Technology Adoption and Productivity Growth: Evidence from Industrialization in France

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New technologies tend to be adopted slowly and—even after being adopted—take time to be reflected in higher aggregate productivity. One prominent explanation is that major technological breakthroughs create the need to reorganize production. We study a unique setting that allows us to examine this mechanism: the adoption of mechanized cotton spinning during the first Industrial Revolution in France. Using a novel hand-collected, plant-level dataset from French archival sources, we show that a process of "trial and error" in reorganizing production led to initially low and widely dispersed productivity across firms operating the new technology. In the subsequent decades, we observe high productivity growth as knowledge diffused through the economy and new entrants adopted improved methods of organizing production.

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> [T]here were strong pairwise complementary relations between factory organization and machinery . . . employers needed to simultaneously determine the choice of technique, the level of worker effort, and the way incentives were set up and communications and decisions flowed through the firm hierarchy. . . . Factories were the repositories of useful knowledge . . . but they were also the places in which experimentation took place. Mokyr (2010, 345–46)

I. Introduction

The diffusion of innovation is at the core of aggregate productivity growth in the long run. Yet many technologies that ended up being widely adopted were slow to diffuse across firms (Griliches 1957; Mansfield 1961; Rosenberg 1972; Hall 2004; Comin and Hobijn 2010). This slow adoption is particularly puzzling, given that new technology can provide a substantial boost to firm productivity (Syverson 2011; Bloom et al. 2013; Giorcelli 2019). There is also a second, well-documented puzzle. When major innovations such as information technology (IT) or electricity spread across firms, the widely expected boost in aggregate productivity has proved hard to document in the data. This prompted Robert Solow (1987) to remark that "you can see the computer age everywhere but in the productivity statistics."

One prominent explanation for both puzzles is the need to modify and reorganize the production process when adopting major breakthrough technologies (David 1990; Brynjolfsson 1993; Brynjolfsson and Hitt 2000; Hall and Khan 2003; Brynjolfsson, Rock, and Syverson 2021). Initially, many firms operate the new technology inefficiently—often because complementary organizational innovations are missing. If these challenges are indeed important during the early phase of technology adoption, we expect them to be reflected in a highly dispersed productivity distribution—because of a lack of standardized organizational knowledge that adopting firms can

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draw from. However, empirical evidence on this mechanism is scarce, as measuring the productivity distribution specific to new adopters is challenging for numerous reasons. First, standard data sources rarely make it possible to observe the use of specific technologies. Second, it is difficult to observe whether an adopting plant has also reorganized production. Third, productivity under the old technology and that under the new are typically correlated.

This paper shows how the need to reorganize production affects the productivity distribution of adopting plants during the diffusion of a major new technology. We bypass the typical challenges by studying a unique historical setting—the adoption of mechanized cotton spinning in France during the nineteenth century. Importantly, the macroinventions that mechanized cotton spinning (the famous spinning jenny, the water frame, and the mule) went hand in hand with the need to reorganize production on a revolutionary scale. Before mechanization, workers produced in their homes in a cottage-industry setting. Adopting the new technology required setting up factories from scratch and moving workers there from their homes, because of the reliance on inanimate power sources and the need to monitor workers more closely (Williamson 1980; Szostak 1989). This led to one of the most dramatic shifts in the organization of production in economic history (Mokyr 2011). While the key elements of the new spinning technology itself were well known across France (Horn 2006) and multiple domestic producers supplied firms with the machinery (Chassagne 1991), its adoption occurred in the absence of complementary knowledge on how the new cotton-spinning plants should be organized (Pollard 1965).

A number of features of this setting allow us to isolate the productivity distribution of adopters and study its evolution over a long time horizon (3 decades), making headway on the typical empirical challenges faced by the literature. In particular, the sharp break in the location of production due to its organization in plants makes it possible to distinguish adopters of the new technology from old producers. This addresses the first two empirical challenges mentioned above. Moreover, the first generation of mechanized cotton spinners did not typically have a background in the old technology, suggesting that productivity under the old technology and that under the new were not systematically related, which addresses the third challenge.

Our empirical analysis is based on a novel hand-collected, plant-level dataset from historical surveys covering three sectors (mechanized cotton spinning, metallurgy, and paper milling) at two points in time, around 1800 and in the 1840s. To help distinguish the effect of reorganization from broader trends such as general productivity growth, political and institutional change, and enhanced regional integration, we compare the evolution of the plant productivity distribution in mechanized cotton spinning to that in two comparison sectors (metallurgy and paper milling). This is similar in spirit to a difference-in-differences strategy. Crucially, in both comparison sectors, production was already organized in plants for centuries before the Industrial Revolution because of their reliance on water power and high-fixed-cost machinery. As a consequence, these sectors possessed fairly standardized knowledge about how to organize plant-based production. Moreover, during our sample period, all three sectors witnessed the arrival of new technologies that could be introduced fairly seamlessly into the existing organization of production.[1] Thus, while all three sectors were adopting new technologies, only mechanized cotton spinning had to adapt to a radically reorganized production process.

We document four main findings for mechanized cotton-spinning plants: (1) we observe a highly dispersed productivity distribution in the initial period (1806) relative to 1840; (2) we estimate that the industry underwent a substantial (82%) increase in plant productivity between 1806 and 1840, after mechanization had already been adopted; (3) this aggregate productivity growth was largely driven by the disappearance of plants in the lower tail of the distribution (which we refer to as "lower-tail bias" of productivity growth); and (4) the disappearance of the lower tail took place almost exclusively through plant exit and entry. Inefficient producers were replaced by more efficient entrants. In the comparison sectors, we also find a sizeable increase in plant productivity during the sample period (68% in metallurgy and 33% in paper milling). However, the lower-tail bias of productivity growth is unique to mechanized cotton spinning. In contrast, in the comparison sectors, the entire productivity distribution shifted right. Taken together, we interpret these results as suggestive of a link between the lower-tail bias of productivity growth and the feature unique to the mechanized cotton-spinning industry—the need to reorganize production.

The second part of the paper examines why the need to reorganize production would lead to a lower-tail bias in productivity growth. Central to our argument is the fact that, at early stages of technology adoption, plants need to learn about optimal organizational forms. To fix ideas, we provide a simple framework in which plants endogenously learn about the optimal organization of multiple inputs or tasks in the spirit of Perla

[1] In mechanized cotton spinning, there were improvements to the existing vintages of machinery and in preparatory processes (Allen 2009). In paper milling, one part of the production process was mechanized (André 1996), and in metallurgy, charcoal was replaced with coal as the source of fuel (Pounds and Parker 1957). As we discuss in more detail below, the three industries shared important similarities in adopting these new technologies during our sample period. This supports our implicit assumption that technological additions to the existing production setups did not lead to differential productivity trends.

and Tonetti (2014). These tasks reflect organizational challenges, such as optimal plant layout, and they exhibit complementarities in the production function. We show that these features initially, when plants have little knowledge about the optimal ways to perform these tasks, lead to a fat lower tail in the plant productivity distribution. Over time, as plants learn about the efficient organization of inputs, the lower tail disappears. We present both historical and empirical evidence consistent with this.

According to the historical literature, there were two broad classes of challenges that early cotton-spinning mills faced. First, they needed to contend with a range of issues related to mill layout and design. As Allen (2009, 184) writes, “The cotton mill, in other words, had to be invented as well as the spinning machinery *per se*.” Second, a set of labor management innovations were required for setting up and operating spinning mills at a scale not seen elsewhere in the economy (Pollard 1965). We examine the data for evidence consistent with the spread of organizational practices. We provide evidence for the spatial diffusion of knowledge during the early phase of industrialization, by showing that cotton plants located closer to high-productivity peers were themselves more productive. Strikingly, this spatial productivity pattern is not present in the comparison sectors, where plant-based production methods were more mature, or in cotton spinning in the long run, once organizational knowledge had diffused. We show, using a rich set of controls and placebo tests, that these results are unlikely to be driven by either selection into productive locations or omitted variables.

While these results are suggestive of a role for the spatial diffusion of knowledge, they do not distinguish between learning about the new technology itself (i.e., how to operate and maintain the new machines) and learning about efficient organizational forms. We provide direct evidence for the latter, using detailed metrics on cotton-spinning plant design from our sample period. We find that during the early phase of adoption, two key design features (number of floors and squareness of layout) were chosen almost at random—consistent with plants experimenting with how to organize the factory floor optimally. Later, as best-practice knowledge spread, these metrics converged toward much narrower distributions around the optimum. We provide additional complementary evidence that helps us to distinguish the two forms of learning. If plants were learning mostly how to operate the newly adopted technologies, we would expect incumbents to have an advantage relative to newer entrants. On the other hand, if organizational knowledge on plant design diffused over time, we would expect later adopters to have an advantage in setting up their factories. Two features in the data point to the latter: First, cotton-spinning plants that entered the market later had higher productivity during the initial phase of adoption. This holds even after we control for newer capital vintages, and it does not hold for the comparison sectors or for cotton spinning in later periods. Second, the exit rate of plants in mechanized cotton spinning was substantially higher than that in other sectors between 1800 and 1840, and buildings were also abandoned for use by the industry at higher rates. These findings suggest that knowledge of how to set up and organize cotton plants spread over time (and space), giving an edge to new entrants.

We examine alternative explanations that could account for our results. While our difference-in-differences-style evidence based on the comparison sectors addresses many potential concerns, it is possible that some alternative channels affected mechanized spinning differentially. We control for a large set of these directly, showing that the lower-tail bias of productivity growth remains robust. For example, our results hold with region fixed effects, suggesting that the sorting of cotton plants into areas with better location fundamentals, better market access, or better input markets is unlikely to drive our results. Region fixed effects also make it unlikely that the Napoleonic Blockade, which had a regionally differential effect across France in mechanized cotton spinning (Juhász 2018), drives our findings. We also account for possible more localized confounders, such as battles during the Napoleonic Wars or location-specific market access. Finally, plant-specific features such as size, output quality, capital deepening, and plant life-cycle characteristics do not confound our results, and they are also robust to excluding all plants that could be smaller "spinning workshops" (which shared some, but not all, characteristics of mature factory-based production). For a systematic overview of alternative mechanisms and the corresponding robustness, we refer the reader to the summary table in appendix F (apps. A–F are available online).

Related literature and contribution.—Our paper is closely related to a literature on innovation and technology adoption in manufacturing—particularly the strand that has studied the productivity effects of the adoption of IT.[2] Interestingly, some of the patterns we document for mechanized cotton spinning have been found in other settings. For example, Syverson (2011) discusses that the adoption of IT capital is associated with increased within-industry productivity dispersion. Foster et al. (2018) provide empirical support for the argument by Gort and Klepper (1982) that periods of rapid innovation are associated with a surge in firm entry, followed by a period where experience with the new technology is accumulated, eventually leading to a shakeout where unsuccessful firms (or plants) exit. Brynjolfsson and Hitt (2000) conjecture that the surge in

[2] See Hall and Khan (2003) and Hall (2004) for an overview of the literature on technology diffusion. Brynjolfsson and Hitt (2000) and Syverson (2011) discuss the literature on the productivity effects of IT.

aggregate productivity in the 1990s was explained in part as a return on the large, intangible complementary organizational innovations that firms had undertaken in prior decades to make efficient use of IT. Our paper contributes to this literature in two ways. First, we provide evidence that these patterns generalize to other settings in which major new technologies are adopted. Second, our unique setting allows us to more closely tie these patterns to the need to reorganize production that often accompanies major technological change. In particular, initial information disparities about the optimal organization of production can help to explain why breakthrough technologies tend to be adopted slowly and—even after being adopted—take time to be reflected in higher aggregate productivity. Along this dimension, our paper relates to recent work that documents how a variety of organizational barriers can impede technology adoption (Atkin et al. 2017; Feigenbaum and Gross 2021).

