# Skill Choice and Skill Complementarity in Eighteenth Century England*

This paper analyzes the effects of technological change on skill acquisition during the British Industrial Revolution. Based on a unique set of data on apprenticeships between 1710 and 1772, we show that both the number of apprentices and their share in the cohort of the fifteen year-olds- increased in response to inventions. The strongest response was in the highly skilled mechanical trades. These results suggest that technological change in this period was skill biased due to the expansion of the machinery sector they induced.

## Introduction

The effect of technological change on skill demand is a key issue for modern-day economists. Recent increases in wage inequality in the U.S. and elsewhere since the 1980s fostered the belief that technological change is inherently *skill-biased,* favoring skilled labor over unskilled labor by increasing its relative productivity and, therefore, its relative demand. Empirical studies have shown technology-skill complementarity to be prevalent in the US during the twentieth century (Goldin and Katz 1998; Autor, Katz, and Krueger 1999). At the same time, the classical economists typically viewed technological change as deskilling, replacing highly skilled artisans with physical capital, raw materials, and unskilled labor, in particular in the context of the British Industrial Revolution in the eighteenth century.[1] This view has become so deeply rooted, that new theories were constructed to account

[1] The de-skilling view has been attributed to Carl Marx by writers as Braverman (1974), and others. There is however, an ongoing discussion as to the right interpretation of Marx's writings in this topic. For later economists supporting this view see Goldin and Katz, 1998.

for the discontinuity in the impact of technological change in the twentieth century (e.g. Goldin and Katz, 1998; Ciccone, 1996; Acemoglu, 2002; O'Rourke, Rahman, and Taylor, 2013). It therefore appears that the historical record is ambiguous about the interactions between technology and skill demand.

The current paper provides evidence for skill biased technological change during the Industrial Revolution. It draws on a comprehensive data set from stamp tax records, which documents skill formation through apprenticeship throughout England between 1710 and 1772 and examines how the number of apprentices in different occupations responded to the pace and scope of invention.

We examine the effect of technological change during the eighteenth century, when English cotton manufacturing was in the beginning of its remarkable expansion and intense activity in the development of textile machinery and other inventions was taking place. This period can be compared with the pre-personal computer era, when considerable research and development activity was undertaken in the semiconductor industry, but the full impact of digital technology could not yet be felt. The first half of the eighteenth century has been relatively neglected in the Industrial Revolution literature mainly due to the enormous progress that followed. In the words of Edward Baines (1835): *"In a rapidly advancing country, the great things of one age are insignificant in the eyes of the succeeding age. Thus, the period of 1739, whose prosperity was so much vaunted, is now looked back upon as the mere feeble infancy of the cotton manufacture-a trickling rill, compared with the mighty river to which that manufacture has since swelled."*[2] Concentrating on this period however, enables us to identify the effects of technological change on human capital before the transition to large scale production in the factory based system when other factors come into play.

Our hypothesis is that the wide spread technological changes that were taking place in eighteenth century England, mainly in the textile industry, triggered an expansion in the development, production and maintenance of machinery and other new products and processes. This expansion increased the demand for skilled workers,

[2] Baines (1935), p. 109.

particularly in the highly skilled mechanical occupations.[3] As the intensity of this process--reflected by the number of inventions--grew, and, with the supply of workers fixed in the short run, the relative returns to these occupations (i.e. skill premium) rose. This subsequently affected parents' decisions regarding the occupation they desired for their children.[4] In addition, these technological changes also impacted the demand for skilled workers in other skilled occupations relevant to machinery production, however, as our results show, these impacts were much weaker.

