta_0} = \beta_0 + \beta_1 \ln A_F - \ln A_B$ controls for the country fixed effects.

Hence, we do not know whether the result $\beta_1 > 0$ was caused by the sector shifters A_i or by $\mathrm{Cov}(\eta_{B,i}, \eta_{F,i}) > 0$. (In contrast, $\beta_1 < 0$ must be due to $\mathrm{Cov}(\eta_{B,i}, \eta_{F,i}) < 0$.) Nevertheless, the result will inform which hypotheses can explain the acceleration in invention during the Industrial Revolution. Suppose that $\beta_1 > 0$ and that $\mathrm{Cov}(\eta_{B,i}, \eta_{F,i}) < 0$. Then, the positive covariance of invention in France and Britain must be due to the sector shifters A_i. Therefore, whatever the differences in market size between France and Britain, be they caused by directed technological change towards coal intensive technology or some other factor, such cross-country differences are less important than a common sector shifter which

[13]Endogenous growth theory typically models the inventiveness $\eta_{c,i}$ as a combination of the quantity of researchers and their research efficiency (Romer, 1990, e. g.,).

[14]To see why it is equivalent, start from $\beta_1 = \frac{\mathrm{Cov}(\ln N_F, \ln M)}{\mathrm{Var}(\ln N_F)}$. Then, using (2), it follows because $\mathrm{Cov}(\ln N_F, \ln M) = \mathrm{Cov}(\ln N_F, \ln \alpha N_B) = \alpha\, \mathrm{Cov}(\ln N_F, \ln N_B)$ is proportional to $\mathrm{Cov}(N_F, N_B)$ (linear positive transformation), and $\mathrm{Var}(\ln N_F) > 0$.

increased invention in both countries simultaneously.

Nevertheless, we can go deeper and ask whether "inventiveness" was positively or negatively associated between France and Britain, i.e. whether $\mathrm{Cov}(\eta_{B,i}, \eta_{F,i}) \lesseqgtr 0$. Put differently, we would like to estimate

$$\ln A_i \eta_{B,i} = \gamma_0 + \gamma_1 \eta_{F,i} + \gamma_2 \ln A_i + \epsilon \tag{5}$$

and know whether $\gamma_1 \lesseqgtr 0$. This result would inform the relative strength of economic mechanisms that predict a positive or negative covariance of "inventiveness" across countries. For example, if knowledge spillovers from complementarities between invention across countries were more powerful than directed technical change, we should find that $\gamma_1 > 0$.

Our strategy is to estimate equation (5) at the level of a more disaggregated sector (technology) using fixed effects for more aggregate sectors plus additional controls. To do so, we first rewrite the reduced form idea production function as $N_x = A_x\, A_i\, A_j\, \eta_{x,i,j}$, where i denotes (sub-)industries and j technologies. Then, we can estimate

$$\ln A_i A_j \eta_{B,i,j} = \gamma_0 + \gamma_1 \eta_{F,i,j} + \phi_i + X_j \delta + \epsilon \tag{6}$$

where ϕ_i are industry or sub-industry fixed effects and X_j additional controls for technology characteristics.

3.4. Technological leadership

To measure technological leadership, we introduce the concept of revealed relative technological lead.[15] For sector $i \in 1, \ldots, I$, it can be calculated as

$$\mathrm{RRTL}_i = \frac{\frac{M_i}{N_{F,i}}}{\frac{1}{I}\sum_I \frac{M_i}{N_{F,i}}}\,. \tag{7}$$

Given the reduced form idea production function (1), the revealed relative technological lead measures

$$\mathrm{RRTL}_i = \frac{\eta_{B,i}/\eta_{F,i}}{\overline{\eta_B}/\overline{\eta_F}}\,, \tag{8}$$

where $\eta_{c,i}$ is the country c inventiveness in sector i and $\overline{\eta_c}$ the aggregate (average) inventiveness of country c. Note that, different to the cross-sectional regression (3), the sector shifters

[15] The concept is inspired by the revealed comparative advantage from the trade literature (Proudman and Redding, 2000).

A_i cancel out due to the within sector comparison of British to French invention.

The revealed relative technological lead compares, for a given sector, the observed inventiveness of Britain to that of France relative to the observed ratio of aggregate inventiveness. It ranges from zero (maximal French lead) to $+\infty$ (maximal British lead), with 1 denoting equality. Thus, a $\mathrm{RRTL}_i = 0.5$ will mean that France was twice as inventive as Britain compared to the aggregate relative inventiveness, and a $\mathrm{RRTL}_i = 2$ that Britain was twice as inventive as France compared to the aggregate relative inventiveness. As the revealed relative technological lead is non-linear when computed by (7), we will rescale it for empirical applications by using the natural logarithm. In logs, negative values correspond to a relative French lead, zero to relative equality, and positive values to a relative British lead. Additionally, the absolute distance from zero will symmetrically measure the size of the technological lead.

The revealed relative technological lead refers to a relative advantage in inventiveness. What can we learn from it about absolute advantages? The problem is that the ratio of aggregate inventiveness in Britain and France, $\overline{\eta_B}/\overline{\eta_F}$, is not identified. As a result, it could be the case that one country had an absolute advantage in every sector i. Fortunately, this case is implausible given historical case-study evidence that at least one sector with $\mathrm{RRTL} < 1$ had an absolute technological lead in France and at least one sector with $\mathrm{RRTL} > 1$ had an absolute technological lead in Britain. Furthermore, because the available case-study evidence on absolute technological lead in France or Britain generally aligns well with $\mathrm{RRTL} \lesseqgtr 1$, we can conclude that the ranking of sectors in terms of technological leadership is meaningful. However, we will still not know the value of RRTL for absolute technological equality. We will discuss the historical case-study evidence, which allows us to draw these conclusions after presenting the main result on the revealed relative technological lead, in section 5.2.

Moreover, the revealed relative technological lead can be used to estimate the absolute technological lead based on the absolute lead for one single sector. Suppose we have historical case-study evidence for sector k that Britain was about as inventive as France, $\eta_{B,k} \approx \eta_{F,k}$. Then, we can estimate the absolute technological lead for other sectors $\eta_{B,i}/\eta_{F,i}, i \neq k$ as follows

$$\frac{\eta_{B,i}}{\eta_{F,i}} = \frac{\mathrm{RRTL}_i}{\overline{\eta_B}/\overline{\eta_F}} = \frac{\mathrm{RRTL}_i}{\overline{\eta_B}/\overline{\eta_F}} \frac{\overline{\eta_B}/\overline{\eta_F}}{\mathrm{RRTL}_k} \frac{\eta_{B,k}}{\eta_{F,k}} \approx \frac{\mathrm{RRTL}_i}{\mathrm{RRTL}_k} \tag{9}$$

where the first equality is the rearranged equation for RRTL_i and the second equality follows from expanding and dividing by RRTL_k. Again, we will discuss historical case-study evidence for one such sector k after the main result in section 5.2.

4. Data

Our principal data set covers the universe of French patents from 1791 to 1855 and is provided by the French National Patent Office (INPI).

4.1. Background on French patents

The patent law was enacted in 1791 and remained essentially unchanged until 1844.[16] It replaced an earlier institution of proto-patents and state-granted financial rewards that existed since the seventeenth century. Patents could be obtained for novel ideas related to production in all areas except finance, pharmaceuticals, science, or unlawful things.[17] They were granted based on the requirement to pay a fee and deposit a technical documentation. Patent duration varied between 5 and 15 years. After expiry, the invention entered the public domain. The patent office did not verify the information given, nor did it evaluate novelty or usefulness. Instead, courts validated the patent claim and the technical documentation ex-post during disputes about priority or infringement suits. If the information given was found faulty, the court could invalidate the patent as a whole.

There were two principal categories of patents: First, the "patent of innovation" (*brevet d'innovation*), the standard category for inventions, which was essentially the same as it is today. Second, the "patent of importation" (*brevet d'importation*), the category for the first introduction of a foreign invention. Such importation patent could be granted to anyone, be they imitator or true inventor, if they were the first to patent the idea in France and if the idea was not already present in France. Thus, the copying and stealing of foreign technology were legal for the first person who documented the act of imitation by registering a patent. The category existed until the reform of the patent law in 1844.[18] The patent categories were non-exclusive, and some patents were both "patent of innovation and importation."[19]

The patent duration was determined by a patent expenditure choice along two dimensions. First, patents could be obtained for five, ten, or fifteen years at the cost of 300 Franc, 800F, or

[16]The following history is based on Beltran et al. (2001) and Galvez-Behar (2008). Galvez-Behar (2019) provides a valuable summary in English.

[17]In the patent law of 1791, it was not clearly defined what constituted a patentable idea. The 1844 reform defined it more precisely as a new product or a new method or a new application of a known method in industrial production (Beltran et al., 2001, 31).

[18]The reform reserved the foreign inventor the exclusive right to apply for a patent in France and created the new category "foreign patent."

[19]There was an additional category, the "patent of improvement" (*brevet d'amélioration*, after 1844 *certificats d'addition*). It allowed the inventor to modify the patent of invention or importation and add improvements and extensions to an existing patent without taking out another one. Improvements were linked to the original patent, did not prolong its duration, and would expire with it. We do not consider improvements in the baseline analysis because it is not clear whether they constituted a new idea.

1500F, respectively, plus a registration fee of 50F. This choice was made with the registration of the patent. Second, the patent fee was paid in two installments, the first half at registration and the second half six months later. If the patentee defaulted on the second installment, the patent was in a protection gray-zone for up to two years until the default was officially publicized.[20]

Patents were not exactly cheap considering that the cheapest patent cost 200F whereas, in 1847, the median daily wage for male non-agricultural workers was 1.8F, but the fees were probably not prohibitive.[21] Hence, the patent fee worked as a screening device in an open registration system and provided an incentive for patentees to form an expectation about the economic value of their idea.[22]

4.2. Distinguishing invention and imitation patents

Following the literature on international technology diffusion (Keller, 2004; Acemoglu, 2009; Comin and Mestieri, 2014), we define *imitation* as the set of (technological) ideas that were invented abroad and transmitted to France. This definition of imitation is appropriate given our goal to measure the international idea diffusion from Britain to France. We consider patents as invention if there is neither definite nor potential evidence that they could be an imitation. In total, we observe 11387 patents in the period 1791–1844.

The definite evidence for imitation is the patent category "importation." The category can include both imitation in the narrow sense by a proper imitator and imitation in the broader sense by an original inventor who is foreign. In the period 1791 to 1844, there were 1,512

[20] Defaults were publicized in lists of expired patents about every other year in the official government law paper (*Bulletin de lois*). (The lists excluded regular patent expiries after 5, 10, or 15 years.) Until the next edition of the expiry list, only the patentee and persons who consulted the patent document in the patent office would know about the default.

The INPI dataset reports whether patents expired but not whether the reason was a default or a court invalidated it. Nevertheless, defaults constituted most likely the large majority of expired patents, as evidenced by the large spikes in the number of expired patents in the INPI data in years when such expiry lists were publicized in the *Bulletin de lois*. Based on this evidence, we estimate that the expiries in our data were true defaults within a margin of error below 10 percent.

[21] The median daily wage is calculated from Chanut et al. (2000). Concerning the question of whether the patent fee was prohibitive, what matters is the income and access to capital of *inventors*. Inventors came by and large from the upper end of the income distribution based on patentees' occupation titles. However, we observe inventors only conditional on patenting, which leaves open the possibility of selection into patenting based on capital access. To address this issue, one can consider as a metric of accessibility the frequency of one-off inventors, who plausibly had, on average, worse access to capital. Nuvolari et al. (2020) find it to be similar to the USA, where patents were much cheaper relative to the median wage, which suggests that the French fees were not prohibitive.

[22] MacLeod et al. (2003) argue similarly for the case of Britain where patents cost £100 plus registration fees. (One pound was about 25 Francs. Both currencies adhered to the gold standard, £1 was 7.3g fine gold, 1F was 0.29g fine gold.)

importation patents. For 605 of them, a French name and address (see next paragraph) indicate that they were most likely imitations in the narrow sense. For the rest, we do not know whether the foreign-based or foreign national patentee was an imitator in the narrow sense or the actual inventor. Nevertheless, as our definition clarifies, both should be considered as evidence for imitation.

The evidence for potential imitation is that patentees of "innovation" category patents have some foreign connection. Foreign actual inventors could use either innovation or importation category. Thus, we need to identify actual foreign inventors within the innovation category, for otherwise, we will likely underestimate imitation by France. We consider foreign nationality and foreign address as the primary indicators of a foreign connection. As the historical patent office did not record the nationality of patentees, we infer nationality from their last names based on a two-step procedure that combines dictionary approach and machine learning algorithm to classify names as French or British.[23] The addresses of patentees were fully recorded by the historical patent office, even if a patent agent was involved.[24]

In total, we classify as imitation 1026 innovation patents with an indication of a foreign connection. For 700 innovation patents, we find a British named patentee with a French address, which is consistent with the historical evidence that there was migration of British inventors, engineers, and mechanics to France (Buchanan, 1986; Harris, 1998; Bensimon, 2011). For 109 innovation patents, we find a British named patentee with a British address, indicating an actual foreign inventor who protected their idea in France by taking out a standard patent instead of an importation patent. For 217 innovation patents, we find a French named patentee with a foreign address. This group includes, but is not limited to, British nationals with Huguenot emigrant ancestry[25] and French emigrants to Britain from the heyday of the French Revolution (Franck and Michalopoulos, 2017). In appendix B.2, we show that our results are quantitatively robust when we instead drop the innovation patents with a foreign connection.