In addition, our paper brings the insights of the firm productivity literature to the most important structural break in economic history—the first Industrial Revolution, which saw unprecedented growth in manufacturing productivity (Crafts 1985; Crafts and Harley 1992; Galor 2011). So far, productivity growth during this period has been studied mostly at the country level, or—in some cases—at the aggregate sectoral level.[3] Our paper is the first to study the contribution of plant dynamics to manufacturing productivity improvements during the Industrial Revolution. Our focus on the overall plant productivity distribution allows us to shed new light on how productivity growth evolved during this important period.[4] In particular, we isolate and track the productivity distribution of newly created adopting plants in cotton spinning. This goes beyond previous work (including with modern data), where major new technologies are typically introduced by existing producers, so that the changes in the productivity distribution reflect both the productivity differential of the new technology and subsequent gains due to organizational improvements. We are also the first to show that the extensive margin of plant entry and exit contributed decisively to productivity growth during the Industrial Revolution. Finally, we complement a rich historical literature by providing the first systematic empirical evidence for the importance of organizational innovations in driving productivity growth during the Industrial Revolution (Pollard 1965; Sokoloff 1984, 1986).

[3] Closely related, Clark (1987) studies cross-country differences in the productivity of mechanized cotton spinning, but only at the sectoral level. Braguinsky et al. (2015) study the Japanese cotton-spinning industry in the late nineteenth and early twentieth centuries. Rather than technology adoption, their paper focuses on the effects of acquisitions on acquired plants.

[4] In related work, Braguinsky et al. (2021) study how cotton firms grew by innovating vertically and horizontally in Japan's Meiji period in the late nineteenth and early twentieth centuries.

The paper is structured as follows. The next section discusses the historical context. Section III describes the data, while section IV presents and discusses our empirical results. Section V sheds light on the underlying mechanism, and section VI concludes.

II. Historical Background

In this section, we describe the key features of the historical setting. First, we discuss why mechanized cotton spinning and its adoption in France present a well-suited setting to examine the productivity effects of major technological breakthroughs. Second, we introduce the three sectors that we analyze in the paper. We first describe the process of mechanization in cotton spinning and discuss the reorganization of production that it entailed. Finally, we introduce our two comparison sectors. We summarize the most important aspects in the main text. Appendix A contains a more extensive discussion.

A. The Industrial Revolution in Britain and Its Spread to France

Early-nineteenth-century France presents an opportune setting for our study of technology adoption. First, the development of mechanized cotton spinning during this time period is widely seen as a macroinvention (or general purpose technology), whose effects on the economy were similar to the development of the steam engine, electrification, or the IT revolution.[5] Mechanized cotton spinning belongs in this category partly because its pathbreaking innovations enabled the subsequent mechanization in other branches of the textile industry, such as wool, linen, and silk (e.g., Jenkins 2003). Freeman and Louçã (2001) include innovations in the cotton textile industry among the first major wave of industrialization, with steam power and railways fueling the second wave and electrification the third. As Freeman and Louçã (2001, 156) put it, "many of the organizational as well as technical innovations in cotton were followed later by other branches of the textile industry and by manufacturing more generally." Similarly, Pollard (1965) and Mokyr (2016) emphasize that mechanization in cotton spinning was the birth of the modern factory system, which fundamentally altered the organization of production—first in this industry itself and later in manufacturing more broadly.

[5] Macroinventions, or general purpose technologies, are typically defined as generic products, processes, or organizational forms (Lipsey, Carlaw, and Bekar 2005) that generate spillovers across sectors and set in motion a whole stream of advances that result in large productivity improvements (Bresnahan and Trajtenberg 1995; Lipsey, Carlaw, and Bekar 2005; Allen 2009). See Dudley (2010) for a discussion.

Second, studying mechanized cotton spinning in France—a follower country—allows us to focus on technology adoption, as opposed to innovation. As is well known, the flagship inventions of the Industrial Revolution—most notably the spinning jenny and the coke-fired blast furnace—were developed in Britain. While England was the first country to industrialize, France was an early follower. The latest estimates for France find an acceleration in economic growth around 1800, well after growth in England took off (Ridolfi and Nuvolari 2021). During the initial phase of French industrialization, new technologies arrived from Britain (Mokyr 2021). The processes of innovation and adoption differed in the two countries. While Britain may have had a comparative advantage in developing commercially viable machines and mills due to its highly skilled workers (artisans, engineers, millwrights), France was arguably the world leader in science (Gillispie 2004), which may have facilitated technology adoption. Indeed, Nuvolari, Tortorici, and Vasta (2023) use patent data to show that France was able to effectively absorb key technologies from Britain in this period. However, the mere adoption of these technologies was only one step. Their integration in factory settings and efficient operation presented major challenges (Mokyr 2021). The tacit, noncodified aspect of British industrial know-how is important in this context, as it explains why the French needed to undertake costly experimentation to efficiently operate the technology. Appendix A.1 contains further details about the Industrial Revolution in France.

B. *Cotton Spinning: Mechanization and Reorganization of Production*

This section discusses the main historical features and challenges in the transition to mechanized cotton spinning. Appendices A.2 and A.3 provide further detail.

1. Development of Mechanized Spinning

Cotton textiles was the flagship industry of the first Industrial Revolution, contributing one-quarter of TFP (total factor productivity) growth in Britain during the period 1780–1860 (Crafts 1985). Cotton spinning is the process by which raw cotton fiber is twisted into yarn. Traditionally, this task was performed mostly by women in their homes, using a simple spinning wheel (see fig. A.1; figs. A.1–A.19 are available online). With this old technology, each spinner was able to spin only one thread of yarn at a time. The industry was rurally organized and generally centered around a local merchant-manufacturer who would supply spinners with the raw cotton, collect their output, take care of the marketing, and often also owned the spinning wheels (Huberman 1996).

The breakthrough "macroinventions" in spinning were forged in Britain in the 1760s and 1770s, when three new vintages of machinery (the spinning jenny, the water frame, and the mule) were developed in quick succession. The left-hand panel in figure A.2 depicts the mule; Allen (2009) provides an in-depth discussion of each vintage. These new machines made it possible to spin multiple threads simultaneously, as twist was imparted to the fiber not by using the workers' hands but rather by using spindles. These innovations required production to move from workers' homes to the factory floor for two reasons. First, the machines almost always used inanimate power sources (typically water power), which led to the concentration of production in one location. Second, mechanized production increased the need for monitoring workers because of the complementarity of their tasks, but also because the machinery with which they worked was both more complex and more expensive (Williamson 1980; Geraghty 2007; Mokyr 2010).

The productivity effect of these innovations was enormous. Allen (2009) estimates that the first vintage of the spinning jenny alone led to a threefold improvement in labor productivity. Correspondingly, the price of yarn declined rapidly in the late eighteenth century (see fig. A.3), especially for the highest-quality yarn, where prices declined from 1,091 pence per pound to 76 pence per pound in real terms between 1785 and 1800 (Harley 1998).

During the early decades of the nineteenth century, the mechanized cotton-spinning industry was characterized by a steady stream of microinventions (Allen 2009, 206). Importantly, the next major innovation, the self-acting mule (a completely new vintage of spinning machinery), did not spread widely until the 1840s, that is, until after our sample period (Huberman 1996). Thus, there was no major technology switching during our period of study, but rather a steady stream of inventions that improved existing vintages.

2. Adoption of Mechanized Spinning in France

Mechanized spinning was adopted with some lag in France. Efforts to adopt the technology had begun with state support during the *ancien régime*. By the time of our first cotton-spinning survey in 1806, the large-scale expansion of the industry documented in Juhász (2018) had just begun. The existence of the technology was known throughout the country (Horn 2006), and a number of domestic spinning-machine makers had been established (Chassagne 1991). The spinning machinery itself was produced locally (using British blueprints) because of a ban on exporting machinery (and the emigration of engineers and skilled workers) from Britain until 1843 (Saxonhouse and Wright 2004). All three vintages (the spinning jenny, the water frame, and the mule) were used in France.

Importantly, when widespread adoption in France began, the technology—and in particular its optimal organization—was far from being mature in Britain. Thus, while France was a follower country, it could not copy a "mature" technology, as we discuss in more detail below.

3. The Challenging Transition to Factory-Based Production in Cotton Spinning

The transition of workers from their homes to the factory floor has been characterized as "one of the most dramatic sea changes in economic history" (Mokyr 2010, 339). It fundamentally altered people's lives and, importantly for our setting, posed a host of challenges for the first generation of large-scale factories.

In the case of cotton spinning, adopting the first generation of mechanized spinning machinery went hand in hand with the need to organize production in plants rather than homes. While cotton spinning was not the first sector to organize production in plants, the industry faced challenges for which a standard set of solutions did not exist at the time. Partly, this was because the knowledge required was largely technical and hence industry specific (Pollard 1965, 158). In addition, mechanized cotton-spinning mills pioneered flow production—that is, the production of standardized goods in huge quantities at low unit costs by "arranging machines and equipment in line sequence to process goods continuously through a sequence of specialized operations" (Chapman 1974, 470). This led to a finer division of labor and larger-scale plants than had been seen before in other sectors, raising novel challenges (Chapman 1974).

Flow production meant that machines and equipment had to be spatially organized and coordinated such that the "continuous (twenty-four hours a day) synchronisation of a sequence of highly specialised machines" (Chapman 1974, 472) could be achieved. This organizational innovation, pioneered in cotton spinning, distinguishes "proto-factories" from the "factory proper" (Chapman 1974; Markus 2013). Under the former, older, system, "several batch processes are centralised into a large unit with a systematic grouping of machines, with or without water power, without linked semi-automatic processes" (Markus 2013, 262). In the factory proper, "power and automatic machinery are organised for flow production in 24-hour operation. Water or steam power is a necessary but not sufficient defining feature" (Markus 2013, 262).

Mechanized cotton-spinning firms needed to resolve a range of issues related to mill layout and design. Allen (2009, 202) discusses some of the key challenges in developing the first mills in Britain: "design issues emerged regarding the spatial location of the various machines, the flow of materials from one to the next, and the provision of power throughout a multi-story building." It is useful to highlight three complementary aspects of mill design challenges that spinners faced. First, as we have seen, flow production meant that the production line had to be synchronized so that the layout (i.e., the floor plan) of the building became important. For example, factories needed to be sufficiently wide for a mule operative to work two mules alternately, which were placed back to back in pairs (see Markus 2013, 265; also illustrated on the right-hand side of fig. A.2). Second, flow production relied on the mechanization of each step of the production process (Chapman 1974), which meant that power had to be continuously distributed throughout the building. In Britain, Chapman (1970, 239) claims that there were only a handful of millwrights, qualified from experience, capable of undertaking the construction of the gearing for the new cotton mills. Third, a mechanized production line at this scale introduced a host of structural challenges. For example, building structures had to withstand the stress they faced from the vibrations of machines (Chassagne 1991, 435). Iron rods with plates held beams to the masonry walls to prevent the vibrations of machines from shaking the walls apart (Langenbach 2013). Similarly, buildings had to be well lit, which created design challenges to let as much daylight as possible reach the spindles, and it implied massive fire hazards when gas lights were used, due to the highly inflammable cotton dust (Markus 2013).