To examine our hypothesis we regress the annual number of new apprentices on the number of inventions to proxy for technological change. In the regression analysis we control for a set of variables that capture other important economic, demographic and political events that were taking place at the same time. The relationship between technological change and human capital is assumed to be a dynamic one, in which technological change causes an increase in the stock of human capital, which in turn induces technological change. There is nevertheless little reason to suspect the existence of endogeneity in our regression due to the long interval of 4-7 years between the timing in which the children enter apprenticeship until they become productive.[5]

The results show that the number of inventions had a significant effect on the number of apprentices with an additional invention associated with roughly 4 percent, or, 210 more apprentices per year. Similarly, we find a positive and significant effect of the number of inventions on the share of apprentices within the cohort of 15 year-olds (the typical age for those entering an apprenticeship) suggesting that technological changes were skill biased at the aggregate level in this period. Since the system is in fact a dynamic one and the capability of masters to respond to rising demand for apprentice positions clearly increased, we also employ a Vector Autoregression (VAR) model to test the short-run and long-run response of

[3] This view is consistent with the claim in Goldin and Katz (1998) that capital and skilled labor are always complements in the machine-maintenance segment of manufacturing for any technology.
[4] Obviously, people were not informed of every invention that took place but rather of the intensity of development activity reflected by the number of inventions.
[5] Wallis (2008) showed that that a high proportion of apprenticeships in seventeenth-century London ended before the term of service was finished (usually seven years).

the number of apprentices to technological changes in the aggregate level, as well as in specific occupational categories. The VAR analysis has the additional advantage of allowing us to examine the effect of technological shocks accounting for the dynamic interaction between the variables since it involves jointly regressing all variables on their own lags. This analysis shows that quantities responded in a hump-shaped manner to technological shocks, increasing in response to the shock and gradually returning to their initial level in the long run.

A further examination of the effect of technological change on the occupational structure reveals that the effect of the number of inventions on most occupations was significantly weaker than the average and that instrument and machine making occupations were most strongly affected, with the number of apprenticeships increasing by 16 percent in response to an additional invention.

There is a growing number of empirical studies that challenge the "deskilling view" based on new archival evidence and theories that present a more nuanced view of the mechanism underlying skill-biased technological change.[6] For example, Katz and Margo (2013) revisit the deskilling view in the American context claiming that technological change triggered a change in the occupational distribution such that deskilling did not occur in the aggregate economy. Rather, the share of middle-skill jobs declined and the share of high-skill – white collar – jobs and low-skill jobs increased from 1850 to the early twentieth century.[7] Chin, Juhn and Thompson (2006) examine the impact of the steam engine on the demand for skills in the merchant shipping industry and find that while technological change had a deskilling effect on production work---where moderately skilled able-bodied seamen were replaced by unskilled engine room operatives---it created a new demand for engineers, a skilled occupation. They also find that able-bodied seamen, carpenters, and mates employed on steam vessels earned a premium relative to their counterparts on sail vessels implying that capital and technological change increased

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[6] The renewed interest in the role of human capital during the BIR has been triggered in the last decade following the publication of unified growth theories, which model the process by which economies transition from Malthusian stagnation to modern economic growth and give an important role to technology-skill complementarity (see Galor, 2011 for a summary).

[7] Katz and Margo (2013), p. 3.

their productivity. Similarly, Van Lottum and Van Zanden (2014) find that high quality labor was required to operate the increasingly complex ships and their equipment. Becker, Hornung, and Woessmann (2011) show that basic education in Industrializing Prussia was significantly associated with non-textile industrialization, and finally, Squicciarini and Voigtländer (2015) show that in France, upper-tail knowledge, measured by the number of subscriptions to the famous Encyclopédie in the mid-18th century, raised productivity in innovative industrial technology. In contrast, Clark (2005, 2007) argues that technological changes in Britain did not trigger an increase in formal education nor increase the skill premium of artisans in the building sector and were therefore not skill biased.[8]