[23]First, we create a dictionary of French and British last names from the sample of all people on Wikipedia (Wikidata) born in France or Britain during the eighteenth or nineteenth century and classify the unambiguous names. Then, we train a random forest on this data, classifying names as British and French with an out-of-sample accuracy of more than 95%. We use the algorithm to classify missing and ambiguous last names and reject implausible dictionary entries. Appendix A.3 provides more details.

[24]In the British data until 1850, only the addresses of the patent agent are known in many cases. We identified the exact location of the addresses using Google Map API. For France, we matched latitude–longitude to historical mainland départements in the borders of 1830 (Friendly and Dray, 2020). That means we exclude Corsica, the Savoy départements, which came to France around 1860, the colonies, and regions in Belgium and Germany that were occupied and belonged to Napoleonic France at the time of patenting.

[25]Harris (1998) documented many cases where Huguenot emigrant's connections to France were used for technology transfer from Britain.

4.3. Aggregating patents to sectors

We aggregate invention and imitation patents to the nested sectors of industry, sub-industry, and technology. We create 30 industries by re-grouping the industry classification from INPI. The goal is to create a technologically and economically sensible industry classification that is not too fine (at least 100 patents per industry) and can be matched to the French industry census of 1839–46 (Chanut et al., 2000).[26] For sub-industries, we use the classification provided by INPI that gives 94 sub-industries in total, of which 21 are small and have less than 30 patents in total during the observation period. Technologies are unique keywords assigned to the patents at registration until 1852 by the historical patent office based on the technical documentation. We obtain 587 technologies in total, of which 251 are small and have less than ten patents per technology.[27]

When aggregating patents to sectors, we adjust for variation in the patents' economic value—in short, patent quality—to get more accurate measures of invention and imitation. In general, it is well known that the quality of patents varies widely across patents (Schankerman and Pakes, 1986; Griliches, 1990; Nuvolari and Tartari, 2011 for Britain during the Industrial Revolution). This variation might not get averaged out when counting the total number of patents per sector. Therefore, we adjust for variation in quality by weighting patents with patent expenditure. This quality measure exploits the inventor's willingness to pay for patents. It assumes that inventors have private information on the expected economic value of patentable ideas and are willing to spend more on patents if they expect a higher value.[28] The French patent system provides two margins of willingness to pay, the patent duration choice at registration and the renewal/expiry choice after six months.

The resulting quality-adjusted invention and imitation measures provide a lower bound estimate of ideas' true expected economic value. Within the 3×2 expenditure categories, we effectively price the patents at the marginal value. The obtained ranking of sectoral invention and imitation patenting will reflect the distribution of the true economic value of ideas accurately under the following condition. Let $F(\cdot|g)$ denote the distribution of expected patent values within sector g. If for any two industries their respective $F(\cdot|g)$s can be ranked according to the criterion of first-order stochastic dominance, then the ranking will preserve

[26] The industry census provides information on output and value added (output minus value of raw materials and energy) in Francs.

[27] The INPI applied the industry classification of 1904 retrospectively to the data from 1791 to 1852 based on the keywords. INPI harmonized the historic keywords during digitization to reduce redundancy, which results from using different words for the same concept or from different spelling. We use the harmonized version of the keywords provided by INPI and corrected a few further such redundancies in the harmonized keywords.

[28] Mokyr (2009b) argued for Britain that the median actual economic value of patented ideas could have been below the patent price, which was about 2500F in Britain (compare footnote 22).

the true expected economic value of ideas.

4.4. Descriptive evidence

We first document patenting rates over time. Figure 2 compares the time trends of invention and imitation patenting in France to that of Britain. Note that the British imitation patenting is proximate because it is not possible to adjust for address or nationality as in France. (For British patents, we do not know the inventor if a patent agent registered the patent.) Nevertheless, the figure shows that invention patenting rates accelerated in parallel in both countries, as did imitation patenting rates. The acceleration was particularly fast around 1820–1830, which coincides with the acceleration of GDP per capita growth rates (the "take-off" in economic growth). Figure 3 zooms in on France and documents that invention and imitation patenting accelerated in parallel within France, such that their shares in total patenting were broadly constant over time. This evidence motivates us to sum patenting rates over the entire period 1791–1844 in the baseline analysis and only consider the cross-sectional variation. In the robustness analysis, we show that we obtain quantitatively similar results for sub-periods.

5. Main results

5.1. Association of invention and imitation

We begin by documenting the association of invention and imitation rates in the imitation–invention-space. As argued in section 3.1, the simultaneity hypothesis predicts a positive correlation, whereas the leader–follower hypothesis predicts a negative association. To interpret the hypotheses geometrically, plot the "average line" whose slope equals total imitation over total invention (the denominator of the revealed technological lead). If invention and imitation rates are strongly positively associated across sectors, observations will be scattered closely around the average line. Inversely, if invention and imitation rates are strongly negatively associated across sectors, observations will be scattered far away from the average line (orthogonal to its slope).

Figure 4 graphs our main result of a strong, positive association of invention and imitation expenditure at the industry level. The pairwise correlation coefficient in logs is 0.832 (p-value < 0.0001). Graphically, one can observe that the variation in the direction of the average line, leading to a positive association, is much more considerable than the variation in the orthogonal direction, which would lead to a negative association.

A significant concern with the industry level result is that it could be an artifact of aggregation to industries. Any assignment of patents to unique industries is necessarily imperfect (Griliches, 1990). Furthermore, it could be driven by a composition effect of summing over negative correlations within industry at different levels or of grouping technologies in a way such that the negative correlation is obscured.

Disaggregated evidence at the technology level shows that the positive association of invention and imitation is no artifact of aggregation. Figure 5 shows the same strong, positive association of invention and imitation at the technology level. The pairwise correlation coefficient in logs is 0.674 (p-value < 0.0001). Moreover, figure 6 shows that the result holds equally within industries. It appears that invention and imitation are positively associated within every single of the 30 industries. In sum, the geometrical evidence plausibly rules out aggregation and composition effects as an explanation.

We next move to regression analysis because it allows us to infer the sign of the association while controlling fixed effects and covariates. Table 1 presents OLS regressions of log imitation on log invention at different levels of aggregation.[29] All regression coefficients on log invention are statistically different from zero at the one percent significance level. At the industry level (column 1), the regression coefficient is 0.998. Thus, at the mean, a one percent increase in invention is associated with a one percent increase in imitation, implying a linear, positive association of invention and imitation. At the sub-industry level, the regression coefficient is 0.851 without industry fixed effects (column 2), 0.761 including industry fixed effects (column 3), and 1.075 if we drop small sub-industries with less than 30 patents. Furthermore, the adjusted R^2 increases by less than 5% from columns (2) to (3). At the technology level, the regression coefficient is 0.694 without fixed effects (column 5), 0.699 including industry fixed effects (column 6), 0.749 including sub-industry fixed effects (column 7), and 0.924 if we drop small technologies with less than ten patents. The inclusion of fixed effects improves the adjusted R^2 by about 10 percent.

The regression results have two implications. First, they show that the positive association of invention and imitation—that is, of the invention rates in France and Britain—is a granular feature of the data that holds both at all levels of aggregation, including the most disaggregated level of technology. Second, they show that while industry and sub-industry shifters have some explanatory power, they are not a first-order determinant of the positive association. As seen through the lens of our empirical framework, if sector shifters were relevant, they must have primarily operated at the level of technology but not at the level of industry

[29] Using logs is appropriate here because invention and imitation patenting follow a log-normal distribution. However, it implies that we lose some observations, particularly technologies, with zero invention or imitation.

or sub-industry. Furthermore, it appears likely that the covariance of the inventiveness in France and Britain, η_F, η_B, was positive. This would suggest that invention in both countries cross-fertilized each other because of complementarities between ideas or the sharing of a joint knowledge base.

Robustness: Technology characteristics One concern with this conclusion is that the positive association of invention and imitation could be a spurious outcome of some technology level characteristic that drives up invention and imitation mechanically but should not be considered a sector shifter of the idea production function. One such characteristic could be the age of technologies because younger technologies could have on average less of both invention and imitation while older technologies could have more of both. We measure age as years since the first patent within technology in 1855. Another characteristic could be the complexity of technologies because more complex technologies may have lower "technological opportunities," implying that it is generally more challenging to improve existing ideas by creating new inventions. We classify technologies as complex if they require engineering knowledge (Hanlon, 2020a) or scientific knowledge (Mowery and Rosenberg, 1989) for invention and adaptation.[30] Finally, one such characteristic could be foreign and principally British origin because British origin technologies will probably have more imitation on average and might also have more invention as a result of spillovers from imitation on invention. We measure foreign origin by whether the first patent within technology was an imitation.

Table 2 shows that the positive association of invention and imitation is highly robust to controlling for technology characteristics that could drive it mechanically. We first show that the technology characteristics predict a higher imitation patenting rate individually (conditional on industry fixed effects). The coefficient of 0.04 on the age of technologies (column 1) implies that a ten years older technology does have, on average, 40 percent more imitation patenting. (It also has more invention patenting, not reported.) The coefficient of 0.41 on the complexity indicator (column 2) implies that a complex technology does, on average, also have about 40 percent more imitation patenting, though the coefficient is not precisely estimated. Similarly, the coefficient on the foreign origin indicator implies that such technologies have, on average, significantly more imitation patenting. Then, we include the technology characteristics jointly with log invention and industry fixed effects, one by one (columns 5 to 7) and all together (column 8). We find that the coefficient on log invention is highly robust as it varies between 0.653 and 0.721, which is well within the range of the baseline

[30]We code as complex all technologies in the fields of steam and motors, transport (railways, vehicles, ships, aviation), chemicals, electricity, precision instruments, printing, and photography.

estimate without technology characteristics of 0.699 (std.err. 0.047). As for the technology characteristics, the coefficient of age becomes a precisely estimated zero, that of complexity stays positive but drops by half and becomes insignificant, whereas that on foreign origin doubles and predicts significantly more imitation, yet without affecting the coefficient on invention. Only the indicator for foreign origin appears to improve the regression fit (by about 10 percent). In sum, we find evidence of more imitation in technologies of foreign origin and some such evidence for more complex technologies, yet no evidence that technology characteristics would explain the association of invention rates in Britain and France.

Robustness: Sub-periods One concern is that the positive association between invention in Britain and France emerged only after the major acceleration in the aggregate rate of invention. As shown in figure 2, patenting accelerated around 1820/1830 in both Britain and France. In table B.5, we split the sample in 1830 and replicate the regressions of log imitation on log invention at industry, sub-industry, and technology level, including fixed effects for more aggregate levels where applicable. We find that all estimated coefficients stay significant before and after the acceleration of the aggregate invention rate. Also, the magnitude of coefficients is similar for the two sub-periods and the whole period, with the only exception for the technology level estimate before 1830, which is about 1/3 smaller. We also find that the standard errors are smaller after 1830, which is as expected given the increase in patenting rates that allow observing invention and imitation more precisely. In sum, the evidence shows that the positive association existed already before the acceleration of invention.

5.2. Technological leadership

Figure 7 documents the revealed relative technological lead at the industry level. Britain had the largest relative lead in the maritime, mining, railways, and textile/spinning industries. The coefficients imply that Britain was 2.1 times as inventive in the maritime industry as France relative to the average relative inventiveness, in mining 1.9 times, and 1.7 times in railways and textile/spinning. France had the largest relative lead in the watchmaking, furniture, music, and health industries.[31] Here, the coefficients imply that in watchmaking, France was 2.4 times as inventive as Britain relative to the average relative inventiveness, in furniture 2.2 times, in music two times, and in health (which includes medical and hygiene inventions, but no pharmaceuticals) 1.9 times. Between those industries with the largest

[31] We discuss below in the robustness section "differential demand" why the coefficients for agriculture and entertainment might overestimate the relative French lead.

lead in Britain or France, many industries are close to the average ratio of relative inventiveness, including machines (Britain 1.26 times as inventive), chemicals (Britain 1.02 times as inventive), and paper (France 1.16 times as inventive).