These were novel, complementary challenges for which a standard set of solutions did not exist at the time. The industry experimented through a process of trial and error. Successful mill designs in England were observed and copied (Chapman 1970, 239). It took time for design defects to be improved; for example, contemporaries were aware of ventilation problems in the Arkwright-style mills but continued to use the same layout regardless (Fitton and Wadsworth 1958, 98). Appendix A.3 provides further detail on the process of trial and error in developing solutions to building design challenges.

In addition to design-related organizational challenges, a large set of management innovations were required to run spinning mills efficiently. In *The Genesis of Modern Management*, Pollard (1965, 160) described the development of efficient labor management practices as the primary management challenge facing early factories. There were three salient aspects of this for cotton-spinning mills: (i) how to get workers who were used to the independence of the domestic system to adapt to the rhythm and hierarchy of factory work, (ii) how to coordinate and implement a fine division of labor, and (iii) how to solve monitoring problems. Appendix A.3 discusses these challenges in more detail. Here, we give one illustrative example.

Remuneration in the preindustrial home spinning system was characterized by piece rates. This made sense, given that the merchant had no way to monitor worker effort. The move to continuous-flow production made piece rates unworkable. The speed of production was controlled by the entire production line, not individual workers. This is illustrated by Karl Marx, who quoted a large cotton manufacturer, Henry Ashworth, “When a laborer lays down his spade, he renders useless for that period, a capital worth eighteen pence. When one of our people leaves the mill he renders useless a capital that cost *£100,000*” (Clark 1994, 129). Piece rates became impractical because the teamwork inherent to flow production made it difficult to determine the contribution of individual workers (Mokyr 2016, 344). The alternative, a time wage, raised incentive issues because monitoring individual worker effort was difficult in cotton mills (Huberman 1996). The solution was not obvious, and it was context specific. In cotton mills, employers experimented with a variety of techniques: some paid the entire team (which in turn created issues with the internal distribution within teams); other early factories solved the team production issue by hiring entire families as a work unit and paying them a piece rate (Mokyr 2016). Huberman (1996) estimates that it took two generations for efficient labor management practices to be developed in cotton spinning. Finally, around 1830, the industry in Britain settled on efficiency wages (Huberman 1996).

The first generation of mechanized cotton spinners faced these complementary design and management challenges all at once. Not only did best-practice solutions emerge slowly, but it also took time for this new body of knowledge to coalesce. According to Pollard (1965), the process was more or less complete around 1830 in Britain: “a cotton mill was so closely circumscribed by its standard machinery, and there was so much less scope for individual design, skill or new solutions to new problems, by 1830, at least, . . . that little originality in internal layout was required from any but a handful of leaders” (Pollard 1965, 90).

4. Knowledge Diffusion in Mechanized Cotton Spinning

How did the first generation of mechanized cotton spinners learn the solution to these organizational challenges? Given our discussion above, it is unlikely that there were important spillovers from home spinning to mechanized plants. The sharp break in organizational form under the new technology rendered experience with the old technology effectively useless. Chassagne (1991, 274) presents suggestive evidence to support this assertion: According to data on owners of 148 mechanized cotton-spinning establishments between 1785 and 1815 in France, “traders, bankers and commercial employees” accounted for the vast majority (62.5%) of entrepreneurs. While these figures have to be interpreted with caution (they probably oversample larger, better-known plants), they point to the importance of commercial knowledge, as opposed to previous experience with hand-spinning, in setting up cotton-spinning factories. This suggests that productivity under the old technology and that under the new were not systematically related.

Knowledge spillovers across sectors are also unlikely to have played an important role. As we discussed above, mechanized cotton spinners had to contend with new challenges that had not been encountered in other sectors, even those that were organized as “protofactories” in 1800. For example, André (1996) notes that there were no standardized mill designs in paper milling (one of our comparison sectors)—arguably because it did not feature flow production, making it less crucial that all production steps were efficiently integrated. Moreover, much knowledge was highly industry specific (Pollard 1965). Again, Chassagne (1991) presents suggestive evidence to support this pattern. Only 10% of early cotton spinners in his sample had a background in another industry—of these, most came from cotton printing, a relatively close industry, and almost none came from other sectors whose production was organized in plants (Chassagne 1991, 274).

For French cotton spinners, the most important source of knowledge about plant design and organization was Britain. However, spillovers from Britain were limited for a number of reasons: It was not until the 1830s that the British began to codify best practice in manuals (Pollard 1965), and even that was limited because a lot of the industry’s knowledge was tacit (Mokyr 2001, 2010). In addition, there were British bans on knowledge transfer (Chassagne 1991; Horn 2006). Finally, the best practice that the British industry eventually converged to was not necessarily applicable to plants in France, as local conditions were different. For example, the abundance of water power meant that French spinners mostly relied on hydropower throughout our sample period, in contrast to the British reliance on steam power (Cameron 1985). Chassagne (1991) notes that the French solution eventually developed for mitigating fire hazards in cotton mills was to build factories with fewer floors. This may have been possible in France, as water power allowed the industry to remain more rural than was the case in Britain, where the industry moved into dense, urban environments.

When knowledge about plant design diffused, this often occurred in spatial proximity. For both Britain and France, the historical record is full of examples of knowledge diffusion embodied in engineers and other skilled workers, who were hired by local entrepreneurs to design and build plants (Chapman 1970; Chassagne 1991). For example, English engineers were recruited in Toulouse (circumventing legal bans) to build a cotton-spinning plant. Once they had finished, a number of them were hired by other local entrepreneurs, and some set up their own mills nearby (Chassagne 1991, 243–44). Additionally, the French (local and central) government often incentivized the diffusion of knowledge. Horn (2006, 83–84) describes how the Bureau of Encouragement at Amiens (in Picardy) provided capital for an English machine builder to install machines for one French plant. In exchange, the firm had to commit to sharing "their techniques and technical know-how" with other firms. Other entrepreneurs in Picardy came to the plant in Amiens to study their machines and processes. The technology transfer that took place was not passive. Local workers tinkered with the machines installed by the English and improved on their designs in various ways, adapting them to local needs (Horn 2006).

C. Comparison Sectors: Metallurgy and Paper Milling

We have highlighted the challenges in reorganizing production in mechanized cotton spinning. To distinguish these from other, broader, trends at the time, we examine two sectors that did not need to reorganize production during this period—our "comparison sectors." We summarize the most important characteristics of these industries for our purposes below. Appendix A.4 contains a more detailed discussion.

Metallurgy, the sector that supplied iron and steel to the rest of the economy, was a flagship industry of the Industrial Revolution. Paper milling—while not particularly important for other sectors—also underwent mechanization, which renders it a useful comparison sector. Despite the obvious differences in the production processes, metallurgy and paper milling share an important characteristic that differentiates them from mechanized cotton spinning.

1. Difference with Cotton Spinning: Plant Production before 1800

Both metallurgy and paper milling had already organized production in plants well before the Industrial Revolution. In metallurgy, plant production was mostly due to a reliance on high-fixed-cost machinery, such as the furnaces used in both smelting and refining. In paper milling, production was organized in plants because of a reliance on water power. The early start to plant-based production meant that these sectors had already accumulated industry-specific expertise in building design and labor management. Thus, both comparison sectors fit well the characterization of "protofactories" described above. Appendix A.5 uses *Encyclopédie* plates to show that best-practice methods and codified knowledge already existed for the two comparison sectors in the late eighteenth century. These plates illustrate crafts, processes, and inventions, thus representing a unique source of information to study the existence of codified manufacturing knowledge at the time. As André (1996, 21) writes about the entries referring to paper milling, "The classic reference for technical descriptions of paper milling is Diderot and D'Alambert's famous 18th century *Grande Encyclopédie*. . . . [Here], one will find the different practices, with the terminology used in different provinces." For metallurgy and paper milling, there were many *Encyclopédie* plates illustrating information on plant organization and production technology, while there are no such plates for mechanized cotton spinning (fig. A.9). Note that the absence of plates on mechanized cotton spinning is not surprising, since this technology had just been invented; the most important takeaway from these data is that codified knowledge was indeed available for our two comparison sectors in the late eighteenth century.

2. Similarities between the Comparison Sectors and Mechanized Cotton Spinning

Once cotton spinning had mechanized and shifted to plant production, the subsequent development shares important similarities with the comparison sectors. All three experienced a steady flow of productivity-enhancing "microinventions" over our sample period, and in all cases, these were integrated into existing plants. In each sector, workers needed to be retrained to work with the new equipment (Gille 1968; André 1996; Horn 2006). However, there was no need to reorganize production, as the plant setup was not affected.

The source country of the technology in each case was Britain. Thus, similar barriers to diffusion applied to all sectors, and machines were typically built in France because of the ban on exports from Britain. Appendix A.6 presents patenting data from Britain, showing that all three sectors witnessed the consistent arrival of patents during our sample period. Spinning was the third-most patent intensive out of the 146 categories; metallurgy ranked ninth and paper milling twenty-first. It should be noted that spinning patents include those for all textile fibers, so that patent intensity in cotton spinning was actually closer to those in the comparison sectors.

In what follows, we briefly discuss the most important innovations in the comparison sectors, showing that they were integrated into the existing plant settings. In paper milling, the main technological innovation was the mechanization of forming paper with the Fourdrinier machine (one step in the production process). This invention still forms the basis of paper making today. Changes in the factory layout were not required to introduce the Fourdrinier machine (see figs. A.6 and A.7). It was thus uncommon to establish new plants for the sole purpose of mechanization. Modifications and enlargements of existing plants were often undertaken without having to substantially modify other parts of the production process, and—in contrast to flow production in cotton milling—different parts of the paper-milling process could be hosted in different buildings. For example, when plants adopted the Fourdrinier machine, they typically merely reconstructed the two sections hosting the cylinders and the machine while reusing the buildings previously devoted to the other operations (André 1996, 178). Similarly, while workers had to be trained to operate the new technologies, there is little surviving record of substantial labor conflicts or management challenges (André 1996, 246).

Metallurgy in France also witnessed technology adoption in existing plants (Gille 1968), suggesting that major reorganization of production was not necessary. The most prominent innovation was the switch from charcoal to coal. Given that the new equipment itself was similar to the older (Pollard 1965), its introduction merely required modification or replacement of existing machines and ovens (see figs. A.4 and A.5). The main reason for setting up new plants was not technological but to locate closer to coal sources.

In summary, the three industries share important similarities in adopting new technologies during our sample period. However, the need to reorganize production, and the introduction of flow production, was unique to cotton spinning.

III. Data

Our analysis is based on a novel, plant-level dataset for the initial phase of industrialization in France. The data have a panel-like structure covering three industries: mechanized cotton spinning, metallurgy, and paper milling. We observe plants in these sectors at two points in time: around 1800 and around 1840. We construct the dataset from four main sources, which we describe below. We also discuss the construction of the main variables in our analysis: plant-level labor productivity, plant location, and plant survival for all sectors. Appendix B contains further information on data sources and processing.