Numerous recent studies, mainly those concentrating on the British Industrial Revolution, focus on alternative measures of human capital. These studies do not dispute the fact that standard measures of human capital such as literacy rates and formal schooling did not play a decisive role in Britain's industrialization. Thus, the English school system was not impressive by contemporary standards and there is no evidence for any increase in enrollment rates to primary school (Mitch, 1999), nor in male literacy rates (Schofield, 1973) during the eighteenth century. Britain led the rest of the world despite and not because of her formal schooling system (Mokyr, 1990, p. 240). Recent scholarship has concluded that these measures are not relevant for eighteenth-century England when apprenticeship was the main formal system for acquiring skills (Humphries, 2003, 2011; Allen, 2003; Mokyr, 2009; Mokyr and Voth, 2010; McCloskey, 2010; Kelly, Mokyr and O'Grada, 2013).[9] Despite a growing interest in the importance of apprenticeship (e.g. Wallis, 2008; Minns and Wallis, 2013; Humphries, 2003; De Munck, Kaplan and Soly, 2007; De Munck 2010), few studies have quantitatively examined the role of human capital during the

[8] Clark however disregards the fact that the skill premium is a short run phenomenon, which depends on the responsiveness of the supply of skilled workers and may therefore remain constant even in the presence of an increase in demand for skilled workers. In addition, he concentrates on a specific sector which may not be a representative one as has also been noted by Mokyr and Voth, 2010, and van der Beek, 2014.

[9] Human capital has been shown to play a role during the BIR in studies that concentrate on alternative indicators of human capital, such as books per capita (Baten and van Zanden, 2008), or, the physical condition of the average British worker (Kelly, Mokyr and O’Gr'ada, 2013).

Industrial Revolution using skills acquired by apprenticeship as an alternative measure to formal schooling and literacy. This paper has two main advantages over existing studies. First, the data are very broad, covering large part of the eighteenth century, all of England and a wide range of occupations. Second, it examines the net effect of technological change on apprenticeship, controlling for other major events that were taking place at the time.

The paper also relates to the more nuanced view of skill offered by Autor, Levy and Murnane (2003) whereby technological change (in the case of Information and Communication Technology) substitutes for routine tasks but complements non-routine analytical tasks.[10] We find the greatest impact of invention on apprenticeship in an eighteenth century variant on the modern category of non-routine mechanical occupations, which we identify using Robert Campbell's categorization of trades as *ingenious* in his widely cited manual for prospective apprentices, *The London Tradesman* (1747). In this work he set out to describe in detail the educational and financial requirements a master would make of an entering apprentice, as well as the innate qualities each trade requires.[11] This latter group is, in fact, the occupational group which Meisenzahl and Mokyr (2011) view as the main force behind the Industrial Revolution and refer to these workers as *tweakers*, i.e., the top three to five percent of the labor force in terms of skills who introduced the kind of small cumulative improvements that made a technique work. These include engineers, mechanics, millwrights, clock- and instrument makers and similar workmen.

The paper proceeds as follows. Section 2 provides a short historical background to the early mechanization in England. Section 3 introduces the database. The empirical model and the results are presented in section 4 and Section 5 concludes.