Figure 8 documents the revealed relative technological lead at the technology level for the 30 most dynamic technologies (those with the highest total patenting expenditure). The overall gradient from relative British lead to relative French lead appears similar, though the revealed relative technological lead variation is magnified. Britain had the largest relative lead in tulle (3.7 times),[32] spinning technology (3.02 times),[33] steam engines (2.88 times), and shipbuilding (2.2 times). France had the largest relative lead in distillation (2.5 times), watchmaking technology narrowly defined (2.17 times), shoes (2.1 times), and hydraulic pumps (2 times). However, the relative technological lead appears minor for most technologies, as in 20 out of 30 technologies, the relative lead is within 1.5 times (marine machines down to hydraulic motors).

The technology level evidence also reveals heterogeneity of technological leadership at the industry level. The machine industry, for example, includes steam engines with a notable British lead, but also diverse motors where Britain and France are effectively equal (France leading 1.03 times), and technologies where France is leading, hydraulic motors (1.33 times) and hydraulic pumps. This variation is consistent with geography as a determinant of the direction of technological change, given that water power was relatively cheaper in France and coal energy relatively cheaper in Britain (Mokyr, 2009a). In the chemical industry, there was also substantial heterogeneity. Britain and France were equal in chemical products (Britain was leading 1.06 times), but France led in distillation. Similar heterogeneity existed in the textile industry, the largest industry in France in terms of output, value added, and labor force. In the sample of top 30 technologies in textiles (tulle, spinning, carding, looms, cloth, and silk), Britain was leading in many technologies but not all.

The revealed relative technological lead ranks industries and technologies according to relative leadership of Britain or France, but what about absolute technological leadership? The first question is whether it could be the case that one country was an absolute leader everywhere. If that can be ruled out, the second question will be for what value of revealed relative technological leadership Britain and France are equal. Given that value, we can calculate the size of absolute technological leadership for all industries and technologies.

Anecdotal and qualitative case-study evidence confirms that Britain or France's most out-

[32]While the name "tulle" derives from a French city, the key breakthrough was the bobbinet lace machine, invented in Britain by John Heathcoat in 1808 (https://en.wikipedia.org/wiki/Bobbinet).

[33]Spinning technology differs from the textile/spinning industry because the industry also comprises different steps of pre-processing of fibers, including cleaning and carding.

standing observed values of revealed relative technological lead align with British or French absolute technological leadership. For example, the estimated British lead in maritime and shipbuilding is consistent with the evidence on absolute leadership as discussed by Kelly and Ó Gráda (2019) and Hanlon (2020a). In mining and railways industries and steam engines technology, it is consistent with the evidence on absolute leadership in coal-related sectors (Landes, 1969; Harris, 1998; Allen, 2009a). Similarly, the lead in spinning (industry and technology) is consistent with the qualitative evidence on absolute leadership in Allen (2009b); Juhász (2018). For France, the estimated lead in watchmaking is consistent with the qualitative evidence on absolute leadership of the French industry (though many watchmakers were, in fact, francophone Swiss nationals based in Paris, Landes, 1979).[34] Based on this evidence, we can rule out the possibility that one country was the absolute leader everywhere. Thus, there must be a value of revealed relative technological lead for which Britain and France are equal between the values for spinning (.53 log points at industry level) and watchmaking (-.77 log points at technology level).

Anecdotal evidence on the technological equality of Britain and France in sectors where invention was most constrained by scientific knowledge suggests that the revealed relative technological lead plausibly approximates the absolute technological lead between Britain and France. Anecdotally, Britain had no clear-cut advantage over France in terms of practical science and applied mathematics. This knowledge was crucial for invention, in particular in technologies related to chemicals and engineering (Mokyr, 2002). In our setting, this argument applies to "chemical products" and "diverse motors" technologies.[35] If invention was most constrained by knowledge in these sectors, and the same knowledge was available in both countries, then the genuine inventiveness should be approximately equal. We find that their revealed relative technological lead is close to zero, with Britain 1.06 times more inventive than France in chemical products and France 1.03 times more inventive than Britain in diverse motors. Thus, it appears that a revealed relative technological lead of zero is a reasonable estimate of the absolute technological lead between Britain and France. In turn, this would imply that we do not have to rescale the revealed relative technological lead levels because they already approximate the levels of absolute technological lead.

[34] Kelly and Ó Gráda (2016) argue there were much more watchmakers in Britain than in France and that their mechanical skills contributed to the British advantage in human capital over France, allowing Britain to implement more inventions, and implement them more intensely. There is no contradiction to a simultaneous French lead in invention because different skills may be necessary for the rate of invention, and thus the quantity of workforce may be less relevant.

[35] The same knowledge could have been crucial for steam engines and hydraulic motors, yet the revealed relative technological lead of either Britain or France varies with the geographic endowments of coal and water power. We need to consider technologies that are not affected by (differential) directed technological change for the argument made here.

Robustness: Over time By and large, the revealed relative technological lead persisted over time. Figure 9 plots the revealed relative technological lead for the later period from 1830 to 1843 against that of the earlier period until 1829.Most industries cluster around the 45-degree line, which denotes that the relative technological lead did not change. For example, industries as spinning or machines were consistently leading in Britain while industries as construction, food, and watchmaking were consistently leading in France. Only in a few industries, the revealed relative technological lead change notably. On the one hand, France caught up relative to Britain in mining and perhaps overtook Britain in leather and printing. On the other hand, Britain forged ahead in maritime, where it cemented an initial technological lead of the early period of Industrial Revolution (Kelly and Ó Gráda, 2019) during the middle of the nineteenth century (Hanlon, 2020a).

Robustness: Differential demand One concern is that the documented pattern of revealed relative technological lead is biased by differential demand for French rather than British ideas. The demand differences could result from differential preferences as, for example, a taste for French fashion in clothing and furniture rather than British fashion.[36] Alternatively, the demand differences could result from different appropriateness of British inventions given the French economic environment as, for example, in agriculture (different climate and soil), food (different ingredients due to different agriculture), fuel (different supply of energy sources), or maritime (Britain being an island).[37]

The home-biased preferences for French rather than British inventions do not affect our main result of evident variation in leadership across sectors. True, such preferences could lead to an underestimation of the technological lead in the affected sectors. However, if we excluded the sectors potentially affected by fashion tastes as clothing, furniture, or entertainment, the main finding of variation in the leadership from mining to watchmaking by about a factor of four remains valid. Similarly, if we considered only sectors in which inventions from Britain are less appropriate than the French ones, as in agriculture, food, fuel, and maritime, we could again confirm the main finding of variation in the leadership by about a factor four within these sectors. Moreover, home biased preferences will not affect our estimates of revealed relative technological lead if they affected all sectors similarly. To see this, denote the home preference $\phi > 0$. Then, $M_i = \tilde{\alpha}\, N_i^B$, with $\tilde{\alpha} = (\alpha - \phi)$. As $\tilde{\alpha}$ appears both in the numerator and denominator of RRTL, it will cancel out. Relatedly, if ϕ_i varied across sectors but orthogonally to the technological lead, it would cause measurement error in the individual estimates of RRTL_i but not affect our main result. Thus, we can conclude

[36]On the development of British tastes in consumer goods during the eighteenth century, see Berg (2004).
[37]For the concept of appropriateness of technology, see Basu and Weil (1998); Acemoglu and Zilibotti (2001).

that home-biased preferences are a minor concern in our setting.

Robustness: Differential superstar inventions Another concern is that the patent expenditure measures may not account for high economic impact "superstar" inventions. The expenditure measures assume that the ranking of high-impact inventions is preserved when patents are priced at the marginal expected value and aggregated to invention–sector or imitation–sector observations. If the distribution of high-impact inventions differed from the distribution of patent expenditure, the expenditure measures would be biased measures of true technological creativity.

To address this concern, we study whether we obtain a similar ranking of revealed relative technological lead when using a different measure that better reflects high-value inventions. For our empirical exercise, we use the first patents within their technology, which plausibly captures patents of high technological creativity, as a proxy for high-impact inventions. Indeed, we find a similar pattern of revealed technological lead at the industry level when considering this proxy for high-impact inventions. Figure 10 plots by industry the share of technologies whose first patent is an imitation patent from Britain, weighting technologies by importance (total patents). As before, there is a considerable variation in technological leadership across industries as measured by the origin of high-impact inventions. Furthermore, the same industries as before have the highest and lowest first imitation shares. For example, most high-impact inventions in railways and maritime industries originated in Britain, while in watchmaking, the majority originated in France. In sum, this evidence supports the assumption that high-impact inventions and (aggregate) patent expenditure follow a similar distribution.

Robustness: Differential spillovers from imitation on invention Finally, there is a concern that French inventions could be copies or minor variations of British superstar inventions. The revealed relative technological lead would be biased if such spillovers from imitation on invention varied across sectors. This bias could go in either direction and lead to overestimating or underestimating the relative technological lead. To evaluate the direction of bias, we assume that spillovers from imitation are plausibly the largest in technologies introduced from Britain (those whose first patent is an imitation patent).

We find that the omission of spillovers from imitation to invention leads, if anything, to an underestimation of comparative advantage in invention. To provide an upper bound of spillovers from imitation, we count as "British technology" all patents in technologies with first imitation patent (invention or imitation) in addition to all other imitation patents. Figure 11 shows that if we re-calculate the imitation–invention–ratio in such a way, the observed revealed relative technological lead gets magnified.

Given the finding that the distribution of high-impact patents is similar, the new ranking of the technological lead across industries is, as expected, similar. As before, railways, maritime, spinning, fuel, other textiles, and metals are leading in Britain; and industrial arts, music, and watchmaking are leading in France. Nevertheless, in some details, the ranking changes. In particular, it appears that we have previously underestimated the British technological creativity in fuel, health, and precision instruments; and previously underestimated the French technological creativity in mining, ceramics, and paper.

6. Conclusions

This paper provides the first empirical evidence on invention and technological leadership in a two-country, multi-sector setting during the Industrial Revolution. The evidence is based on patent data in France, where it is possible to distinguish between invention and imitation patents. As imitation patents predominantly reflect British inventions, the patent data provide quantitatively comparable measures for the French and British invention rates. The indirect comparison within France allows us to effectively control for country fixed effects when comparing the invention rate across or within sectors.

Based on the novel measures, we provide two principal stylized facts on invention and technological leadership during the Industrial Revolution. First, we document that French and British invention rates covary strongly positively across sectors, which holds robustly at different levels of aggregation, conditional on more aggregate sector fixed effects, and within sub-periods. Second, we document the heterogeneity of technological leadership in invention of the British relative to French sectors. Our evidence documents in which sectors Britain was ahead of the continent and by how much, in which sectors the continent was ahead of Britain and by how much, and in which sectors Britain and continent were technologically neck-on-neck.

The stylized facts distinguish empirically leading hypotheses of technological progress during the Industrial Revolution. Fact one, the positive association of invention in France and Britain, is consistent with hypotheses that predict the simultaneous acceleration of invention rates in both countries. In contrast, it rejects hypotheses that predict that invention rates accelerated in some sectors mainly in Britain but in others mainly in France, resulting in a negative association of invention in France and Britain. Fact two, the heterogeneity in technological leadership, shows that economic mechanisms that predict a negative association of invention on the aggregate are nevertheless present in the data and valuable for explaining technological leadership.

The key questions that remain open are what economic mechanisms caused the positive association of invention in France and Britain and the technological leadership. The baseline finding of positive association is consistent with sector shifters that affected invention in both countries equally, for example, if the market for inventions was the same. Furthermore, we find the same positive association on the finest level of aggregation (technologies) when conditioning on industry or sub-industry fixed effects and additional controls. This finding suggests that complementarities (another form of knowledge spillovers) between inventions in France and Britain could have played a role in creating the positive association of inventiveness across countries. Regarding technological leadership, proposed explanations explain the heterogeneity by demand factors like variation in energy and labor prices and by supply factors like skills of inventors and implementors. Future work shall identify and distinguish these economic mechanisms empirically.