A. Plant-Level Industrial Surveys

Detailed, plant-level industrial surveys form the basis of our dataset. We build on large-scale data collections by the French state over the period 1789–1815. France's innovations in data gathering during this period are frequently praised as the basis of modern statistical data collection (Perrot and Woolf 1984). We use data from three industry-specific surveys conducted around 1800 and link these to the first manufacturing census in France, 1839–47.

The survey for paper milling was implemented in 1794, during the French Revolution; it contains data on 520 plants. The most important survey for our analysis—mechanized cotton spinning—was conducted by the Napoleonic regime in 1806, covering 340 plants. The survey for metallurgy in 1811 covers 470 plants. Finally, the first manufacturing census in France was initiated in 1839, and the results were published in

1847. While this census covers all manufacturing establishments, we use only data for cotton spinning (528 plants), metallurgy (896 plants), and paper milling (347 plants). For simplicity, we use "1800" throughout the paper to refer to the period of the three early surveys, and "1840" to refer to the later manufacturing census.

The quality of our data sources is high. Each has been scrutinized by economic historians (Chassagne 1976; Woronoff 1984; Bonin and Langlois 1987; Chanut et al. 2000), allowing us to understand their strengths as well as their limitations. The three industrial surveys and the first industrial census were conducted in a similar way. The central government sent detailed, standardized questionnaires to local government officials (usually prefects at the *département* level). The officials and their subordinates (subprefects and mayors) were tasked with identifying and enumerating the relevant plants in their jurisdiction. Plants themselves typically submitted the requested information to local officials, who were also tasked with validating that the submitted records were correct (Ministère de l'Agriculture et du Commerce 1847, xviii). In all cases, the motivation for collecting the data was to gather statistical information, as opposed to tax collection.

The fact that the surveys were carried out by local officials contributed to the high data quality, as they were able to cross-check the responses against other sources and use expert guidance (Perrot and Woolf 1984, 161).[6] Furthermore, France had experience in conducting industrial surveys dating back to the *ancien régime*. Thus, in many cases officials merely needed to update existing knowledge, as opposed to starting from scratch (Ministère de l'Agriculture et du Commerce 1847; Chassagne 1976). For all surveys, the geographic coverage is close to complete, with only a handful of *départements* failing to submit returns. These surveys have been characterized as a true administrative feat of the French government (Chassagne 1976, 350).[7] Figure A.14 shows the spatial distribution of plants around 1800 and in 1840 for the three industries. Although plants are more concentrated in some regions than others, we have broad coverage across all of modern-day France. For the three industry-specific

[6] For example, Perrot (1977, 161) writes, "Woronoff has demonstrated the high level of reliability of the statistics on mines and forges, where the visitations by engineers corresponded to the sophisticated elaboration of questionnaires calculated to trap forge owners into revealing accurate figures."

[7] In particular, Chassagne (1976, 350–51) describes the mechanized cotton survey as follows: "the survey obviously testifies first of all to the efficiency of the prefectural system. Of the 109 prefects questioned, 107 responded. . . . This represents a real administrative performance, since none of the prefects had the information immediately available to respond to requests from the central administration. The realization of this work certainly made it possible, at all levels of the administrative hierarchy, to appreciate the competence and to stimulate the zeal of the civil servants, who were always candidates for a promotion."

surveys from the 1800s, the data that have survived are the handwritten returns submitted by the *département* and are located in the National Archives (*Archives nationales*) in Paris. These are at the plant level in all cases but were not cleaned or harmonized by the central authorities in any way at the time. We use the data assembled by Juhász (2018) for the mechanized cotton-spinning industry. For the other two sectors, we collected, digitized, cleaned, and harmonized the handwritten surveys. For the manufacturing census from 1840, the data were cleaned, harmonized, and organized centrally. The results were published by the Ministry of Agriculture and Commerce in four volumes in 1847 (*Statistique de la France: industrie*). These volumes served as the raw data for the digitization undertaken by Chanut et al. (2000). We use the latter source for our analysis.

Appendix B describes the specific context for each individual survey and assesses their quality along a number of dimensions. A limitation of our overall setup arises from the different years in which the initial surveys were carried out across the three sectors (1794, 1806, and 1811). This may present a challenge if the economic environment changed over this period. We confront this issue by examining the robustness of our results to some of the most important shocks in this period (in particular, the Napoleonic Blockade and the Napoleonic Wars).

B. Main Data Construction Steps

In what follows, we discuss the most important steps in the construction of our dataset.

1. Estimating Labor Productivity

Our main variable of interest is plant-level labor productivity, defined as log revenues per worker. We use this measure in our baseline estimates because it can be constructed for all sectors and in both time periods. For mechanized cotton spinning, we can also construct plant-level TFP. We face two challenges in constructing consistent productivity measures across plants and time. First, while the surveys for the three sectors around 1800 report output quantity (and some information on product-specific prices and quality), the census in 1840 reports plant-specific revenues (but not output quantities). To render productivity measures comparable over time, we have to construct revenues for 1800. Second, worker categories are not consistently reported across all plants in 1800 in metallurgy and paper milling. We describe how we deal with each of these issues below.

2. Estimating Plant Revenues in 1800

In cotton spinning, the 1806 survey reports the quantity of yarn spun as well as the minimum and maximum count of yarn spun—where the count of yarn is the standardized measure of quality in the sector.[8] We construct plant-level revenue by multiplying the quantity of plant-level output by the price of the average quality of yarn produced by the plant. We use a schedule of prices for different counts of yarn reported by the French government (*Archives nationales*, F12/533). In practice, the adjustment in price for the different qualities produced is not crucial for our results (which we confirm with a battery of robustness checks). The reason for this is that the quality produced by the majority of plants is fairly similar. The interquartile range (25th–75th percentile) for the average quality of yarn produced by the plants in our sample is 20–47.5. That is, most plants produced relatively low-quality cotton yarn in this period (high-count yarns typically start around 100). This is consistent with the British experience (Harley 1998).

In metallurgy, the 1811 survey asked for the quantity of output produced (by product, e.g., pig iron and natural steel), as well as the price charged by the plant, by product type. While product-specific output quantity is reported by all plants, the product-specific price is reported by only a subset of plants. We compute the average price for each product using the subset of plants where the price information is available. We obtain plant revenues by multiplying product-specific plant output by the average price for the respective product and summing across products of a given plant.

In paper milling, the 1794 survey reports the total quantity of paper products produced, but it does not provide plant-specific output prices. To construct revenues, we multiply plants' output quantity with the average price of paper products as reported in the *Tableaux du maximum*—a data source compiled in 1794, during the French Revolution, that provides detailed data on goods prices and trade links across French regions.

Finally, to compare revenues in the earlier periods and in 1840, for all three sectors, we deflate revenue data using the wholesale price index for the respective survey years from Mitchell (2003). We note in passing that potential errors in the deflators would affect our estimates for average growth rates in the three sectors between 1800 and 1840, but they would not change the growth patterns over the plant distribution (e.g., the lower-tail bias in cotton spinning).

3. Constructing Consistent Labor Variables

Next, we describe how we harmonize labor input in our two comparison sectors. In cotton spinning, we observe the total number of workers, so that no adjustment need be made.

[8] We use the (unweighted) average of the minimum and maximum counts of the yarn produced by the plant as a proxy for its average output quality. The maximum and minimum counts are the only information that plants provided on the quality of yarn that they produced.

In metallurgy, about 40% of the plants reported either "internal" labor only or both "internal" and "external" labor separately. The remainder of plants reported only total labor, with no indication of whether this includes external labor.[9] To construct a consistent measure of labor input, we estimate the size of the internal labor force for the 60% of plants that reported only total labor. We use a matching procedure based on plant characteristics that is described in appendix B.2. We also show below that our empirical results for metallurgy hold when we restrict the 1811 data to the 40% of plants with direct information on internal labor.

In paper milling, many plants reported only male labor in 1794, while the 1840 survey reports both male and total labor. In order to compare output per worker consistently, we need to impute total employment in 1794. We scale male labor in 1794 by the average proportion of total employees to male employees in 1840.[10] We show that our results are robust to using only male employees in both periods.

4. Distinguishing Plants from Home Production in Cotton Spinning

Mechanized spinning was operated in centralized locations (plants), while the old technology relied on home production. We can thus identify the users of the new technology (i.e., all plants observed in our data). Consequently, we are able to isolate the productivity distribution for plants that used the new, mechanized technology under the new organizational form.

5. Plant Linking and Plant Survival

We link plants across the two sample periods within communes on the basis of two metrics: (i) the plant had the same (or very similar) owner name in both periods, and (ii) there was only one plant in the respective sector in the commune in 1800 and at least one plant in the same sector in 1840. In what follows, we describe each step of this process and the assumptions it entails.

[9] Woronoff (1984, 138) describes external labor as having only very loose ties to the plant. These workers did not typically work at the location of the plant, their work was not supervised by the manager, and their identity was often not even formally known to the manager. They performed tasks such as driving, collecting charcoal for the plant, or performing other jobs without belonging to the hierarchy or reporting to superiors in the chain of command. Thus, external workers were unlikely to be considered formal salaried employees of the plant in the 1840 census.

[10] The validity of this method hinges on the assumption that the ratio of total employment to male employment was constant over time. We are able to check this using the 18 plants in 1794 that reported both types of labor. We find a ratio of 2.11 in 1794, which is very similar to the ratio of 2.29 in 1840 (among all plants).

All three surveys from around 1800, as well as the 1840 census, report the name of the owner and the location of the plant up to the commune level, which is the lowest administrative unit in France. In bigger cities such as Paris, the *arrondissement* is also reported. We construct a consistent measure of plant location across surveys by assigning each plant to its modern-day commune, *département*, and region (as described in apps. B.1–B.4 for each survey in turn).

Linking plants.—We use two pieces of information to link plants over time. First, we match plants by their owner names in a given commune in the respective industry (see app. B.5 for detail on the implementation). Since the name of the owner may change even if the physical structure of the plant was the same, we also match by location in a second step. We match locations that had only one plant in the respective sector in 1800 and at least one plant active in the same sector in 1840. This turns out to be fairly common in the data. An obvious concern is whether this "local matching" indeed identifies the same plant. This is likely, given a fortuitous feature across all three of our industries: their reliance on water power. Only a small number of locations in a typical commune were suitable for setting up a water-powered mill, as rapid stream flow was needed to yield sufficient power. Moreover, the backwater created by one mill meant that another mill could not be located in close proximity. Consistent with this, Crafts and Wolf (2014) argue that agglomeration in the cotton textile industry was not observed until steam became the common source of power in Britain. Consequently, our "local matching" arguably identifies plants that had the same location within communes. Whether these were owned by the same entrepreneur (or their descendants) or whether they had passed on to a different owner is not crucial for our analysis.

Plant survival.—Our main measure of plant survival is based on the combination of matching by owner name and "local matching" that we described above. We define the survival rate as the percentage of plants from the initial period that survive into the later period. The numerator counts all plants that fulfill at least one of the following conditions: (i) the plant had the same owner in both periods, and (ii) there was only one plant in the respective sector in the location in the initial period and at least one plant in the same sector in 1840. The denominator is the sum of all plants in the given sector in the initial period. We provide a verification of this methodology in appendix B.5.