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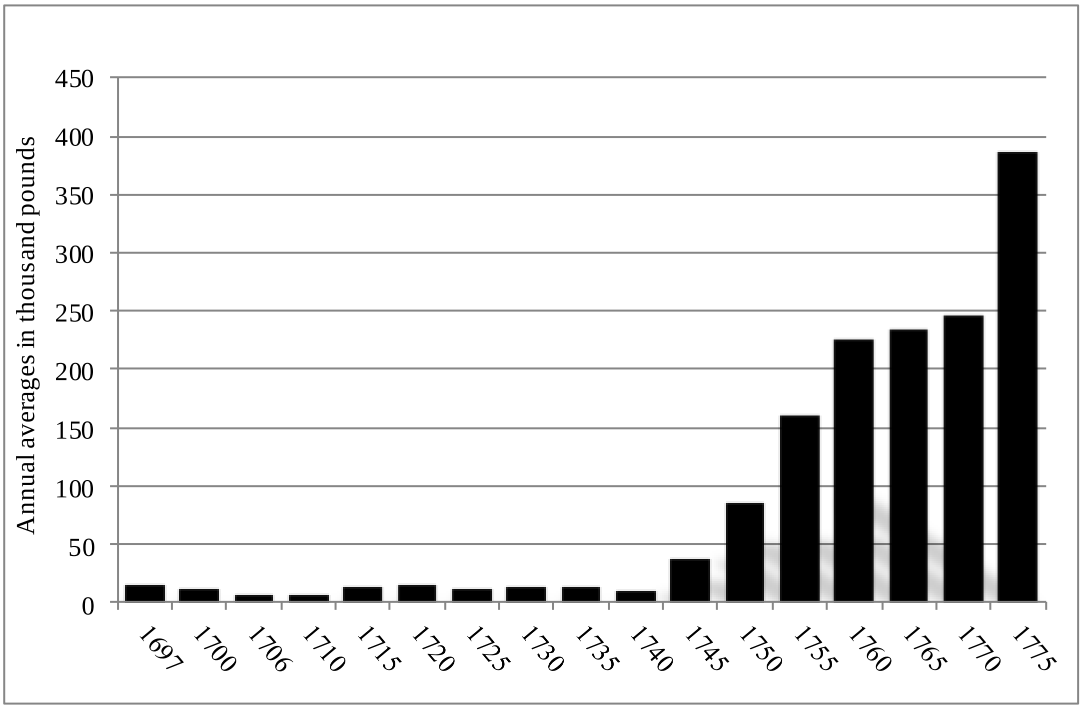
[10] In this spirit, Bessen (2011) who studies nineteenth century textile automation, argues that mechanization eliminated some tasks, thereby reducing the labor required to produce a yard of cloth, but increased the incentives to invest in the skills of workers performing the remaining tasks involving non-routine skills.

[11] See Justman and van der Beek (2014)

## 2. Mechanization in Eighteenth century England

The English cotton industry began to expand in the 1740s and by the early nineteenth century, Britain dominated world markets, exporting cotton textile even to India (see Figure 1). Between 1735 and 1745 exports rose by almost 200 percent (from an official annual average of about 13,000 pounds between 1700 and 1735, to a value of about 38,000 pounds in 1745) and by an additional 325 percent in 1755.[12] These remarkable events involved a profound change in the cotton manufacturing process, including mechanization and the transition from the traditional *cottage based system* to a capital intensive factory system in the last quarter of the eighteenth century in the 1780s.

**Figure 1: Eighteenth century English cotton exports (official values)**



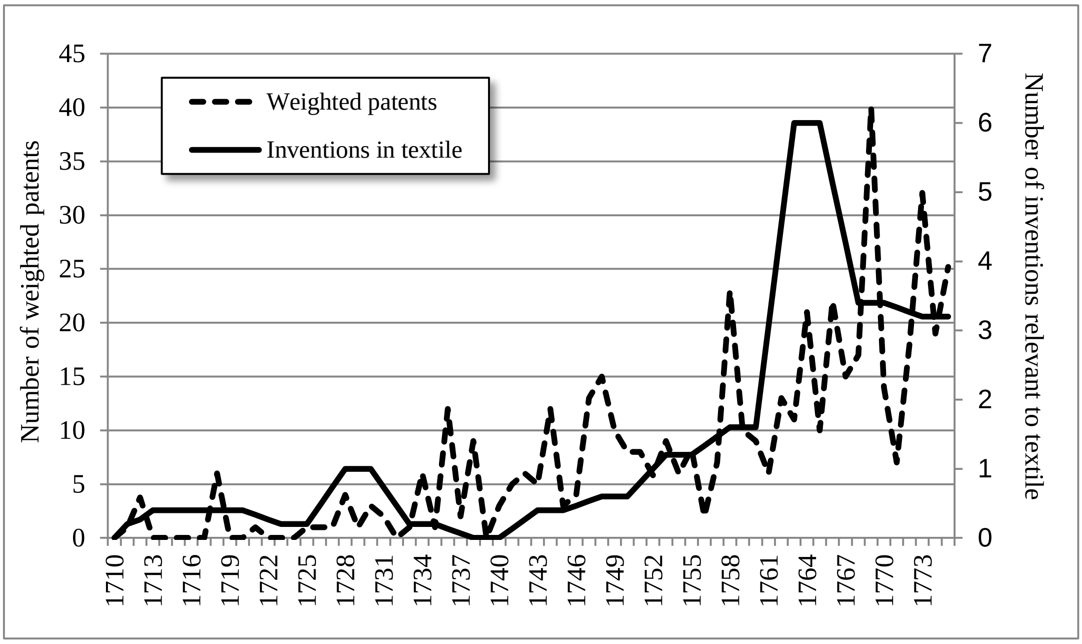

Source: Dean and Cole (1967), Table 16, p. 59.