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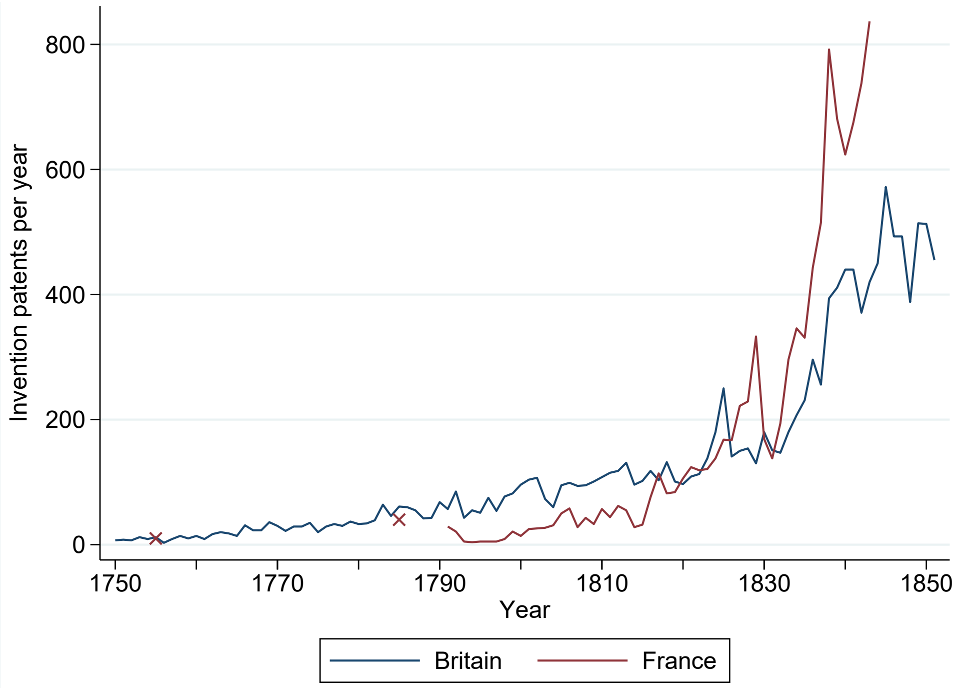
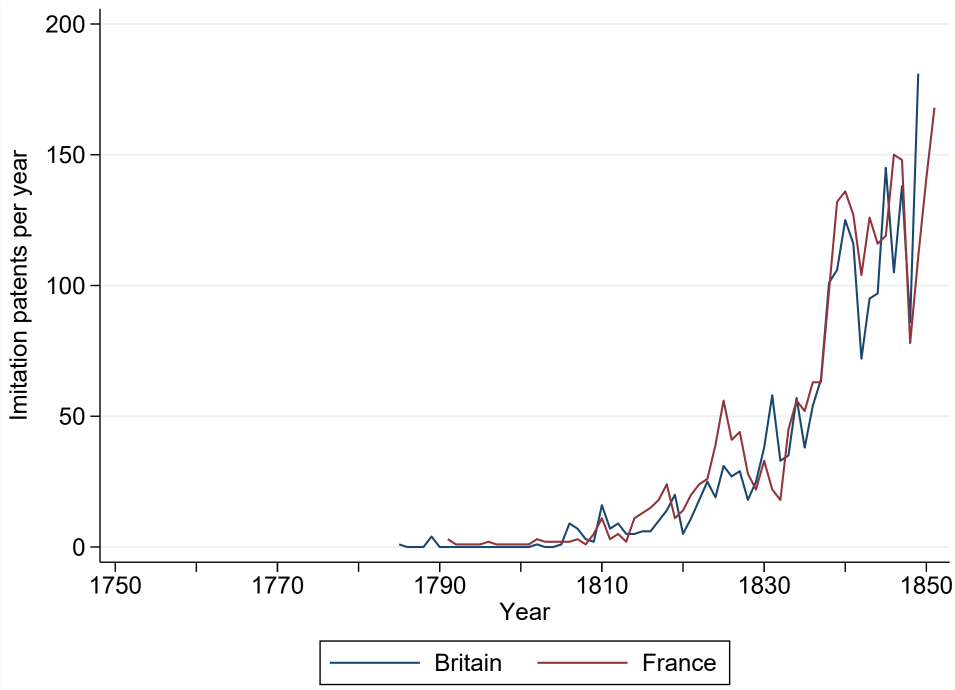


(a) Invention



(b) Imitation

Sources: Invention patenting in Britain: Dutton (1984). Invention patenting in France from 1791: Own calculation, based on *base de brevets historique* by Institut National de la Propriété Industrielle (INPI). Invention patenting in France in 1755 and 1785 (X): Decadal averages of proto-patent applications, Hilaire-Pérez (2000). Imitation patenting in Britain: Data communicated from Walker Hanlon. Imitation patenting in France: Own calculation, based on INPI.

Figure 2: Acceleration of invention and imitation during the Industrial Revolution

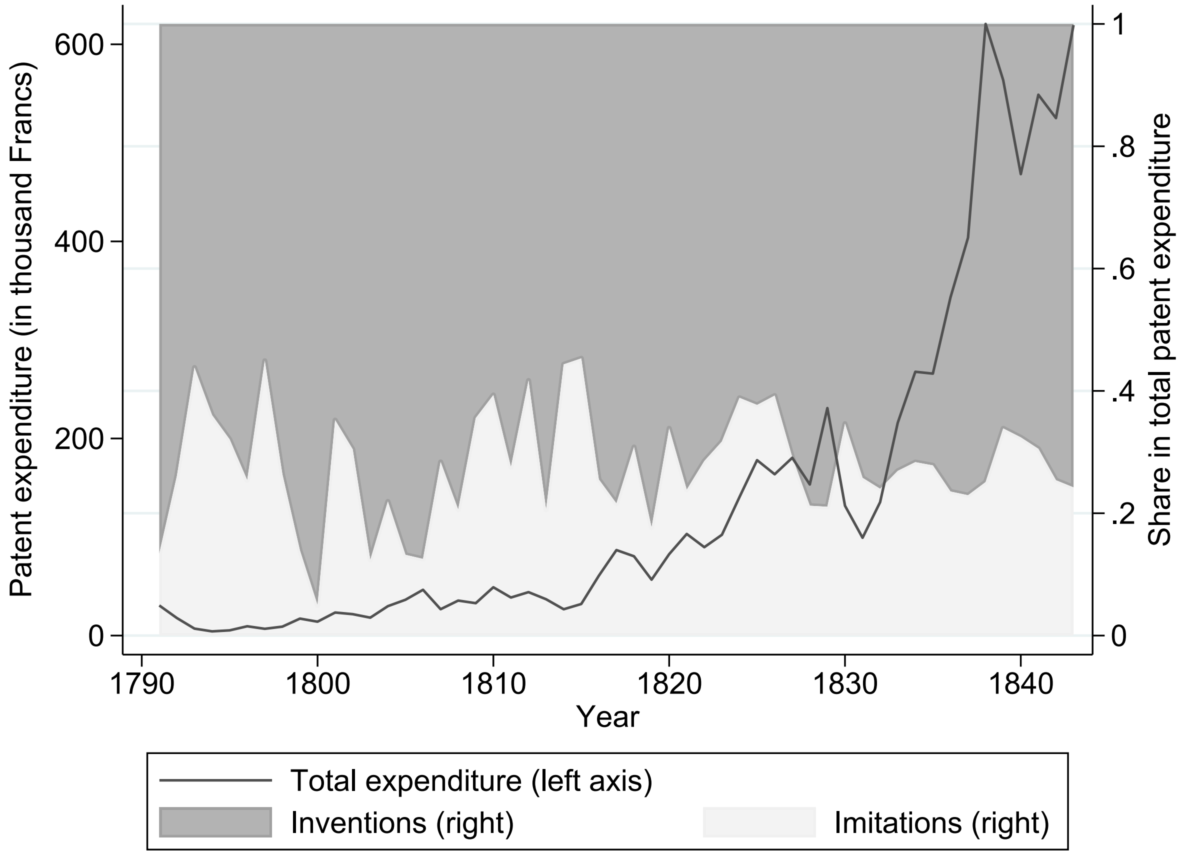
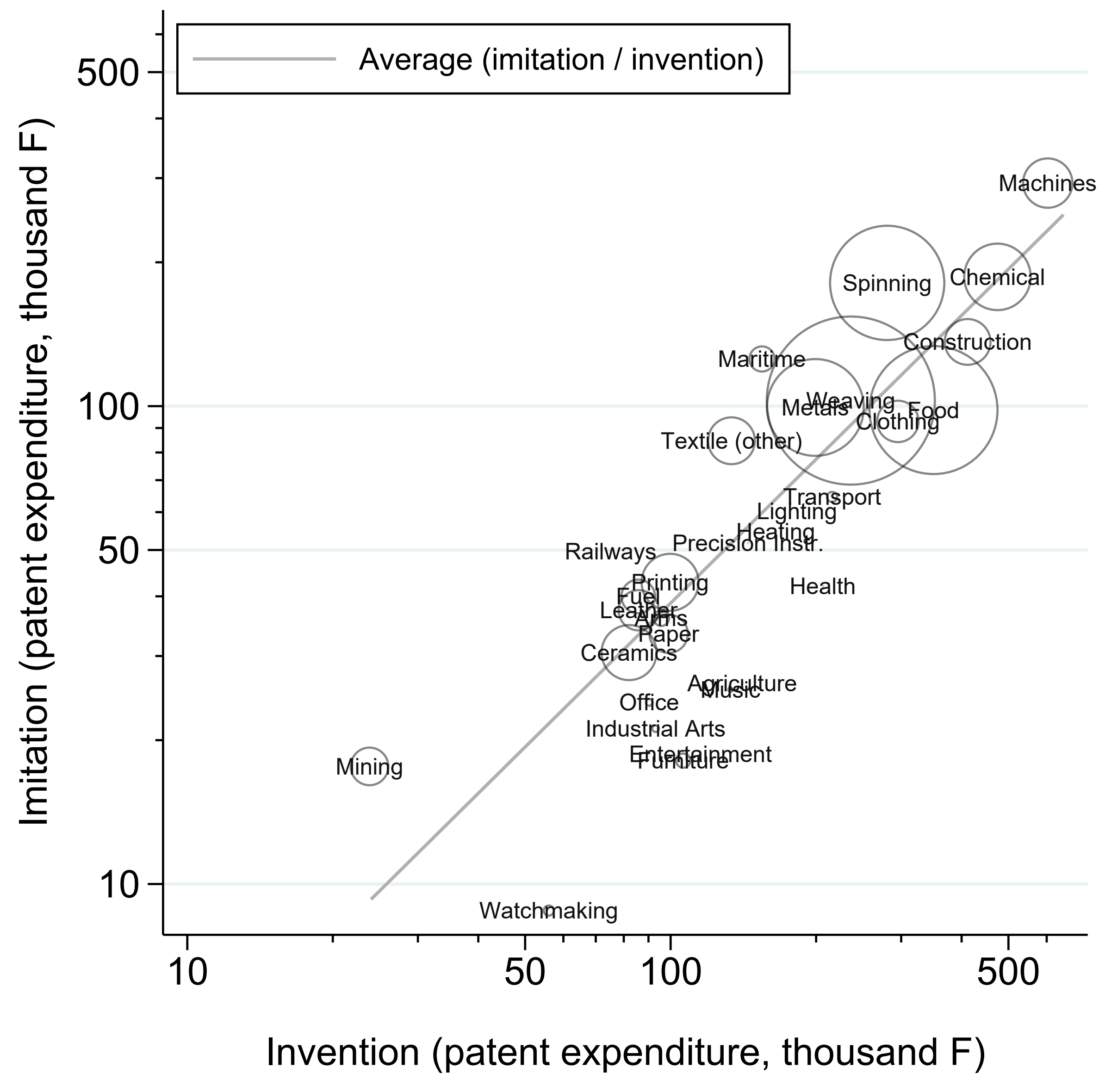
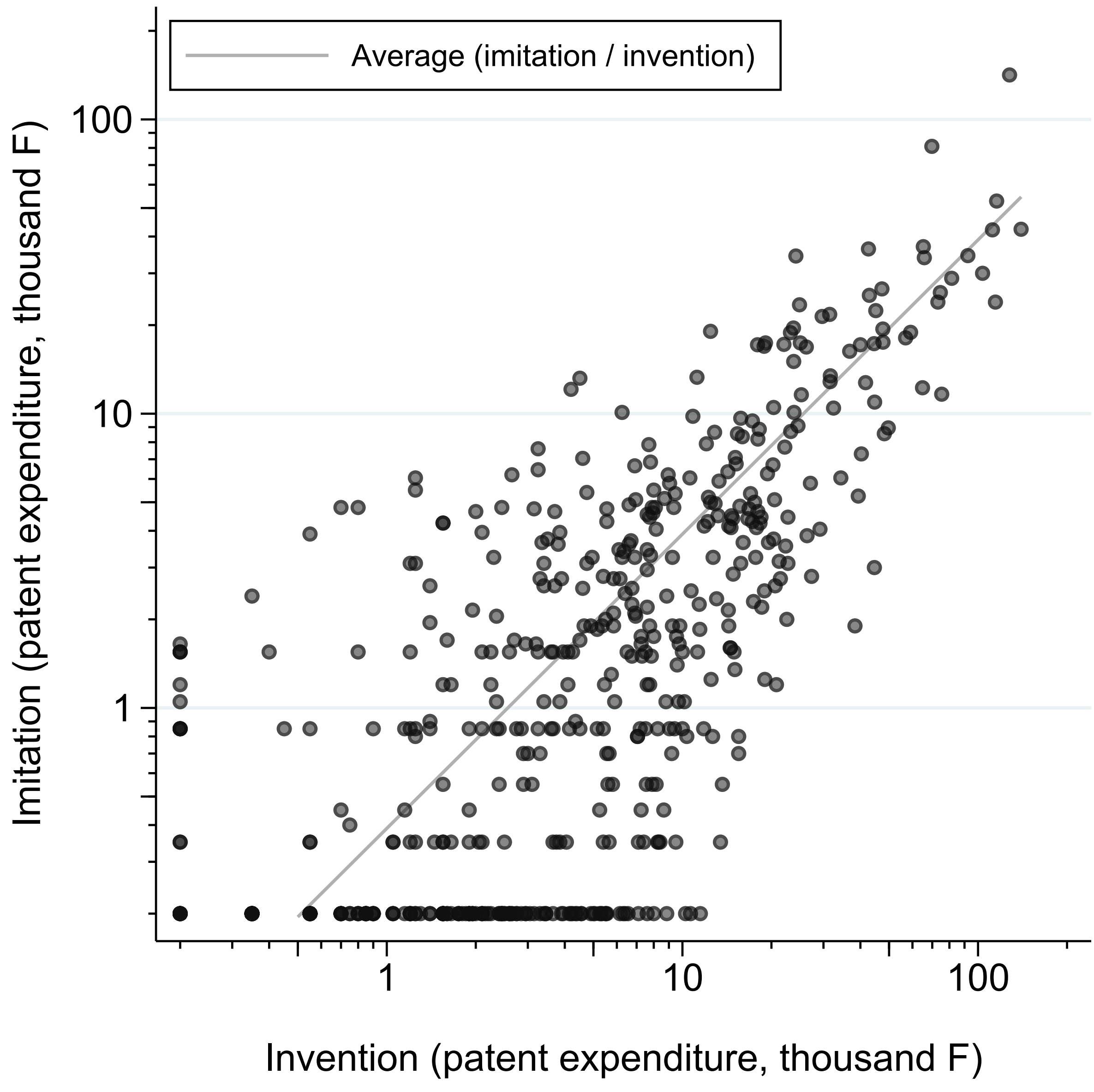