Note that our baseline measure of plant survival does not adjust for the fact that the number of plants located in communes that had only one plant varies across the three sectors in our sample.[11] Thus, we may

[11] Among the 520 plants in paper milling in 1794, 211 (40.6%) were the only plants active in their commune in this sector. For cotton spinning in 1806, the proportion is 25.6% (87 out of the 340 plants), and in metallurgy in 1811, it is 69% (324 out of 470 plants).

mechanically find higher survival rates in a sector where single-plant communes were relatively more frequent. To address this issue, we also construct the "restricted-sample" survival rate as a robustness check. This measure is based solely on single-plant locations. The numerator of the "restricted-sample" survival rate counts the number of communes that had only one plant in the respective sector in the initial period and at least one plant in 1840. The denominator is the set of all single-plant communes in 1800.

C. *Descriptive Statistics*

Tables A.2–A.4 (tables A.1–A.31 are available online) contain descriptive statistics for all variables used in the analysis. Several important features of the data stand out. First, the scale of plants (measured by the number of employees) is striking for cotton-spinning plants (see table A.2). The average spinning plant in 1806 had 64 employees. This is larger than in metallurgy and paper milling, where plants had on average 23 and 13 employees, respectively. Second, between 1806 and 1840, the mechanized cotton-spinning industry expanded substantially, and this expansion was accompanied by an increase in the number of plants active in the market (from 340 in 1806 to 528 in 1840). That is, for every plant that exited the market, more than one new plant entered. Consequently, the results we present below constitute more than a "shakeout" of unsuccessful plants.

IV. The Pattern of Productivity Growth

In this section, we study the evolution of the plant productivity distribution in mechanized cotton spinning after the new technology had been adopted. Similarly in spirit to a difference-in-differences strategy, we contrast the observed patterns with those in the two comparison sectors—metallurgy and paper milling. This allows us to distinguish the unique feature in mechanized cotton spinning—the need to reorganize production—from the common factors that affected productivity growth in all three sectors over our sample period.

A. *Average and Quantile Productivity Growth*

We begin by examining average annual labor productivity growth. Column 1 in table 1 shows that all three sectors experienced a significant increase in labor productivity between 1800 and 1840. This is consistent with the historical evidence that gradual innovations were incorporated in all three sectors during this time period. The largest productivity gains were achieved in cotton spinning (2.42% per year), followed by

TABLE 1
Annual Productivity Growth (%) at Different Quantiles of the Distribution

		At the Quantiles					
	Average (1)	.1 (2)	.25 (3)	.5 (4)	.75 (5)	.9 (6)	N (7)
Spinning (1806–40)	2.420***	3.917***	3.293***	2.234***	1.651***	1.014***	868
	(.154)	(.204)	(.229)	(.151)	(.167)	(.297)	
Metallurgy (1811–40)	2.328***	2.205***	2.068***	1.979***	2.285***	2.998***	1,366
	(.183)	(.530)	(.317)	(.247)	(.193)	(.232)	
Paper milling (1794–1840)	.719***	.697***	.717***	.846***	.691***	.542***	867
	(.111)	(.145)	(.139)	(.092)	(.130)	(.258)	

Note.—The table reports the average annual productivity growth between the initial sample period (around 1800) and 1840 for the three sectors (col. 1), and annual productivity growth estimated at different quantiles (cols. 2–6). Column 7 reports the number of observations. Robust standard errors are in parentheses.
*** $p < .01$.

metallurgy (2.33%) and paper milling (0.72%).[12] It is noteworthy that the large productivity increase in spinning reflects improvements within the mechanized technology.

In which part of the productivity distribution were these gains concentrated? Figure 1 plots the distribution of labor productivity in the three sectors at the beginning and end of our sample period, illustrating our main results. In cotton spinning, two features stand out. First, the initial dispersion in labor productivity was large in 1800 relative to that in 1840.[13] Second, the productivity gains are almost exclusively concentrated in the lower tail: the lower tail disappeared over our sample period, while increases in productivity at the upper tail were modest. In other words, productivity growth occurred largely as a result of the distribution shifting toward the productivity frontier. The contrast between cotton spinning and our two comparison sectors is striking. In metallurgy and paper milling,

[12] Given that we discount revenues using price indices, all our productivity calculations reflect price-adjusted, revenue-based productivity. To obtain the average annual growth rates between the two time periods, we first regress log output per worker, ln Prod, on a dummy for 1840 (separately for each sector, including the data from both time periods). This coefficient measures the percentage growth in output per worker over the entire time period between the respective survey years. We then annualize these values (and corresponding standard errors) by dividing by the number of years between the surveys in each sector. Note that this method delivers average annual growth figures, not accounting for compound growth. In cotton spinning, the overall growth over the period 1806–40 amounts to 82% (2.42% per year × 34 years). In metallurgy, it is 68% (2.33% per year × 29 years), and in paper milling it is 33% (0.72% per year × 46 years).

[13] The 90th–10th percentile productivity range (the difference in log output per worker between plants in the 90th and 10th percentiles) decreased from 2.17 to 1.17. Thus, in 1800, 90th percentile cotton-spinning plants were 8.7 times more productive than 10th-percentile plants, and this ratio fell to 3.2 in 1840. The latter is comparable to the average 90th–10th percentile productivity ratio within 4-digit US manufacturing sectors in 1977, where this factor was about 4 (Syverson 2004).

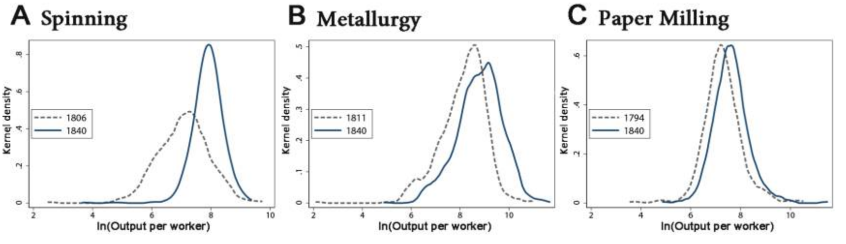

FIG. 1.—Changes in the productivity distributions in the three sectors. The figure shows the distribution of log(output per worker) for the three sectors at the beginning of our sample period (around 1800) and in 1840. Productivity growth in spinning was mainly due to a disappearing lower tail. In contrast, in metallurgy and paper milling, the whole distribution shifted to the right.

the entire productivity distribution shifted to the right between 1800 and 1840. Quantile regressions confirm this pattern. Columns 2–6 in table 1 report these results for the three sectors, estimating regressions for productivity growth at different quantiles of the productivity distribution. Figure 2 displays the corresponding coefficients. In cotton spinning, the bias toward productivity growth in the lower tail is marked. Productivity growth at the 25th percentile was twice as large as that at the 75th percentile (3.3% per year vs. 1.65%), and the rate at the 10th percentile was four times that at the 90th (3.9% and 1.0%, respectively). In the comparison sectors, productivity growth occurred relatively evenly across the distribution; if anything, growth was concentrated in the upper tail in metallurgy. These differences between cotton spinning and the comparison sectors constitute suggestive evidence that the aspect unique to mechanized spinning—the need to reorganize production—was associated with the lower-tail bias in productivity growth.

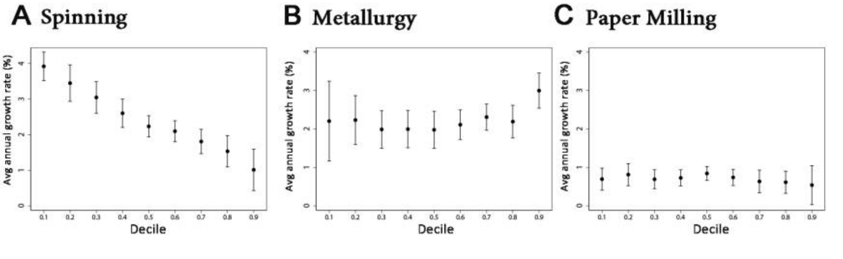

FIG. 2.—Productivity growth at different quantiles of the distribution. The figure visualizes the results of quantile regressions for growth in log(output per worker) for the three sectors, estimated at each decile. Productivity growth in spinning was concentrated in the lower tail of plant productivity. In contrast, in metallurgy and paper milling, productivity growth occurred relatively evenly across the distribution.

B. Robustness of the Lower-Tail Bias to Construction of Productivity

Before we examine mechanisms behind the lower-tail bias in productivity growth in cotton spinning, we document that it is robust to using alternative measures of productivity.

Output quality.—Could the different productivity growth pattern in cotton spinning be driven by differential trends in output quality? Recall that our data for cotton spinning in 1800 enable us to use quality-adjusted prices to compute revenues from output quantities. Panel B in table A.5 presents quantile regressions without quality adjustments in 1800, that is, using the same sector-level price across all plants in cotton spinning. The magnitude of the lower-tail bias is slightly smaller, but it still holds. Quality adjustment does not substantially alter the pattern of productivity growth because most plants produced yarn of a fairly similar (low) quality. The interquantile range for the quality of yarn produced in our data is 20–47.5; high-count yarns typically start around count 100 (Harley 1998). The low-quality output during the initial phase is consistent with the British experience (Harley 1998).

Markup heterogeneity.—In cotton spinning, our plant productivity measure in 1800 is computed from physical output (adjusted by quality-specific sector-level prices), while the 1840 values are based on revenues. The latter also reflect differences in markups across plants (Garcia-Marin and Voigtländer 2019). If more productive plants also charged higher markups (De Loecker and Warzynski 2012), the heterogeneity in markups would lead to a more dispersed productivity distribution in 1840. Thus, this data limitation—if quantitatively important—would work against our finding of a tightening productivity distribution.

Robustness to measuring productivity as TFP.—Our baseline productivity measure is log output per worker. For cotton spinning, we can also compute TFP, using data on physical capital (number of spindles)—see appendix E.1 for detail. Panel C in table A.5 confirms the lower-tail bias of productivity growth in cotton spinning using TFP.

Robustness to imputed variables in metallurgy and paper milling.—Appendix E.2 shows that our quantile regression results are robust to (i) using only those plants in 1800 in metallurgy with direct information on internal labor (table A.6, panel B); (ii) using the plant-product-specific prices for those metallurgy plants that reported them to construct productivity, while dropping the remaining metallurgy plants in 1800 (table A.6, panel C); and (iii) using only male labor in both periods in paper milling (table A.7).

V. Mechanism: Learning about Best Practice in Factory-Based Production

We have documented that the lower-tail bias of productivity growth was present only in cotton spinning. The historical evidence in section II suggests that the need to reorganize production was also unique to this sector. In what follows, we link these two features: the need for reorganization can explain the lower-tail bias. We first discuss a stylized framework that captures the key elements of the historical evidence. Then, we turn to examining the data for evidence compatible with the learning effects that reorganizing production entailed.

A. *A Stylized Framework*

We summarize the key features of our stylized model here; appendix D provides detail and shows simulation results. The model features heterogeneous plants, and we distinguish three phases: initial market entry, exit of particularly unproductive plants, and endogenous search for better technology among the surviving plants. To model the observed thick lower tail in the initial productivity distribution, we use a production function with multiple complementary inputs (tasks). We think of these as the organizational challenges discussed in section II.B, such as plant design, power supply, and management of workers. For each input, a plant receives a random efficiency draw, reflecting the plant's organizational knowledge.[14] Because of the strong complementarity across the inputs, even having one bad draw (say, inappropriate factory layout) substantially reduces overall efficiency. This gives rise to the thick lower tail in the initial productivity distribution.