Such an expansion in the level of production undoubtedly required correspondent increase in production factors, capital and labor. The increase in labor is reflected in the high rates of population growth experienced by cotton manufacturing counties during this period, such as Lancashire where population increased by 33 percent

[12] Dean and Cole (1967), p. 59.

between 1701 and 1751.[13] Although we do not have evidence on investment in capital and in machines from this period, these must have increased as well since more buildings and existing machines (such as carding machines, spinning wheels, looms, and other materials and tools), were required in order to increase the level of production. There is however evidence that productivity increased as well during this period implying that technological changes were taking place.

**Figure 2: Eighteenth century invention measures**




Source: Inventions relevant to the textile sector is from Griffiths, Hunt and O'Brien (1992), Table 1, p. 885. See text for more details regarding the calculation of the annual numbers. Weighted patents were generously provided to us by the authors of Nuvolari and Tartari (2011).

For example, the number of inventions, which represents the amount of resources devoted to the development of new productive processes or products and reflects the probability of a "successful" invention that will be eventually adopted. It can therefore be viewed as a proxy for technological change. Figure 2 presents the two measures of inventions that we use in our study, the number of inventions relevant to the textile sector, and the total number of patents in England, weighted by their

[13] Dean and Cole (1967), table 24 p. 103.

importance, as calculated in Nuvolari and Tartari (2011).[14] As illustrated in Figure 2, the number of inventions relevant to textile began to grow during the 1730s and 1740s in tandem with the rise in cotton manufacturing, reflecting the intense development activity that was taking place in this sector. Interestingly, the weighted number of patents shows a similar increase during these same years, reflecting the rise in the importance of inventions.

One of the earliest and most important inventions in the eighteenth century was Kay's flying shuttle, patented in 1733 and widely implemented. It doubled weaving productivity and generated shortages in yarn spinning, which was still based on traditional single spindle hand wheels. The mechanization of the spinning process began soon after, with the Roller Spinning machine invented by John Wyatt and patented a few years later in 1738 by Lewis. We know very little of the extent to which this machine was adopted. We know that it was unsuccessfully employed in two mills erected by Lewis and Wyatt. One small mill employing 10 girls erected in Birmingham in 1741 or 1742, and a second mill on a larger scale containing 250 spindles and employing fifty workers in Northampton.[15] We do know however that the following years saw intensive attempts of developing an improved version of a spinning machine. In 1758 Lewis took out a new patent for the spinning machine, with some improvements. The "Society for the Encouragement of Arts, Manufactures, and Commerce", established in 1754 has distributed £644. 12s. in premiums for improving several machines used in manufactures. In 1783 it had in its repositories several models of spinning machines including: "A Spinning Wheel, by Mr. John Webb, invented 1761. A Spinning Wheel, by Mr. Thomas Perrin, 1761. A Horizontal Spinning Wheel, by Mr. Wm. Harrison, 1764. A Spinning Wheel, by Mr. Perrin, 1766. A Spinning Wheel, by Mr. Garrat, 1766. A Spinning Wheel, by Mr. Garrat, 1767".[16]

The well-known spinning jenny, invented by James Hargreaves in 1764, was the first spinning machine known to be used on a large scale. It was purchased in large

[14] Calculated by Griffiths, Hunt and O'Brien (1992), who took into account all the known innovations that had a potential application to textile, both patented and not.
[15] Baines (1835), pp. 121-140.
[16] Ibid, p. 154.