Figure 3: Patenting shares of invention and imitation over time



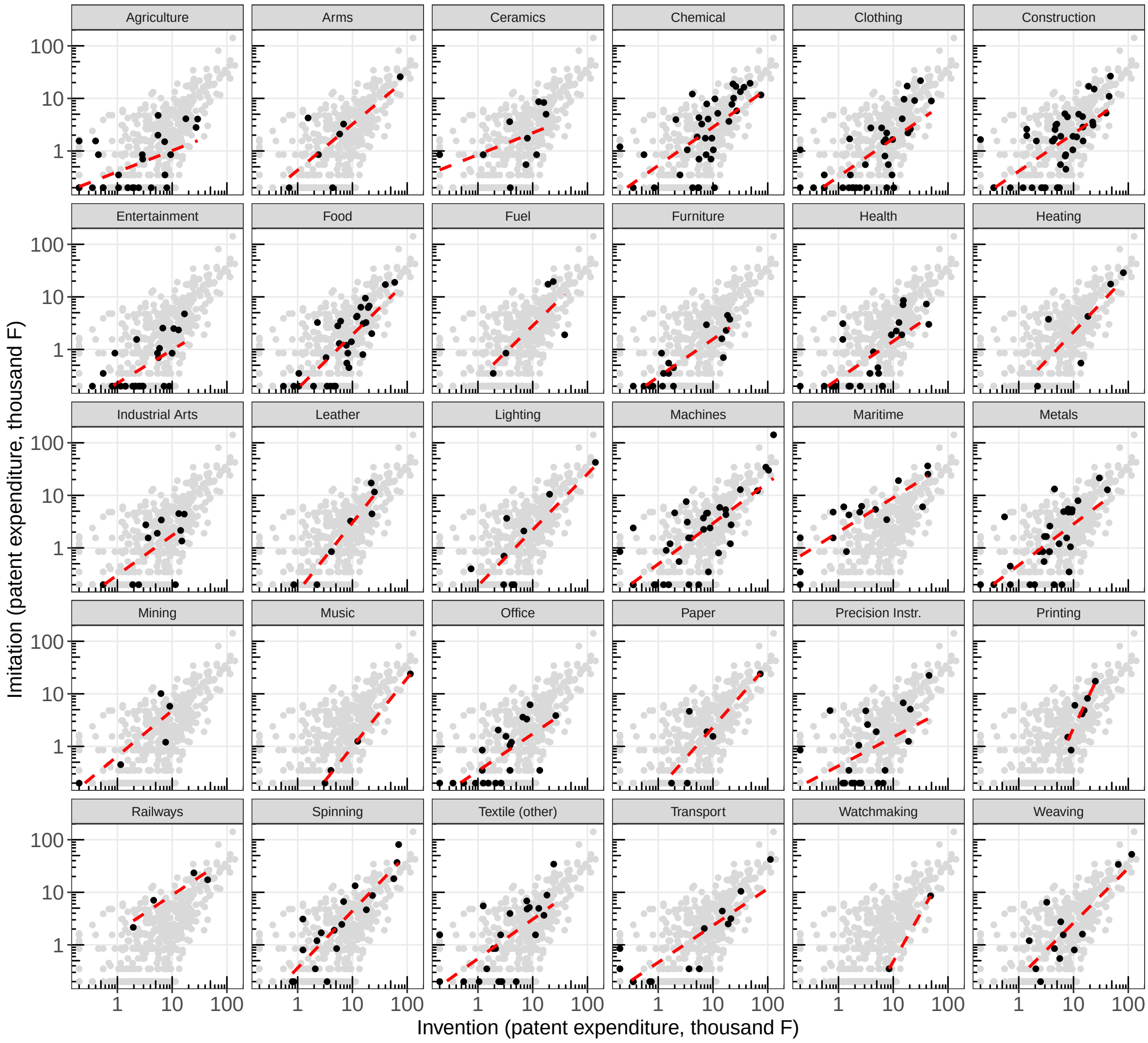
Note: Each circle is one industry. Circle size is proportional to industry value added ca. 1840. The pairwise correlation coefficient of log invention and log imitation is 0.832 (p-value < 0.0001). The bold line plots the average imitation–invention ratio.

Figure 4: Association of invention and imitation at industry level



Note: Each dot is a technology. The bold line plots the average imitation–invention ratio. The correlation coefficient of log invention and log imitation is 0.674 (p-value < 0.0001). Technologies without imitation patent are assumed to have 200F patent expenditure (the smallest possible amount; 143 cases), the same for technologies without invention patent (10 cases).

Figure 5: Association of invention and imitation at technology level



Note: Each box is one industry and each dot is a technology. The dashed line is a linear regression of log imitation on log invention. Technologies without imitation patent are assumed to have 200F patent expenditure (the smallest possible amount; 143 cases), the same for technologies without invention patent (10 cases).

Figure 6: Association of invention and imitation at technology level within industries

Table 1: Association of invention and imitation at different levels of aggregation

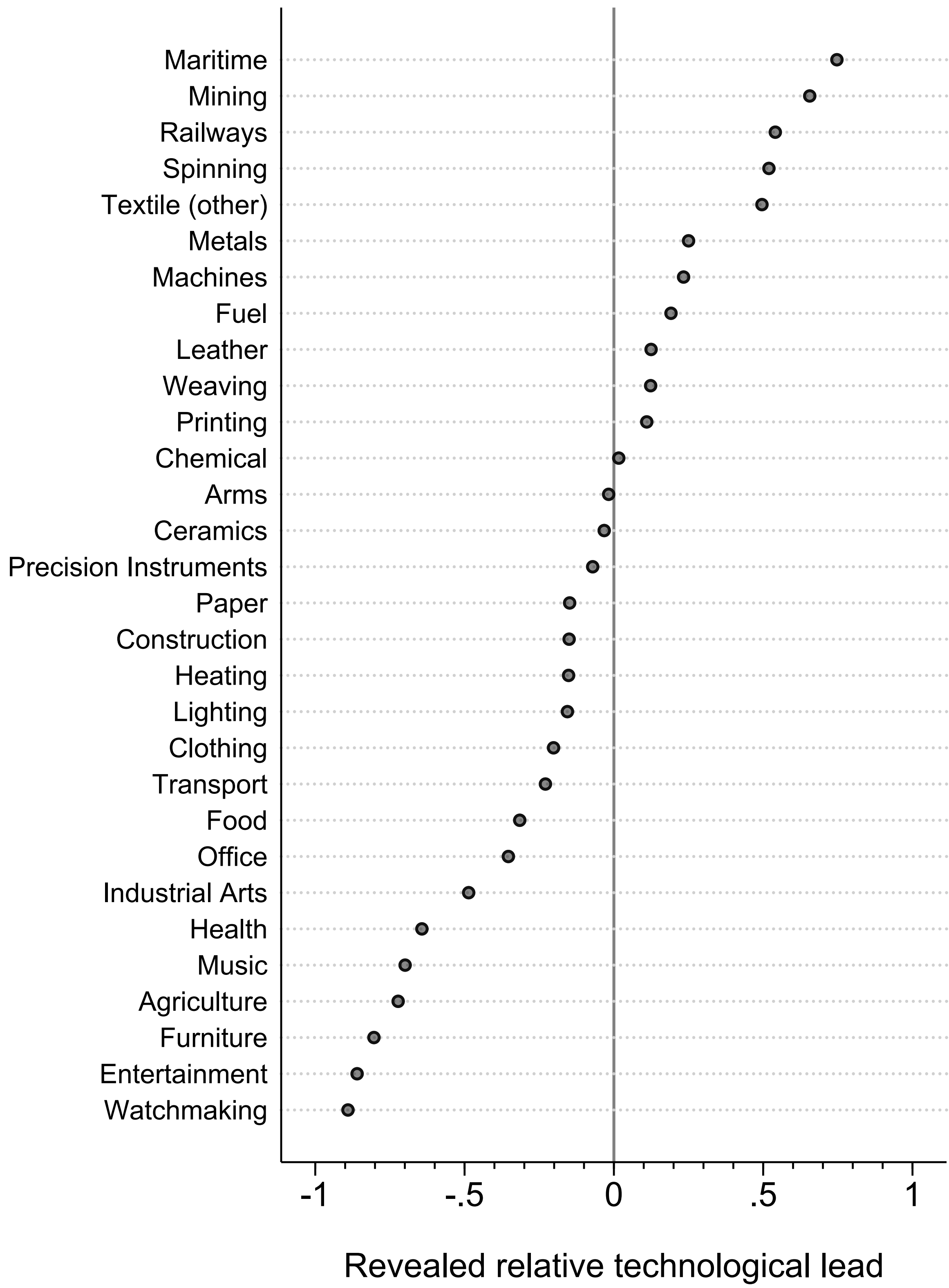
	Dep. var.: Ln imitation							
	Industry	Subindustry			Technology			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Ln invention	0.998	0.851	0.761	1.075	0.694	0.699	0.749	0.924
	(0.139)	(0.072)	(0.079)	(0.153)	(0.047)	(0.047)	(0.053)	(0.085)
Industry FE			Yes	Yes		Yes		
Subindustry FE							Yes	Yes
Observations	30	90	81	61	364	364	345	232
adjusted R^2	0.681	0.694	0.721	0.640	0.414	0.476	0.475	0.452

Observation = industry (column 1), sub-industry (columns 2 trough 4), technology (columns 5 through 9). Invention and imitation are measured as total patent expenditure from 1791 to 1843 (in 1k Francs). Sample size drops from column (2) to (3) because some industries have a single sub-industry and from column (6) to (7) because some sub-industries have a single technology. In column (4), we drop small sub-industries with less than 30 patents in total. In column (8), we drop small technologies with less than 10 patents in total. Robust standard errors in parentheses. All coefficients on ln invention are significant at the 1%-level.