Our model then features two mechanisms that lead to the disappearance of the lower tail over time. First, exit of the least productive firms eliminates the lowest part. This standard mechanism (e.g., Hopenhayn 1992) reflects the significant exit rates of cotton-spinning firms in the early mechanization period. Second, motivated by the historical evidence on the diffusion of organizational practices, we model a process à la Perla and Tonetti (2014) whereby relatively unproductive firms can search for and copy the organizational knowledge of more productive firms. Firms with productivity below an endogenously determined cutoff halt production and search for better organizational knowledge; they are matched to a randomly drawn firm among the higher-productivity firms that continue production. Searching firms thus forgo profits, but they expect higher profits in the future because of the improved organization of production. This process leads to the disappearance of the lower tail, while the productivity frontier remains unaffected.

Figure 3 illustrates the simulated productivity distributions over the three phases. The dashed line reflects the initial productivity distribution. In the first phase, firms with very low productivity draws exit. In the second

[14] Of course, these draws can also be interpreted as technology. Our model is agnostic about the distinction between technological and organizational knowledge. However, our historical accounts and empirical evidence suggest an important role for the latter.

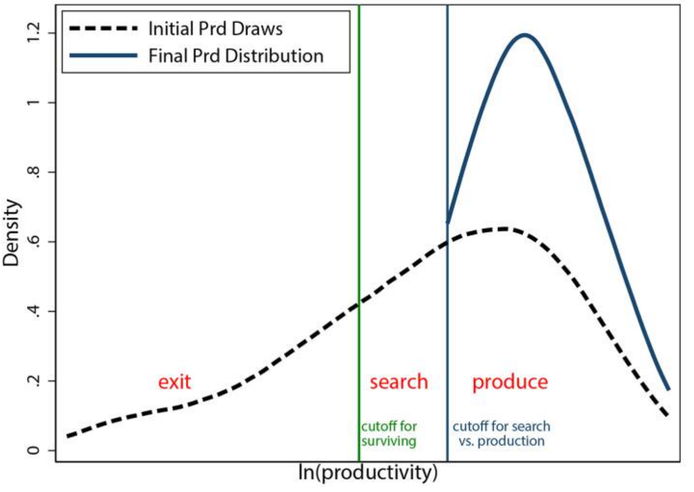

FIG. 3.—Productivity (Prd) dynamics in our stylized model. In the initial period, the least productive plants exit. Subsequently, in the innovation period, surviving plants decide whether to search for better organizational knowledge, forgoing production. The searching plants are randomly matched to continuing producers as in Perla and Tonetti (2014). In the final period, searching plants adopt the improved organizational knowledge from more productive producing plants. Thus, the lower tail of the productivity distribution disappears, and the mass shifts toward higher-productivity draws. At the same time, the productivity frontier remains unchanged.

phase, among the surviving firms, the relatively unproductive ones halt production and search for better organizational knowledge among the more productive firms, who continue to produce. This gives rise to the productivity distribution (solid line), where the initially fat lower tail has disappeared, while the productivity frontier (plants that already operate with high organizational efficiency) remains unchanged. This pattern of productivity growth mirrors the one for cotton spinning in the data (see fig. 1). Note also that the final productivity distribution resembles the one observed for our comparison sectors, where factory production had been adopted earlier, so that the process of exit and organizational learning had already occurred by 1800.[15]

While our stylized theoretical framework is not the only one that gives rise to lower-tail bias in productivity growth, it is a simple setup that represents the key features of the historical context. The empirical results

[15] Note that in order to replicate the right-shift of the whole productivity distribution over time in the comparison sectors, we would have to introduce productivity growth for all plants. In contrast, we do not need this additional feature to rationalize the dynamics in cotton spinning; i.e., learning from more productive plants is sufficient to deliver the observed lower-tail bias in productivity growth.

below provide evidence for these mechanisms, suggesting that the diffusion of organizational practices across plants was an important dimension in the observed productivity dynamics.

B. Learning about Reorganizing Production

In what follows, we shed light on what plants needed to learn to reorganize production efficiently, followed by how plants went about learning. Through the lens of our stylized framework, plants initially had a wide array of efficiency draws, reflecting the fact that they largely experimented with different solutions, rather than having standardized answers to the organizational challenges of factory production. Over time, less productive plants either exited the market or learned better organizational practices from their peers. We present evidence consistent with this initial experimentation and subsequent learning, using one central aspect in the move to factory-based production: optimal mill design.

1. Building Design

The historical literature highlights building design as the foremost challenge faced by French mechanized cotton spinners (Bonin and Langlois 1987). We are able to examine two aspects of mill design for a subset of 59 historical mechanized cotton-spinning plants, using data on their floor plans. The data are from Chassagne (1991).[16] For each plant, we observe the length and width of the plant building, as well as the number of floors. The historical evidence suggests that both dimensions were important: A building with many floors presented a fire hazard, which is why, over time, the French converged to buildings with fewer stories (Chassagne 1991). In addition, a more rectangular (less "square") building shape was more suitable for the optimal layout of machines (Markus 2013, 265–67).

In light of this, we examine the number of floors a building had, as well as its "squareness," defined as $S \equiv (\text{length} \times \text{width})/(\max\{\text{length}, \text{width}\})^2$. This measure of squareness is size invariant. That is, if buildings simply got bigger over time without changing their shape, our squareness measure would remain unchanged. In light of our model, we expect there to be an initially wide distribution of these dimensions, reflecting the dispersed initial draws. Over time, as plants learned about what worked, we expect

[16] Appendix E.3 contains a more detailed description of this source. It is important to note that the data are unlikely to be a representative sample, as records of larger, more important plants were more likely to survive. However, note that this bias would likely lead us to underestimate the extent of initial experimentation, as we arguably undersample less successful plants with less efficient organizational draws.

convergence to best-practice designs. Importantly, the data contain information on the year in which a plant was set up. We thus split the sample into an "early" experimental period (before 1820) and a "mature" period (after 1820). Of the 59 plants for which we have building dimensions, 58 have a date of foundation ranging between 1789 and 1845. Exactly one-half of these plants are assigned to each period.

Figure 4 plots the estimated kernel densities for the number of floors (*A*), and for building squareness (*B*). Consistent with our model and the historical evidence, there is wide variation along both dimensions in the early period. Buildings had anywhere from zero to seven stories above the ground floor and all sorts of shapes, ranging from a squareness measure of $S = 0.1$ (indicating very asymmetric width and length) to perfect squares ($S = 1$). Moreover, as the historical literature claims, over time, best practice converged to buildings with a moderate number of floors (around three) and a more rectangular shape ($S \approx 0.5$).

Was better building layout correlated with productivity? Appendix E.3 explores this question. Since the Chassagne (1991) data do not include the necessary information to compute plant productivity, we examine a proxy: plant survival until the 1840 census (which collected plant data in 1839–47). Table A.8 regresses a dummy for plant survival on each of the two dimensions of plant layout, allowing for a nonlinear relationship. We find a hump-shaped pattern. The estimated coefficients imply that the optimal number of floors was about 3.7, and the predicted optimal squareness was $S = 0.5$, which is close to what the industry converged to after 1820, according to figure 4. These results on building design support the historical account as well as the mechanism outlined in our

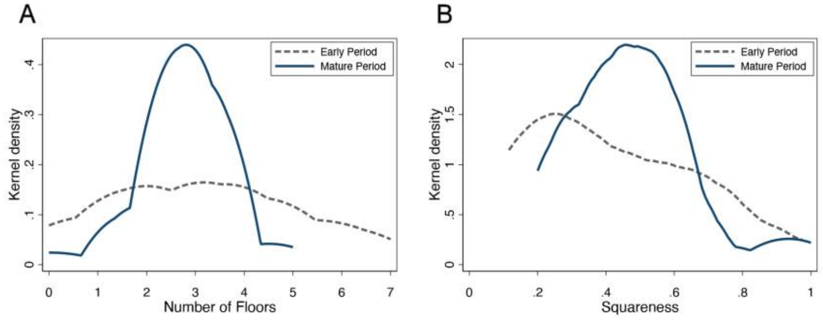

Fig. 4.—Experimentation and convergence in mill design for cotton-spinning plants. The figure shows the distributions of two important features of cotton mill design, in an "early" experimental period (before 1820) and a later "mature" period (after 1820): the number of floors in cotton mills (*A*) and "squareness," as defined in section V.B (*B*). Data on the length, width, and number of floors of 59 cotton plants are from Chassagne (1991).

stylized framework: cotton-spinning plants initially experimented with a wide range of organizational practices, and as the industry matured, they converged to best-practice designs.

2. Strikes

Another organizational challenge that the historical literature highlights is that firms needed to develop new labor management practices (see sec. II.B). While we do not observe historical management practices, we follow recent work that points to a proxy: Bianchi and Giorcelli (2022) show that firms that improved their labor management as a result of a training intervention saw a significant decline in worker complaints and strikes. Historical evidence from our sample period in France also links key labor management challenges in factory-based cotton spinning to strike activity. Through the 1820s and 1830s, there were several strike episodes in France where workers demanded payment as a time wage, as opposed to a piece rate, as well as a decrease in the length of working hours (Chassagne 1991). The former, in particular, is a key labor management challenge that we described in detail in section II.B. In stark contrast, André (1996, 246) notes that paper-milling firms' records do not mention similar conflicts with labor during the mechanization process.

On the basis of this historical evidence, we examine whether strikes were more frequent in textiles relative to our comparison sectors, which did not experience similar labor management challenges. Appendix E.4 provides suggestive evidence, using data on strike activity at the sector-*département* level. Table A.9 shows that the textile sector was subject to about 30% more frequent strike activity relative to the comparison sectors—metallurgy and paper milling. This holds conditional on controlling for employment at the sector-*département* level, total manufacturing employment (across all sectors), and *département* fixed effects. Of course, factors other than management challenges may also be responsible for the differential strike activity in cotton spinning. We thus interpret the evidence from strikes with caution and merely view it as complementary to the historical record in pointing to labor management challenges in mechanized cotton spinning.

C. Spatial Diffusion of Knowledge

In what follows, we shed light on how learning about organizational practices took place. The historical background discussed in section II showed that plants copied successful designs and setups of the production process from each other. To examine this channel, we estimate whether a plant's own productivity was higher in the proximity of other high-productivity plants. We use the following specification:

$$\ln \text{Prod}_{ij} = \beta_0 + \beta_1 \ln \text{Dist}_{ij}^{\text{p90}} + \text{FE}_j + \epsilon_{ij},$$

where $\ln \text{Prod}_{ij}$ is labor productivity (log output per worker) for plant i located in *département* j; $\ln \text{Dist}_{ij}^{\text{p90}}$ is log distance to the nearest plant (in the same sector) with productivity in the 90th percentile (in the distribution of all plants in the sector across France). Plants that are themselves in the top productivity decile are excluded from the sample to avoid introducing a mechanical relationship. All specifications include *département* fixed effects (FE_j) to absorb unobserved location characteristics that may make all plants in a given area more productive, irrespective of local spillovers. Thus, the coefficient of interest, β_1, reflects the extent to which plants in the same *département* benefit from being located closer to a high-productivity plant (which may be located in the same or another *département*). We interpret these correlations not as causal effects but as evidence that is compatible with spatial spillovers of knowledge. We estimate the specification separately for the three sectors and in both time periods. Standard errors are clustered at the *département* level to account for spatial correlation.