numbers for use in cottages, workshops and warehouses and 20,070 Jennies were estimated to be operating in Britain by 1788.[17] The fact that the Jenny was attacked by mobs as early as 1768 when Hargreaves was still operating in Blackburn suggests that spinning machines were already sufficiently known to begin pushing yarn prices down and to threaten the employment of spinners. At roughly the same time, Richard Arkwright and a team of craftsmen developed the spinning frame (patented in 1769), which produced a stronger thread than the spinning jenny. Then, in 1771, Richard Arkwright used water wheels to power the spinning frame, an invention known as the water frame. The inventions that followed took place after 1772, the end of the period of the study, and were adopted in the engine based factories. In 1779, Samuel Crompton combined elements of the spinning jenny and water frame to create the spinning mule, which produced a stronger thread, and was suitable for mechanization on a grand scale. The application of steam engines to powering cotton mills and ironworks to spinning towards the end of the century, shifted textile manufacturing from small cottage-based production in the beginning of the century, to mass production factory in its end.

Although textiles accounted for the largest share of total patents in the years 1710-1780 (10.5 percent on average), inventions were taking place in other industries as well. For example, metals accounted for 8 percent of total patents in the same period, ocean shipping for 7.5 percent and field agriculture for 6.3 percent.[18] The number of patents issued for inventions pertaining to production machines accounted for almost 27 percent of total patents.[19] These included general production machinery (saws, lathes, drills, presses, and so forth), machinery specific to the chemical, metal and mining, textile, clothing and accessories, shipping, railroad, canal, road transport, field agriculture, and food processing industries, as well as bearings, lubrication, and machine parts (drive bands, axles, springs, hinges, steering, brakes, and so forth)[20]

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[17] According to Allen (2009) p. 914), "

[18] Sullivan (1990), Table 2, p. 352.

[19] Ibid, Table 3, p. 355.

[20] Ibid, Appendix, p. 361.

An additional indicator of technological change and an increase in productivity in 1740 England comes from analysis of the trend of growth. Deane and Cole (1962) argued that acceleration of growth was a two-phase process with both the 1740s and 1780s seeing increases in trend growth. Later studies, based on revised series, stressed a more gradual acceleration in trend without providing any precise timing, and more recently, Crafts, Leybourne and Mills (1989), have shown the acceleration in trend growth to occur in the 1740s - 1760s (depending on the series of industrial output they use), steadily increasing trend growth is then found until the 1830s.[21] In this paper we examine the effect of these changes, as reflected by the number of inventions in textile and by the weighted number of patents, on the acquisition of skills.

## 3. Data

### 3.1. Data Source

The main data source for this project comes from Registers kept by the Board of Stamps of the moneys received in payment of the duty on apprentices' contracts (*indentures*). Apprenticeship was the main formal system for acquiring skills in eighteenth-century England. Its general structure can be traced back to the practices of guilds and cities in the Middle Ages, yet it was first regulated nationwide in 1563 in the Statute of Artificers. An apprenticeship indenture was a legal document whereby a master agreed to instruct the apprentice in his or her trade for a set term of years (usually seven) in exchange for a sum of money (the *premium*). The provision of food, clothing and lodging was generally part of the agreement.

Until 1710, there was no centralized record of apprentices. From 1710, however, after the introduction of a stamp duty payment on private indentures of apprenticeship, records of the duty paid for these apprenticeships were kept. The

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[21] Crafts, Leybourne and Mills express a concern that results on the period before 1783 can be interpreted as showing fluctuations which are the result of noise rather than a regular cycle, since in this period wars and harvest failures could be a source of erratic movements in industrial production" (p.57).

tax was at the rate of 6d in the pound (2.5 percent) on agreements of £50 or less, plus one shilling for every pound above that sum (5 percent). These tax payments on apprentices' indentures were recorded and maintained by the Board of Stamps. The payment was entered on the reverse of the indenture, which was void without this payment. Using information from tax records obviously raises the issue of tax evasion, which may be problematic, mainly if evasion varies over time and across occupations. Nevertheless, Minns and Wallis (2013) compared the premiums reported in the stamp tax registers for London to those registered in the company (guild) books and no evidence that masters reported lower premiums for tax purposes was found.