Table 2: Robustness to technology level characteristics

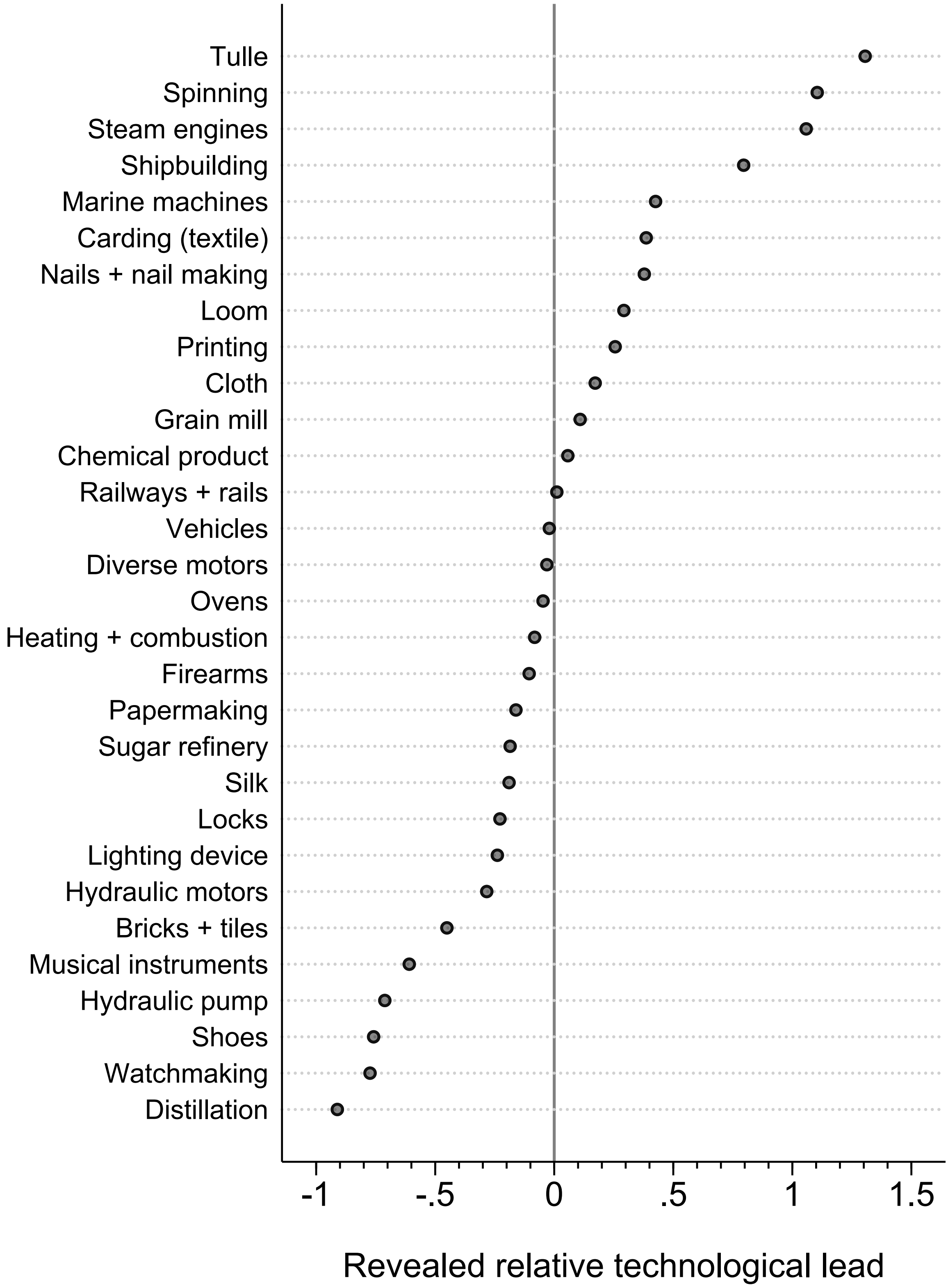
	Dep. var.: Ln imitation						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Ln invention				0.653	0.697	0.721	0.680
				(0.056)	(0.047)	(0.046)	(0.053)
Age	0.040			0.008			0.006
	(0.004)			(0.005)			(0.005)
Complexity		0.410			0.231		0.333
		(0.422)			(0.230)		(0.200)
Foreign origin			0.332			0.633	0.643
			(0.143)			(0.099)	(0.099)
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	374	374	374	364	364	364	364
adjusted R^2	0.219	0.052	0.061	0.479	0.476	0.523	0.526

Observation = technology. Invention and imitation are measured as total patent expenditure from 1791 to 1843 (in 1k Francs). Age is years since the first patent within technology (in 1855). Complexity equals one if technologies required engineering knowledge (Hanlon 2020) or scientific knowledge (Mowery–Rosenberg 1989) and includes all technologies in the fields of steam and motors, transport (railways, vehicles, ships, aviation), chemicals, electricity, precision instruments, printing, and photography. Foreign origin equals one if the first patent within a technology was an imitation. Robust standard errors in parentheses.



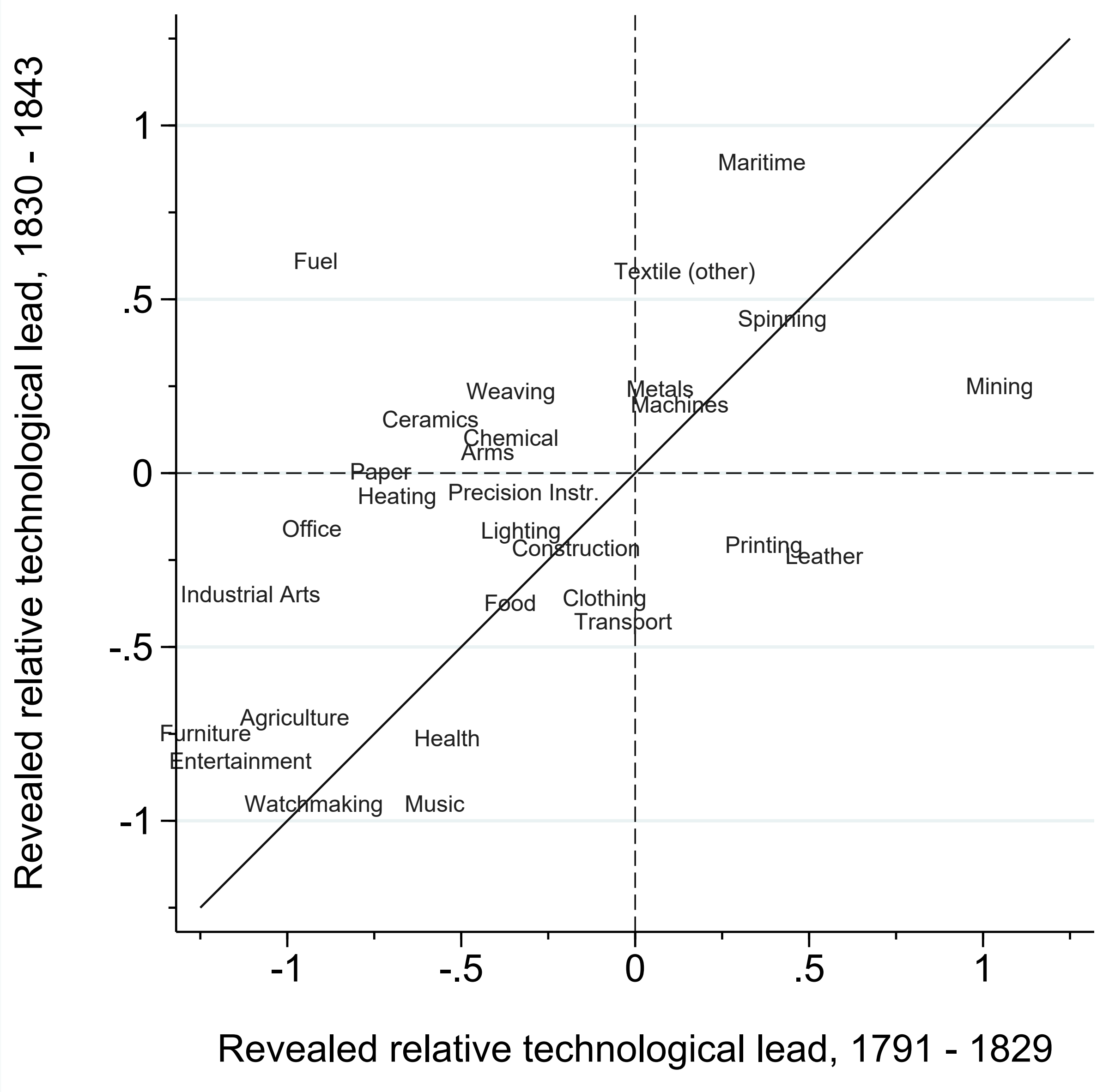
Note: Calculated as ln (imitation–invention ratio in industry / average ratio of total imitation to total invention). For positive revealed relative technological lead, Britain is leading relative to France. For negative revealed relative technological lead, France is leading relative to Britain.

Figure 7: Relative technological lead of Britain or France at industry level



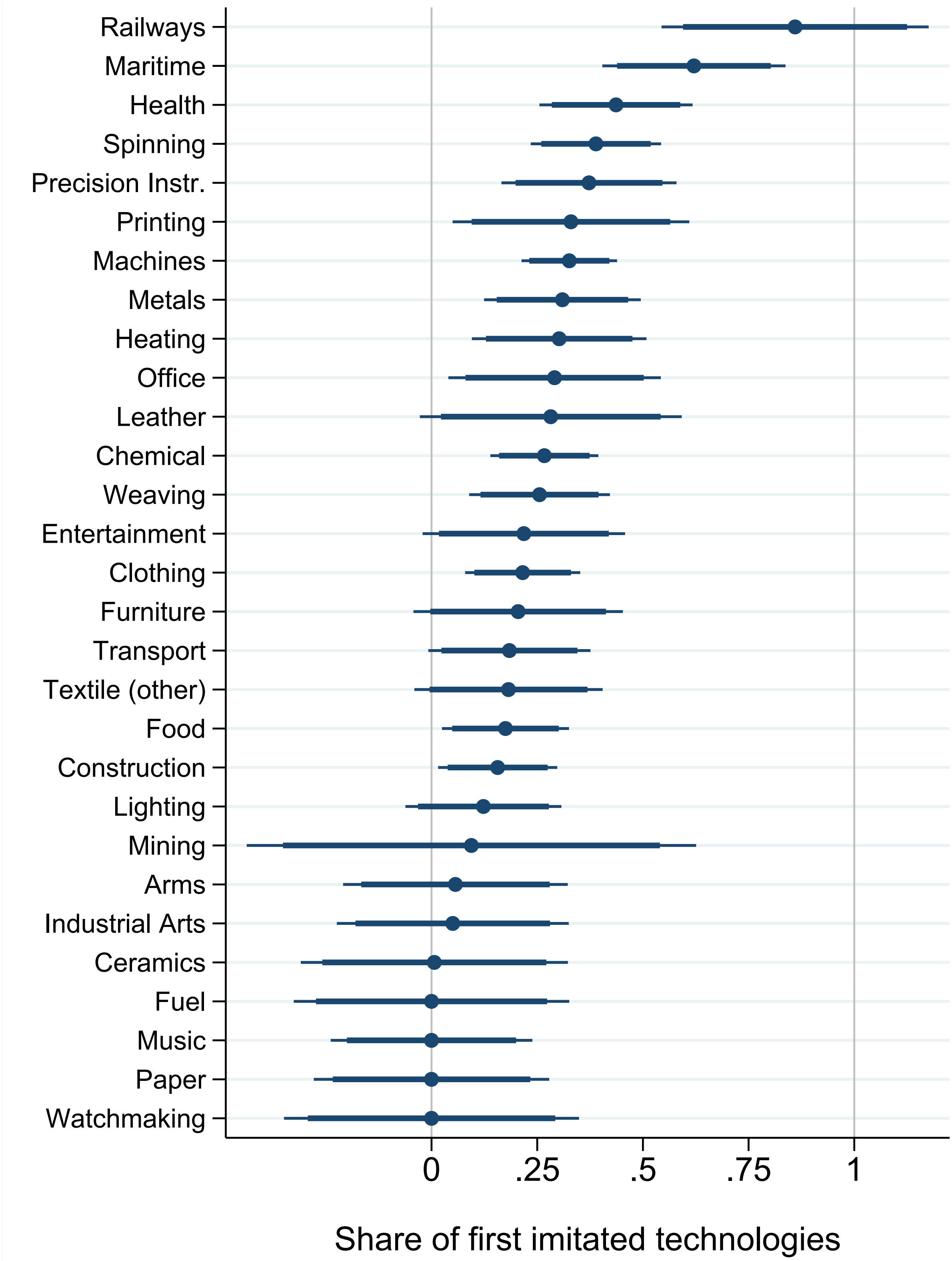
Note: Calculated as ln (imitation–invention ratio in technology / average ratio of total imitation to total invention), for the top 30 most dynamic technologies with largest total patent expenditure. For positive revealed relative technological lead, Britain is leading relative to France. For negative revealed relative technological lead, France is leading relative to Britain.