Before presenting the results, we first examine the spatial distribution of high-productivity plants across our sectors and time periods. Figure A.17 plots the spatial distribution of cotton-spinning, metallurgy, and paper-milling plants, distinguishing those in the 90th percentile of the productivity distribution. Unsurprisingly, some regions have a larger concentration of high-productivity plants than others. Because of our use of *département* fixed effects, these regional differences do not affect our results.

Figure 5 visualizes our baseline results, and table A.10 reports the corresponding regressions. To allow for direct comparability, we report standardized beta coefficients of $\ln \text{Dist}^{\text{p90}}$ for all three sectors in the two

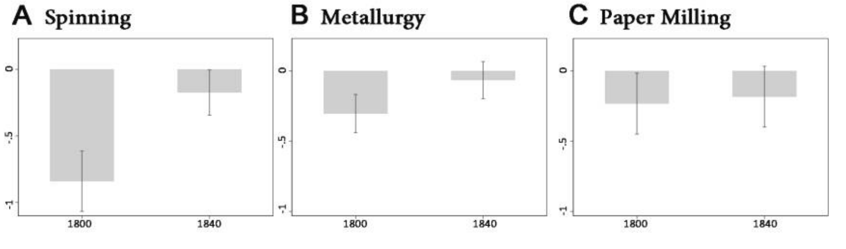

Fig. 5.—Proximity to high-productivity plants. The figure shows that proximity to high-productivity plants mattered the most in mechanized cotton spinning at the beginning of our sample period (around 1800), when the technology had just been introduced in France. The panels plot the standardized beta coefficients of $\ln \text{Dist}^{\text{p90}}$, which measures the log distance to the closest plant with productivity in the 90th percentile (in the same sector and in the same period—1800 and 1840, respectively). The dependent variable is log(output per worker). All regressions include *département* fixed effects (see table A.10). Whiskers indicate 90% confidence intervals.

periods. The estimated coefficient for cotton spinning in 1800 is negative, statistically significant, and large in magnitude. A 1-std (standard deviation) increase in distance to a high-productivity plant is associated with a 0.84-std decline in labor productivity. The pattern is much weaker in the two comparison sectors in 1800—the coefficients are less than one-third of that for cotton spinning. In addition, in 1840, all three sectors show at best a muted relationship: the distance coefficient for mechanized cotton spinning is reduced to less than one-fifth of its initial size, and it is only marginally statistically significant. In the comparison sectors, the coefficients of interest are also further reduced slightly, and they are no longer statistically distinguishable from zero. Thus, proximity to high-productivity plants mattered the most in cotton spinning in 1800, that is, in the period before knowledge about the optimal organization of production had spread widely. Distance mattered much less when organizational knowledge had diffused: in cotton spinning in 1840 and in the comparison sectors in both time periods. These findings are consistent with spatial learning during the early phase of mechanized cotton spinning.

Alternative explanations for the distance results.—In appendix E.5, we examine possible alternative explanations for the relationship between ln Dist^{p90} and productivity. While FE_j capture unobserved differences that vary at the *département* level, they cannot account for unobserved differences at a finer spatial level. To address this possibility, we implement several additional checks. First, we control directly for prominent location fundamentals at the commune level, such as the availability of fast-flowing streams (as a source of water power), proximity to coal (for steam power), and the share of forest cover (for access to charcoal—a major input in metallurgy). Table A.11 shows that our results are highly robust to these controls. Second, we check whether our results are affected by more general agglomeration externalities, as opposed to learning. In table A.12, we control for the density of production at the commune level (measured as the log of total output in the sector, excluding a plant's own output). Our results are essentially unaffected by adding this control. Third, table A.13 conducts a placebo exercise, showing that, in cotton spinning, plant productivity in 1800 was not related to the distance to high-productivity plants in 1840. This suggests that the large estimated coefficient in our baseline specification is not driven by persistent location fundamentals within *départements*. Fourth, we examine whether ex ante high-productivity plants may have selected into "productive locations" (i.e., chose to locate near existing high-productivity plants). Since we observe plant age in cotton spinning in 1806, we can examine selection patterns. Table A.14 shows that our result holds in a subsample of plants that entered before the nearest high-productivity plant, so that the timing of entry rules out the type of selection described above. Finally, we examine whether there is evidence for learning across sectors. Table A.15 shows that there is no consistent pattern in the data: mechanized cotton-spinning plants located closer to high-productivity metallurgy or paper-milling plants in 1800 were not more productive.

In summary, the consistently larger distance coefficient estimated in cotton spinning in 1806, in combination with a series of robustness checks, points to the spatial diffusion of knowledge as one mechanism through which learning across plants took place. The historical accounts of spatial learning in section II.B corroborate this interpretation.

D. *Plant Layout versus Technology: Evidence from Plant Survival and Age Profiles*

Which type of knowledge diffused across space? The results presented above cannot distinguish between the spatial diffusion of knowledge about the technology itself (e.g., how to operate and maintain the machines efficiently) and organizational knowledge (i.e., how to design mills and organize workers within the plant). We now present two patterns in the data that are more consistent with organizational learning.

1. Productivity Handicap of Exiting Plants

If an important component of learning in mechanized cotton spinning occurred along the organizational dimension of factory design, we would expect initially low plant survival rates relative to the other two sectors. Building design and layout are either sunk at the time of building or costly to change, implying that plants that got this wrong were likely to exit the market. On the other hand, inefficient operation of the new technology itself could be adjusted within an existing factory so that, if anything, we would expect incumbents to have an edge over new entrants. The data speak in favor of the former. We find substantially larger exit rates in cotton spinning relative to the other two sectors. Table 2 reports

TABLE 2
SURVIVAL RATES ACROSS SECTORS

Period	Spinning 1806–40	Metallurgy 1811–40	Paper Milling 1794–1840
Baseline sample:			
Survival rate (%)	5.0	37.7	10.8
Number of plants	340	470	520
Restricted sample:			
Survival rate (%)	12.6	52.5	24.6
Number of plants	87	324	211

NOTE.—“Survival rate” is defined as the percentage of plants from the initial period that survived to the later period, based on matching by either name or location (see sec. III.B). The restricted-sample survival rate uses the subset of plants located in communes that had only one plant in the initial period.

plant survival rates over our sample period, using the two measures defined in section III.B in each of the three sectors. On the basis of our baseline measure, survival rates in spinning (5%) were lower than those in paper milling (10.8%) and much lower than those in metallurgy (37.7%). Note that the actual difference in plant survival between spinning and paper milling was likely larger, because the survey for the latter was conducted in 1794, more than 10 years earlier than the cotton-spinning survey (1806).

The "restricted-sample" survival rates in table 2 allow a more direct look at the role of building layout and design in plant survival. By using only single-plant locations in the initial period, we are in effect testing whether a building used for production in a particular industry in 1800 continued to be used in the later period in the same industry (irrespective of who the owner was). The differences across the three sectors are even starker. By this measure, the survival rate is much lower in spinning (13%) than in the comparison sectors: 52.5% in metallurgy and 24.6% in paper milling (with the latter being an underestimate, as discussed above). The low survival rate observed in cotton spinning means that many locations lost their (only) cotton mill—owners who had invested in a mill with poor layout had to exit the market, and the structure of the mill was not subsequently used by other plants in cotton spinning.

Appendix E.6 provides further results on plant survival. We first explain that the differential survival rates are not driven by the shift from water to steam power (which occurred more slowly in France than in Britain). Next, table A.18 shows that exiting plants in mechanized cotton spinning were much less productive than those that survived. In the comparison sectors, the productivity handicap of exiting plants is also present, but less pronounced. In other words, early cotton plants that "got it wrong" were particularly unproductive, which can explain the fat productivity lower tail in this sector. These plants eventually exited the market, and for many of them, the same building was not used by another plant in the industry. This pattern is consistent with large organizational challenges and low initial guidance in switching to factory-based production in cotton spinning.

2. Age Profile of Plant Productivity

To further distinguish the role of best-practice organizational methods, as opposed to learning about technology, we now examine the age profile of plant productivity. For now, assume that spinning technology itself did not change over time (we relax this in the next subsection). Then, if learning how to use the (already installed) technology was the dominant dimension, we would expect older plants to have accumulated more experience and hence have a productivity advantage. On the other hand, if efficient organizational design of the plant was more important, younger plants had a larger pool of knowledge to draw from, as they set up their design later. This would render younger plants more productive than older plants that were locked into less efficient designs (see also our evidence on plant design in sec. V.B.1).

We exploit the richness of our data to test this in both 1800, when best-practice mill design was still evolving, and 1840, when, according to Pollard (1965), the industry had reached maturity—at least in Britain. The 1806 survey in cotton spinning contains the year of foundation of plants. This allows us to compute a dummy for "young" plants, defined as below median age (with the median age in 1806 being 3 years). Column 1 in table 3 shows that "young" plants were 58% more productive in 1806. This could be driven by mechanisms other than the one discussed above. For example, new entrants may have used the most recent vintage of capital, leading to higher physical productivity (Foster, Haltiwanger, and Syverson 2008). To address this issue, we control for several important plant characteristics in columns 2–6 of table 3. These include the capital intensity of the plant (measured as log spindles per worker), the number of workers in the plant, and the vintage of machinery (binary variables for the three

TABLE 3
COTTON SPINNING IN 1806: PRODUCTIVITY AND PLANTS' AGE PROFILE ($N = 340$)

	Dependent Variable: log(Output per Worker)					
	(1)	(2)	(3)	(4)	(5)	(6)
Young plant	.575***	.534***	.608***	.543***	.575***	.493***
	(.088)	(.085)	(.086)	(.083)	(.089)	(.085)
log(Spindles/worker)		.336***				
		(.070)				
log(Workers)			.107***			
			(.025)			
Spinning jenny				−.626***		
				(.087)		
Throstle					−.003	
					(.092)	
Mule jenny						.481***
						(.086)
R^2	.11	.17	.14	.20	.11	.18

NOTE.—The table shows that mechanized cotton-spinning plants that had just entered the market by 1806 had significantly higher productivity. "Young plant" is a dummy variable equal to 1 for cotton-spinning plants with below-median age (with the median age in 1806 being 3 years). The number of spindles is a standard measure of a spinning machine's production capacity, irrespective of vintage. "Spinning jenny," "throstle," and "mule jenny" are binary indicators equal to 1 for plants using the earliest (spinning jenny), intermediate (throstle, or water frame), and latest (mule jenny) vintage of spinning machinery, respectively. Robust standard errors are in parentheses.

*** $p < .01$.

main vintages of machinery, from oldest to newest).[17] The productivity advantage of "young" plants remains quantitatively very similar and statistically highly significant when we add these controls.

Appendix E.6 explores the "young"-plant productivity differential further. Table A.19 shows that in 1840, when the mechanized cotton-spinning technology had reached maturity, younger plants did not have a productivity advantage anymore. For comparison, we also examine the age-productivity pattern for metallurgy plants, where best-practice knowledge had already been established by 1800. Correspondingly, we find that younger metallurgy plants did not have a productivity advantage in either of the two periods (tables A.20 and A.21). In paper milling, data limitations prevent us from examining these patterns.