The Stamp Tax Registers' main limitations are, first, that they do not contain the indentures of pauper apprentices, taken on at the common or public charity, on which masters did not have to pay stamp duty.[22] The second limitation is that they do not contain information on those who were apprenticed in the "modern" trades that did not exist when the Statute of Apprentices was passed, including mainly the new cotton trades. These limitations would bias our results only if the number of omitted apprentices was either declining throughout the period of the study, or, if their occupational distribution changed in a different manner than that of the included apprentices in response to inventions. Since the number of pauper apprentices was growing during the eighteenth century, their omission should only be expected to bias our estimate of the effect of inventions downwards.[23] The changes in the occupational distribution of apprentices, however, may affect our results. Paupers were largely bound in building and clothing occupations and therefore both the omission of "modern trades" and of paupers may imply that these occupational groups are underrepresented in our analysis.[24] Nevertheless, it would most probably only imply that we cannot identify all the occupational groups that were strongly affected by inventions in this period. It is also important to note that the sums that were raised by the overseers of the poor were just high enough to

[22] The Poor Law Act of 1597 gave Overseers of the Poor and Churchwardens the power to put out to pauper apprenticeships children who could not be cared for by their own family, thus reducing the poor rate in their parish.

[23] Lane (1996), p. 16

[24] Ibid, p.73

attract masters to take children, so that paupers were not preferred to other children in any way.[25]

The registers are organized in 72 volumes, which are available on a microfilm format at the National Archives, Kew, in London. The volumes consist of: City (or Town) registers, October 1711 to January 1811, with daily entries of the indentures upon which duty was paid in London; Country registers, May 1710 to September 1808 with entries, made in London, of the indentures upon which duty had been paid to district collectors and which were then sent in condensed batches to be stamped. An index of these records was compiled by the Society of Genealogists in the beginning of the twentieth century, covering the period 1710-1774.[26] In addition to the sums received, the index records the date of the apprenticeship, the name, location and trade of the master, and the name and location of the apprentice.

**3.2 The Data Set**

We use a stratified random sample of 50,200 entries that have been processed and computerized for the purpose of this study. The sample was constructed so as to keep the proportion of observations of apprentices' surnames beginning with the same letter. For example, apprentices' surnames beginning with the letter ``B'' comprise 11 percent of the entries in the index. This proportion was kept in the sample.

Each observation in the data set represents an apprenticeship contract containing information on the year of contract, the occupation and location of the master and the tuition paid by the apprentice. There are some serious drops in the number of entries over 1726-1740, and more moderate drops for the years 1745-1751. These drops in the number of entries happen precisely in the years in which high death rates that were mainly caused by bad harvests and smallpox outbreaks were identified by Wrigley and Schofield (1981, p.162) who note that the upsurge of death rates in the early eighteenth century "owes much to some years exceptionally high

[25] Ibid, p.341

[26] The indexes for the years 1710-1774 are kept with the apprenticeship books at the National Archives, Kew, under Series IR 1. They are also available online at Origins Network, a family history web site.

mortality in the 1720s and early 1740s, and it is noteworthy that around 1750 the number of deaths sinks back to a level not much higher than had obtained in the last quarter of the seventeenth century." The connection between the demographic crises and the drops in observations is straight forward---smallpox caused high mortality mainly among young children and therefore reduced the number of 14--15 year olds to be bound in apprenticeships in subsequent years. To encounter this we add death rates as a covariate in our regression and drop years with less than 100 entries.

**Occupational classifications:**

There are about 900 different occupations of masters in the data, after adjusting for minor variations in the spelling of identical occupations. As such, we aggregate the professions into broader categories based upon the HISCO system (Historical International Classification of Occupations).[27] HISCO is an occupational information system that is both international and historical, and simultaneously links to existing classifications used for present-day conditions. It provides basic information on various trades and was used as the basis for our classification along with Robert Campbell's (1747) manual, *The London Tradesman*. The end result consists of 79 broadly defined trades that reduce to 75 trades after we restrict trades to have at least 85 observations over the entire period (to more accurately capture population means). Trades were also classified into 20 broader occupational groups, whether it was mechanical or not and whether the task could be considered ingenious/non-routine. The list of trades and the classifications we use can be observed in the table A1.