Figure 8: Relative technological lead of Britain or France at technology level



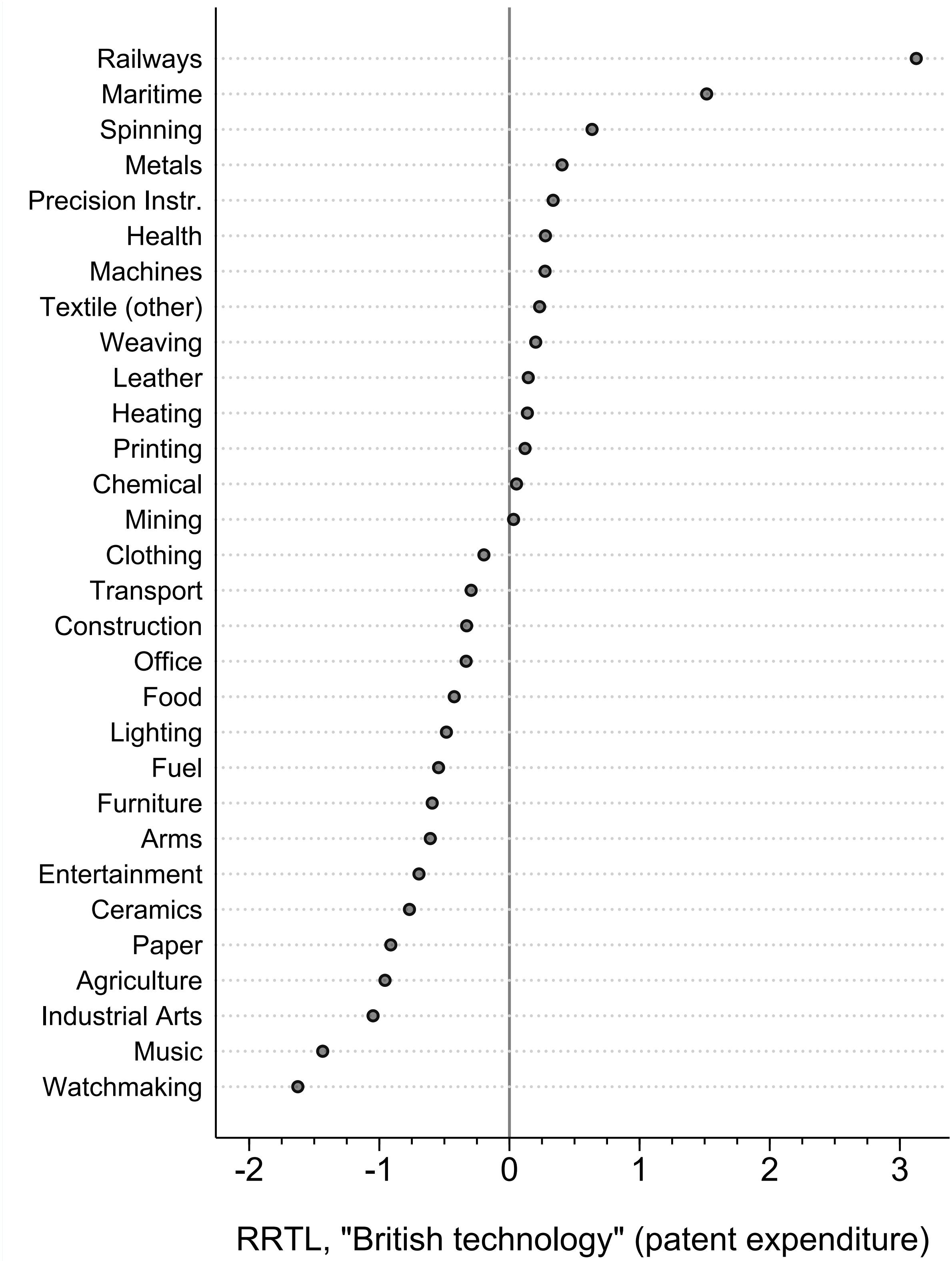
Note: Scatterplot of revealed relative technological lead in later period against earlier period. Bold line is 45-degree line. Industries left of dashed line initially leading in France, right of dashed line initially leading in Britain, below dashed line eventually leading in France, above of dashed line eventually leading in Britain.

Figure 9: Persistence of revealed relative technological lead



Note: The graph plots by industry the share of technologies within industry whose first patent was an imitation patent from Britain. First patent within technology is a proxy for inventions of high economic value. Technologies are weighted by the total number of patents per technology until 1853. The thick horizontal line provides a 90% and the thin horizontal line a 95% confidence interval. In total, 24% of all technologies were first imitated (96 out of 401).

Figure 10: Alternative measure of revealed relative technological lead



Note: Based on patent expenditure, 1791 to 1843. Alternative measure of imitation, counting additionally as imitation all patents in technologies whose first patent was an imitation patent. This wider concept of imitation includes patents invention patents which plausibly profited from spillovers from initial imitation.

Figure 11: Revealed relative technological lead when accounting for potential spillovers from imitation on invention

Appendix (for online publication)

Under construction—please do not cite

A. Data

A.1. Summary statistics

Table A.1: Summary statistics on patent origin

	Type: Innova./inven.		Type: Importa./imita.		Diff.	
	mean	sd	mean	sd	beta	t
Panel A: Patent category						
Foreign address	0.033	0.179	0.489	0.500	0.456	35.1
British address	0.016	0.127	0.409	0.492	0.392	30.9
British name	0.082	0.274	0.420	0.494	0.338	26.0
British address or name	0.089	0.285	0.540	0.499	0.451	34.3
Observations	9875		1512		11387	
Panel B: Our classification						
Foreign address	0.000	0.000	0.420	0.494	0.420	42.8
British address	0.000	0.000	0.307	0.461	0.307	33.5
British name	0.000	0.000	0.569	0.495	0.569	57.9
British address or name	0.000	0.000	0.669	0.471	0.669	71.5
Observations	8849		2538		11387	

Observation = patents 1791–1843. Panel A: Innovation and importation patent categories. Panel B: Invention patents are innovation patents by non-British patentees with French address. Imitation patents are importation patents plus innovation patents by British patentees and patentees with foreign address. Note that patents can have more than one address, mainly as a result of multiple patentees. The incidence of a foreign or British address indicates that at least one of several addresses was from there. There are 1065 patents with foreign addresses in total (9.35%). Among foreign address patents, 779 are British (United Kingdom; 73.15% of foreign, 6.84% of total).

A.2. Validation of quality adjustment

A.2.1. Predictions from empirical framework

The assumption that only a fraction of British ideas $\alpha \in (0, 1)$ is patented in France can be justified as follows. Suppose that the economic value of ideas—in short, quality—is drawn from a distribution $q \in (0, \infty)\tilde{}\Phi$ *after* obtaining a patent (the inventor may receive a signal about the quality). Further, suppose that obtaining a patent is costly, $c > 0$. Then, patented ideas will be selected on their expected value, such that only ideas with $\mathrm{E}(q) > \tilde{q}$ are patented. Now, suppose that for some British ideas, the quality can be observed before they are patented in France, for example, because they were already patented in Britain some time ago. Then, $M_i < N_{B,i}$ because for some British ideas, a quality below the cutoff $q < \tilde{q}$ could be observed before the patenting decision in France.

Two implications for the empirical setting follow. First, the average quality of patented ideas $\bar{q}$ will differ such that the average quality of imitations is higher than that of inventions $\bar{q}_M > \bar{q}_N$. Our empirical measures will account for this quality variation by considering the expenditure on patents. (Actually, in our empirical setting, only heterogeneity in average quality across sectors and heterogeneity in relative quality of imitation to invention across sectors can be problematic for our results.) Second, given that the quality of some British ideas was observed before they were patented in France, but less is known about the quality of French ideas before patenting, there will be more invention patents with $q < \tilde{q}$ than imitation patents. In other words, more invention patents than imitation patents will ex post turn out not to be worth the patenting cost. Our empirical measures of patenting expenditure cannot remove these worthless patents. Thus, after adjusting for patent expenditure, it can still be the case that $N_{F,i} > M_i$ despite potentially $N_{F,i} < N_{B,i}$. Put differently, our adjustment for patent expenditure cannot recover the true ratio of $N_{F,i}$ to $N_{B,i}$.

A.2.2. Evidence

Several patent characteristics indicate that imitation patents are indeed positively selected on quality. Table A.2 panel B compares the patent characteristics by patent type "invention" versus type "importation" (our main indicator for imitation; imitation patents also include inventions by foreigners). Importation patents have an average 45% higher patent expenditure, driven by a longer patent duration of either 10 or 15 years, with the likelihood of a short 5-year patent roughly halved and defaults on the second installment about half as likely. Further, importation patents were on average 25% less likely to be modified or extended by addition certificates. Conditional on at least one addition certificate, importation patents do have on average 0.24 fewer additions (1.73 versus 1.49). In sum, these differences underscore that imitated inventions were more valuable and probably more mature at the time of introduction to France compared to the average French invention at the moment of patenting.[38]

Our empirical strategy holds constant aggregate differences between invention and imitation in France and indirectly between invention in France and Britain. Hence, selection on quality would be unproblematic for our results if both strengths of selection of ideas from Britain and source distribution of invention quality in France and Britain were similar across industries and technologies. To control for the case that selection (and source distribution) might vary differentially across industries and technologies, we measure invention and imitation as total patent expenditure. For example, if imitation were of systematically higher quality in machines than in ceramics, we would underestimate Britain's revealed relative technological lead in the machines industry and add a measurement bias to the estimated correlation between invention and imitation.

We evaluate whether patent expenditure adjusts for quality differences in practice by studying patent sales as an alternative indicator of idea quality. The exercise is based on the notion that patents of high economic value are more likely to be sold than patents of low value. Patent sales had to be documented by a notary, and lists of traded patents were published in the official law publication (*Bulletin de Lois*). According to the INPI data, 5% (573 in 11387) of patents registered until 1843 were sold at least once.

Table A.3 shows that the patent expenditure measures do correct for observable quality differences between patents. In columns (1) to (4), we first confirm that patentees are willing to pay substantially more for imitation patents: On average, patent expenditure is about one third larger, longer duration than five years is about 50% more likely, and defaults are about 25% less likely compared to invention patents. In columns (5) to (7), we instead use patent sales to measure patent quality. Unconditionally, imitation patents are 20% more likely to be sold, consistent with higher quality. Conditional on patent expenditure, however, imitation patents are not statistically different from invention patents regarding the patent sale measure of quality. The quality indicators themselves—duration categories and patenting expenditure—are all significant predictors of patent sales, supporting the validity of patent sales as an alternative quality measure.

A.3. Nationality prediction [incomplete]

In this section, we describe how we identify the nationality of an inventor based on their last name. We first outline the data used, then we describe the algorithm. Last, we validate the results of the classification algorithm and describe the results.

[38]Obviously, these quality differences imply nothing about the underlying distribution of idea quality in Britain and France.

Table A.2: Summary statistics on patent quality

	Type: Innova./inven.		Type: Importa./imita.		Diff.	
	mean	sd	mean	sd	beta	t
Panel A: Patent category						
Patent expenditure (Franc)	629.630	447.408	914.947	478.542	285.317	21.8
Duration 5 years	0.559	0.497	0.250	0.433	−0.309	−25.3
Duration 10 years	0.254	0.435	0.397	0.489	0.143	10.7
Duration 15 years	0.187	0.390	0.351	0.478	0.164	12.7
Defaulted on 2nd installment	0.242	0.428	0.133	0.340	−0.109	−11.2
Prob (additions > 0)	0.259	0.438	0.192	0.394	−0.067	−6.1
Number of additions	0.447	1.114	0.285	0.764	−0.162	−7.2
Patent sold	0.048	0.214	0.064	0.245	0.016	2.4
Observations	9875		1512		11387	
Panel B: Our classification						
Patent expenditure (Franc)	620.313	442.989	832.092	488.132	211.779	19.7
Duration 5 years	0.570	0.495	0.336	0.472	−0.235	−21.8
Duration 10 years	0.249	0.432	0.357	0.479	0.108	10.2
Duration 15 years	0.181	0.385	0.306	0.461	0.125	12.5
Defaulted on 2nd installment	0.243	0.429	0.174	0.379	−0.069	−7.9
Prob (additions > 0)	0.263	0.440	0.205	0.404	−0.058	−6.2
Number of additions	0.459	1.143	0.309	0.791	−0.151	−7.6
Patent sold	0.048	0.214	0.058	0.234	0.010	2.0
Observations	8849		2538		11387	

Observation = Patent. Sample: Raw patent categories (innovation and importation) 1791 to 1843. Invention patents are innovation patents by non-British patentees with French address. Imitation patents are importation patents plus innovation patents by British patentees and patentees with foreign address.

Table A.3: Validation of quality adjustment

	Patent expenditure				Altern. quality measure		
	(1) expenditure	(2) 10 year	(3) 15 year	(4) defaulted	(5) sold	(6) sold	(7) sold
Imitation patent	0.212	0.108	0.125	−0.069	0.010	−0.004	−0.004
	(0.010)	(0.010)	(0.009)	(0.009)	(0.005)	(0.005)	(0.005)
Patent expenditure (1k Francs)						0.068	
						(0.004)	
Duration 10 years							0.037
							(0.005)
Duration 15 years							0.064
							(0.005)
Defaulted on 2nd installment							−0.039
							(0.005)
Constant	0.620	0.249	0.181	0.243	0.048	0.006	0.037
	(0.005)	(0.005)	(0.004)	(0.004)	(0.002)	(0.004)	(0.003)
Observations	11387	11387	11387	11387	11387	11387	11387
R^2	0.036	0.010	0.016	0.005	0.000	0.020	0.021

Observation = Patent. Sample: All invention and imitation patents 1791 to 1843. Imitation patent compares against baseline of invention patent (constant). Standard errors in parentheses.

INPI data provide first and last name(s) for all patentees

Two-step procedure to predict nationality based on last names - Dictionary approach Universe of people born between 1700 and 1900 on Wikipedia Notable people database (De la Croix–Licandro 2015)

- Random forest machine learning algorithm Trained on dictionary data Predict nationality for names not included in dictionary Reject dictionary classification if disagreement (i.e., wiki data implausible)

We find that the adjustment matters.