In summary, the evidence on productivity-age profiles is in line with best-practice organizational methods in cotton spinning spreading slowly over time and space, so that newly constructed plants were more productive around 1800. This advantage eroded when organizational knowledge diffused more broadly by 1840.

E. Robustness to Alternative Explanations

In the final part of this section, we consider additional alternative mechanisms that could also explain our results. We examine these along a number of dimensions.

Gradual innovation and capital mix: common patterns across all three sectors.—We observe the lower-tail bias in productivity growth only in cotton spinning and not in the other two sectors. For this reason, it is unlikely that factors that also affected the comparison sectors in similar ways can explain our findings. For example, the fact that mechanized spinning experienced innovations during our sample period seems unlikely to explain the lower-tail bias, as both comparison sectors also witnessed the introduction of new technologies. In a similar vein, improvements to power sources (notably water power, which remained the dominant source of power in cotton spinning) affected the other two sectors similarly (see also app. E.6). Finally, all three sectors used a mix of vintages of their core capital equipment, suggesting that the choice of capital itself is not a confounder. In fact, below, we show that the lower-tail bias of productivity growth remains intact if we remove all plants that used the earliest vintage of capital: the spinning jenny.[18]

[17] The three vintages of machinery are the spinning jenny (oldest), the water frame (throstle), and the mule jenny (newest). These are not mutually exclusive categories, as some plants used multiple vintages. Young plants tended to be more capital intensive, employ fewer workers, and use the newest vintage of spinning machinery.

[18] In this regard, the metallurgy sector is a helpful comparison, as we observe the use of different vintages of capital in 1811. Some plants used the so-called direct technology widely

Regional differences in productivity distributions.—It is important to highlight the robustness of our results to using only within-region variation (see app. E.7). Table A.22 shows that the lower-tail bias of productivity growth in mechanized cotton spinning remains intact if we add fixed effects for 22 French regions.[19] The lower-tail bias of productivity growth is somewhat muted but still striking. Productivity growth in cotton spinning is almost twice as high at the lowest as at the highest decile. The inclusion of region fixed effects absorbs the effect of different regional fundamentals, input markets, market access, and institutions. In what follows, we examine possible alternative mechanisms at a finer geographic level, that is, potentially even within regions.

Market integration.—Could increased market integration in cotton spinning explain our results? As the French economy became more integrated over time, it is possible that lower-productivity plants faced tougher competition and had to exit the market.[20] We address this concern in appendix E.8. We first use data on trade flows in 1794 from Daudin (2010) to show that market integration was initially higher in cotton yarn than in our comparison sectors—cotton yarn (and textiles more generally) are high–value-to-weight products, which made them more easily tradable over long distances than iron and steel or paper (fig. A.18). Given its higher starting point, if anything, we expect further market integration after 1800 to have been less pronounced in cotton spinning than in the comparison sectors. This renders it historically unlikely that differential (i.e., higher) growth of market integration in cotton yarn drives our results. We complement this argument by controlling for measures of market access (both within France and within Europe) as well as for access to overseas trade (table A.23). The coefficients of interest change only marginally, and the lower-tail bias of productivity growth in cotton spinning remains strong.

Napoleonic Blockade and Napoleonic Wars.—Juhász (2018) shows that temporarily higher trade protection from British competition shifted the location of the mechanized cotton-spinning industry within France. Since our results hold within regions, where the pattern of protection

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known in France as the Catalan forge, while others used the "indirect technology," which separates the production process into smelting and refining. The direct technology was gradually replaced by the indirect technology during our sample period (Pounds and Parker 1957). See app. A.4 for further discussion.

[19] Regions are larger than *départements*: there are 22 regions in France and 86 *départements*. Our data in the three sectors do not have sufficiently many observations to include *département* fixed effects, i.e., to estimate meaningful productivity distributions within *départements*. In contrast, our results on spatial diffusion (fig. 5) do include *département* fixed effects, because they examine the effect of proximity to high-productivity plants on the average productivity of plants, rather than on the full distribution.

[20] Market integration arguably increased during our sample period, both for policy reasons, such as the abolition of internal barriers to trade during the French Revolution (Daudin 2010), and because of infrastructure improvements that reduced transport costs, such as the introduction of railways in the late 1820s.

was very similar, it is unlikely that they are affected by the Napoleonic Blockade (1806–14). Figure A.19 presents further evidence that varying trade protection does not drive our results, by splitting the sample into plants in northern and southern regions in France (corresponding to the main dimension along which protection varied). The productivity distributions in the north and south are remarkably similar, and in both regions, productivity growth until 1840 was due to a disappearing lower tail. Appendix E.9 provides further evidence and shows that (i) the Napoleonic Blockade did not drive the differential plant survival in cotton spinning and (ii) conscription of soldiers and battles on French soil during the Napoleonic Wars (1803–15) are not associated with cotton-spinning plant productivity.

Early spinning workshops.—Another potential concern is that our results may be driven by the disappearance of small cotton-spinning plants (or "workshops"). Indeed, our data may include relatively small plants that operated early vintages of mechanized spinning jennies and did not necessarily need inanimate sources of power. This small-scale setup may have been inherently different from the larger-scale factories powered by inanimate power sources. While the move to factory-based production was swift, systematic differences of smaller mechanized cotton workshops could account for the lower-tail bias of productivity growth in this sector. Our data do not differentiate between these two types of plants, as we observe the capital vintage but not the power source in the 1806 survey. However, we can examine the extent to which our results may be driven by these forces.

In appendix E.10, we adopt a stricter definition of "factory production" and omit plants with fewer than 10 employees from all sector-year pairs. This should exclude the majority of the smaller workshops that may have been organized as factory-based production along some, but not all, dimensions. It also addresses the concern that smaller plants were undersampled in the 1840 manufacturing census (see app. B.4). Table A.27 shows that the lower-tail bias in productivity growth is robust to using only larger plants and that it remains unique to mechanized cotton spinning. In other words, small plants are not responsible for the fat lower tail in 1806. In addition, we implement an even more conservative definition of factory production. We drop the 76 plants from the 1806 survey that used the earliest vintage of machinery—the spinning jenny. These were the types of machines that could, in principle, have been operated also in small workshops without inanimate power sources. Table A.28 shows that the lower-tail bias of productivity growth remains striking. Thus, early spinning workshops that shared some, but not all, features of factory-based production do not confound our results.

Plant scale.—Appendix E.11 shows that it is unlikely that increasing plant size drives our results, as all sectors witnessed an increase in scale. In addition, as the results in table A.29 demonstrate, controlling for the number of workers (at the plant level, in all sectors, and in both periods) does not alter our findings.

Capital deepening.—Over time, spinning machines were equipped with more spindles, and hence less labor was needed to produce a unit of output. We address this in appendix E.12, where table A.30 shows that the lower-tail bias of productivity growth remains robust and similar in magnitude when we control for the capital-labor ratio at the plant level (measured as log spindles per employee).

Machine quality.—Machine production, and even maintenance, was typically in the hands of external regional suppliers (see app. A.2 under "Historical evidence about machinery producers"). Given that we find the lower-tail bias of productivity growth also within regions, it is unlikely that heterogeneity in machine quality was an important driver.

Output quality.—In section IV.B, we examined whether cotton output quality could account for our core result by affecting the computation of productivity. This is not the case—the lower-tail bias of productivity growth continues to hold even when we use output prices in 1806 that do not account for quality differences across plants (see panel B of table A.5). In appendix E.13, we provide one additional check. Output quality could still drive our results indirectly if it led to higher sales and thus larger plant size over time, leading to scale economies. To examine this possibility, we estimate the quantile regressions without adjusting for quality differences in prices across plants in 1806 but controlling for the number of workers. Table A.31 shows that the lower-tail bias of productivity growth continues to hold.

Age profile of plants.—The median age of plants in mechanized spinning in 1806 was strikingly small (3 years). This is consistent with historical accounts that the period witnessed the birth of mechanized spinning in France. Could it be that young plants are always more dispersed in terms of productivity and that this drives the fat lower tail? Our results in table 3 render this interpretation unlikely. We have shown that younger plants were substantially more productive than older ones. Thus, if anything, a predominance of younger plants would tend to lead to a thicker upper tail.

Altogether, the findings of this section show multiple pieces of evidence that point to an important role for reorganizing production in explaining the unique lower-tail bias of productivity growth in mechanized cotton spinning. While this is not the only possible explanation, we have shown that numerous prominent alternative mechanisms are incompatible with the data. Together with the corroborating historical evidence, this leaves organizational challenges in technology adoption as the most promising candidate to explain the observed patterns in the data.

VI. Conclusion

The unique setting examined in this paper allows us to shed new light on important open questions in the technology adoption literature. First, our findings speak directly to why the aggregate productivity effect of major technological breakthroughs, such as IT and electricity, may be hard to pin down in the data. As pointed out by David (1990), the full effects of a new technology may take significant time to materialize, as plants still need to learn how to organize production efficiently. In our context, adopting mechanized cotton spinning required producers to reorganize production from households to factories. Our results suggest that initially, many plants operated the new technology in combination with inefficient complementary organizational practices. This led to a widely dispersed productivity distribution and relatively low average productivity. Observers estimating the productivity effect of switching from hand-spinning to mechanized spinning would significantly underestimate the long-run aggregate productivity gain if they looked only at the initial data around 1800.

Second, our results also shed light on the slow adoption of major new technologies. When there is uncertainty about how to operate a new technology efficiently and the organizational knowledge—once acquired—is observable to competitors, plants face a strategic incentive to delay adoption. The high exit rates observed in cotton spinning relative to other sectors, alongside the higher productivity observed for younger plants in 1806, suggest that plants that entered later were at an advantage. If plants understood the significant uncertainty they faced when setting up a spinning mill at early stages of adoption, they had an incentive to delay the switch to the new technology in order to take advantage of the learning externalities generated by other early adopters.

In summary, our unique setting allows us to speak to a dimension of productivity growth that is usually hidden. Productivity differences across plants reflect both the underlying technology and the complementary organizational practices with which the respective technology is used. Both features play important roles in the decision to adopt new technologies: What are the potential productivity gains of a new technology (i.e., its frontier), and is the organizational knowledge needed to achieve these gains (i.e., operate at the frontier) readily available? Separating these features empirically is difficult because of data limitations. Our results suggest that the need to reorganize production is an important dimension of technology adoption. Approaching the frontier of a new technology via organizational improvements can take a long time, and it can explain some of the salient features in the adoption of major innovations.

Finally, our paper provides a first look at how the unprecedented growth in manufacturing productivity during the first Industrial Revolution played out at the plant level. We show that in mechanized cotton spinning—the flagship industry of the period—a substantial proportion of productivity growth materialized along the extensive margin of plant exit and entry. Our results suggest that throughout this process, organizational innovations (alongside the traditionally emphasized technological ones) were an important driver of productivity growth. Future research—building on the increasing availability of historical data—should examine whether these findings constitute a common feature of the structural transformation from agriculture to modern, factory-based manufacturing. Our paper lays the groundwork by using comparative historical analysis to deepen our understanding of why the diffusion of innovation is often a complex and slow process.

Data Availability

Code replicating the tables and figures in this article can be found in Juhász, Squicciarini, and Voigtländer (2024) in the Harvard Dataverse, https://doi.org/10.7910/DVN/EGWOPG.

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