[Old text]

In order to teach our algorithm to recognize British names, we need a large dataset of historical British and non-British names. We rely on two sources. First, we use the famous people dataset already used in economic history literature (De la Croix and Licandro, 2015). Second, we obtain all European names of people born between 1700 and 1900 from Wikipedia. We use the place of birth as an indicator of nationality. Alternatives are "nationality" and "ethnicity" variables available in Wikipedia. Those seem less reliable because the definition of a person's nationality and ethnicity is not reliable when a person moves. For instance, famous Europeans emigrating to the US are often labeled as American, which may be accurate but is not the information we are looking for. Furthermore, the place of birth is the most widely available variable.

Our algorithm is a simple random forest with 100 trees. As features for the classification, we use the frequency of ASCII signs in last names and the 15 percent two and three-letter syllables for which the frequency is most different between French and British names. The INPI dataset of historical patents necessitates the use of ASCII signs. Apostrophes and other characteristically French signs are not reliably reported, so we cannot rely on them. When learning the three with 80 percent of the Wikipedia data and using the remaining 20 percent as test data, we can achieve 97 percent accuracy. Relying on two and three-letter frequencies is the key for this result, as our classification algorithms using only letter frequencies achieved accuracy rates around 80 percent at best.

Since the ratio of British to French names is about 1 to 10, we were delighted to see that the rate at which we misclassify French names as British is much lower than the rate at which we misclassify British names as French. An example helps to illustrate why this is important. If we have 1000 French inventors and 100 British, and we misclassify 10 percent of the French as British, half of the inventors we classify as British are French. This would make our measure of British inventors extremely noisy. If, on the other hand, we classify 10 percent of British inventors as French, then only 1 percent of French inventors are British, and we catch 90 percent of British inventors.

We can identify British names using a second method as well. Here we create a dictionary of names and nationalities based on all historical names available in either of our two datasets. Then we classify names as British if they are in the dictionary.

In the last step, we then combine the random forest with the dictionary. When the two agree that a name is British, it is considered British. If a name does not appear in the dictionary, the assignment of the random forest is used. If the dictionary and the classification algorithm disagree, we classify the origin of the inventor as unknown. At first, it may seem surprising that we do not trust the dictionary more than the random forest. We take this approach because when inspecting cases when the two disagree, no clear pattern emerges which one is better.

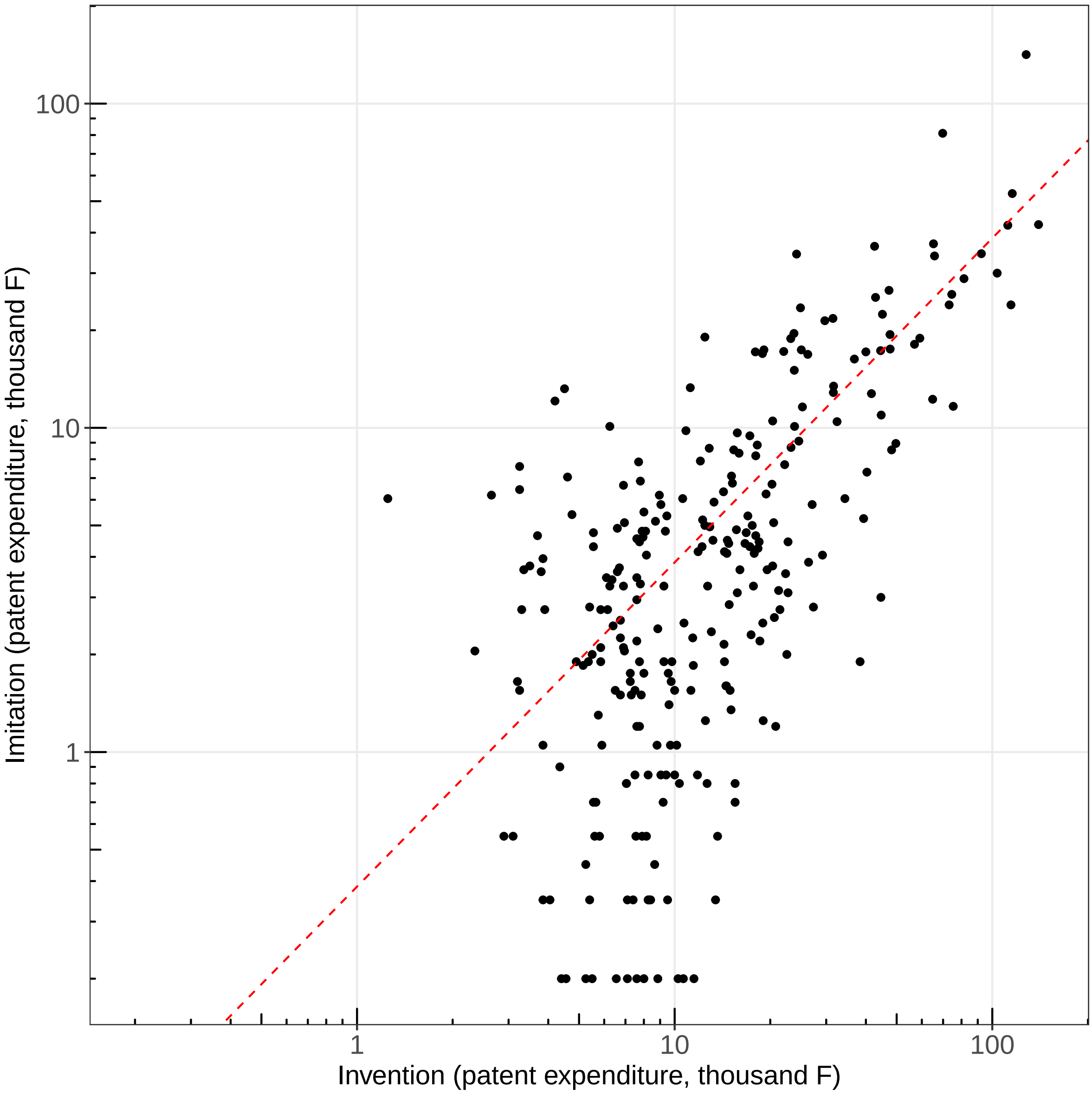
B. Robustness

B.1. Dropping small technologies

Here, we show that the strong, positive association at the technology level, between technologies and between technologies within industries, is robust to the exclusion of small technologies. We drop small technologies with less than ten patents, as they might cause a positive association by fixing the anchoring the regression line at zero in terms of technologies with scant invention and scant imitation. In figure B.1, we reproduce the basic graph at the technology level because it will be the backdrop for the individual industries. As already shown in table 1, column (8), the regression coefficient of log imitation on log invention increases to one if we exclude the small technologies. In figure B.2, we reproduce the graph within industry for each of the 30 industries. The association between invention and imitation stays strikingly positive. The association becomes negative only in two industries (fuel and mining) and flat in one (industrial arts). In all other industries, it is essentially unaffected by the exclusion of small industries.

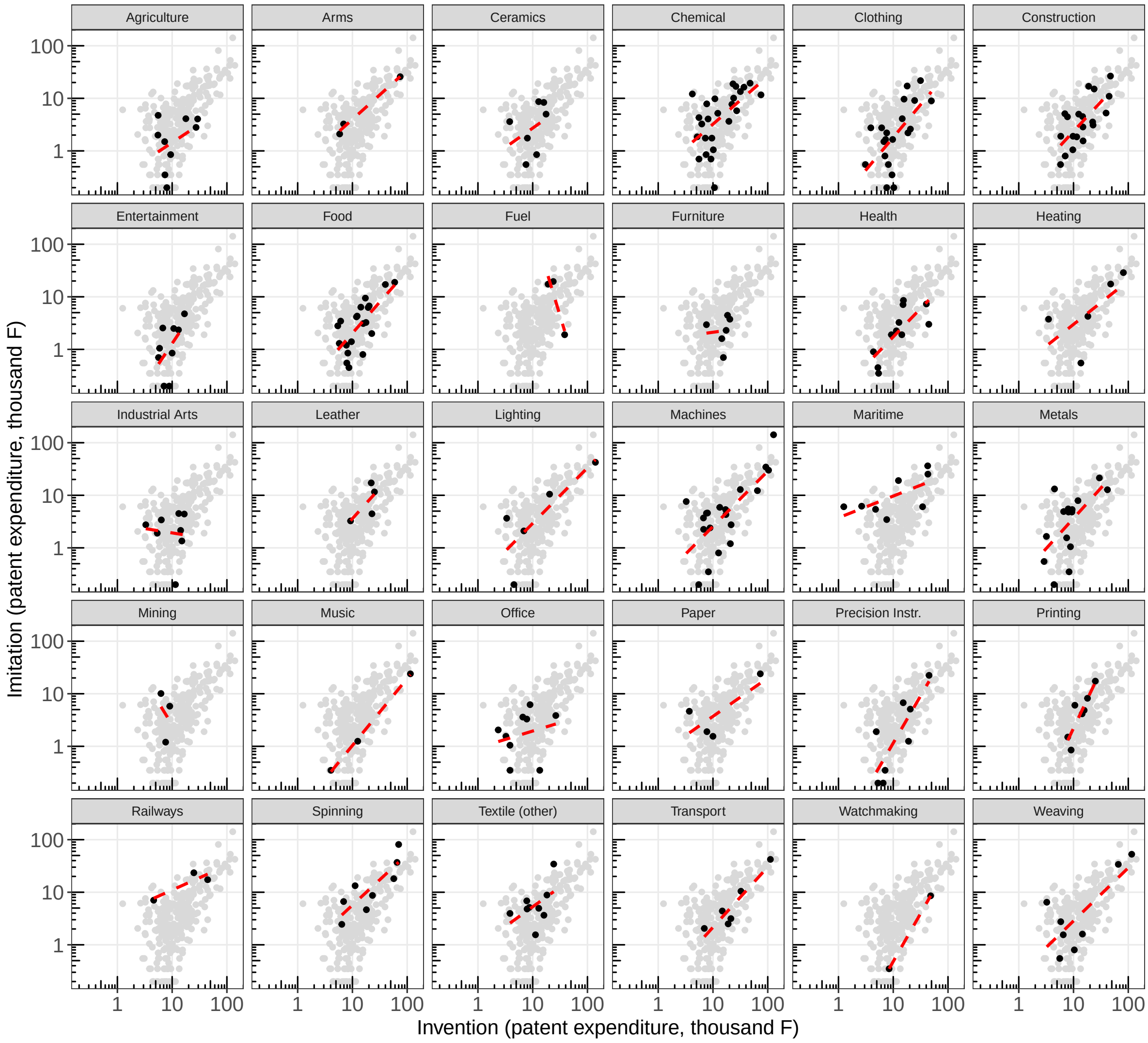
B.2. Alternative classification of invention versus imitation

Table B.4 provides an overview of how many patents there are within the different groups of invention and imitation. It breaks down patents by category (innovation vs. importation), address (French or foreign), and nationality (French or British). In our baseline analysis, we include 8849 patents as invention (innovation category, French name, and address) and the rest (2538) as imitation, which includes importation patents (1512), British migrant inventors (700), and other likely foreign actual inventors (326).



Note: Each dot is a technology. The dashed line plots the linear regression line of log imitation on log invention. Technologies with less than 10 patents until 1843 are excluded. Technologies without imitation patent are assumed to have 200F patent expenditure (the smallest possible amount; 9 cases).

Figure B.1: Association of invention and imitation at technology level



Note: Each box is one industry, each dot is a technology. The dashed lines plots separate regressions of log imitation on log invention within industry. Technologies with less than 10 patents until 1843 are excluded.

Figure B.2: Association of invention and imitation at technology level within industries

Table B.4: Breakdown of invention and imitation into patent groups

	French name			British name		
French address	Innov	8849		Innov	700	34.5%
	Import	605	22.9%	Import	168	
Foreign address	Innov	217	19.2%	Innov	109	23.4%
	Import	272		Import	467	

There were 11387 patents until reform 1844, out of which we classify 2538 as imitation. Importation is the principal category for imitation patents. The most common foreign address is Britain. British nationality is predicted from last names.

Table B.5: Robustness for sub-periods

	Dep. var.: Ln imitation					
	1791 to 1829			1830 to 1843		
	(1)	(2)	(3)	(4)	(5)	(6)
Ln invention	0.773	0.838	0.420	0.970	0.757	0.629
	(0.203)	(0.116)	(0.076)	(0.106)	(0.099)	(0.058)
Industry FE		Yes			Yes	
Subindustry FE			Yes			Yes
Observations	30	68	187	30	79	300
adjusted R^2	0.538	0.531	0.249	0.648	0.642	0.410

Observation = industry (columns 1, 4), sub-industry (columns 2, 5), technology (columns 3, 6). Invention and imitation are measured as total patent expenditure within the sub-period (in 1k Francs). Robust standard errors in parentheses. All coefficients on ln invention are significant at the 1%-level.

B.3. Before and after growth take-off

This section shows that our main results are qualitatively robust in the sub-periods before and after the take-off of modern economic growth. Thus, we split the sample from 1791 to 1830 and 1830 to 1843 (the patent law reform).