The classification of trades into routine and non-routine ones is difficult. It is based upon a task-based approach, a view that is advanced in a growing body of literature. The task-based approach focuses on the effect of technological changes on the set of tasks, job requirements, and the demand for skills. According to Autor, Levy and Murnane (2003), routine tasks are tasks that can be accomplished by following

[27] van Leeuwen, Maas and Miles (2002). The subsidiary HISCO-classification PRODUCT utilizes version 1.0 (draft) of the United Nations Central Product Classification at the two digit level, copyright United Nations, 1998.

explicit rules, and non-routine tasks are tasks that require more complex problem solving. In order to perform this classification in the most objective manner possible, we first relied on Robert Campbell's widely cited manual for prospective apprentices, *The London Tradesman* (1747). In this work Campbell set out in great detail the educational and financial requirements a master would make of an entering apprentice, as well as the innate qualities each trade requires.[28] We use his categorization of trades as *ingenious* or requiring *ingenuity* to identify non-routine occupations. For example, his treatment of the occupation of the gun smith is as follows:

*"It is a very ingenious Business, requires Skill in the Tempering of Springs, a nice Hand at forming a Joint to make his Work close, and a good Hand at the File to polish it handsomely."*[29]

We also classified trades for which Campbell states the need for "a solid judgment" as non-routine, such as in the case of the house carpenter: *"He ought to have solid Judgment in Matters of this Kind, to be able to act not only by the common mechanical Principles of his Art, but to Strike out of the common Road when the Case requires it."* Finally, trades that were described by Campbell as being composed of skills of another occupation which has been classified as non-routine were classified as non-routine as well. For example, we classify the coach maker as non-routine because it has been said by Campbell to be mainly a carpenter.[30]

Although Campbell's characterization of trades as ingenious provides us with an objective classification, we cannot rule out the possibility of unintended omissions, or of intended omissions of characteristics the author saw as self-evident. We therefore employed a second – subjective - classification which was performed on the basis of the definition provided in Autor, Levy and Murnane (2003). About 70

[28] See Justman and van der Beek (1014).
[29] Campbell (1747), p. 242.
[34] Since our analysis is based on occupations which, in many cases, are composed of a number of similar occupations, which do not always have the same classification of ingenious/non-routine, the choice of classification was determined according to the majority (for example, financial services, which are composed of bankers, exchange brokers, pawn brokers and book keepers, were classified as ingenious although book keepers were not classified as ingenious by Campbell).

percent of the trades resulted in a similar classification using both methods. Twelve occupations were classified as ingenious by Campbell but as routine by us. These were coopers, cutlers, hatters, carpenters, joiners, milliners, pewterers engravers, saddlers, stay makers, stone masons and turners. Most of the occupations that have been classified by us as non-routine however were not considered ingenious by Campbell are those of merchants and trades men, which were all classified by us as be non-routine.

**Measuring technological change:**

What we are interested in measuring is in fact the annual adoption of invention. In the absence of standard measures such as annual changes in TFP or R&D outlays, we use two measures of inventions to proxy for technological change.[31] We view the number of inventions in a specific sector as reflecting the intensity of research and development in this sector and representing the probability of reaching a "successful" invention that will eventually be adopted in the producing sector, as in the case of the roller spinning machine in 1738 and its developments until reaching the “successful” inventions of Hargreaves's spinning jenny and Arkwright's spinning mule in the end of the 1760s.

Patents are known to be an imperfect proxy of eighteenth-century inventions due to cumbersome and expensive patenting requirements before the reforms of 1852. This led a large volume of inventive activities to be carried out outside the coverage of patent protection (MacLeod, 1988; Moser, 2005). We therefore use two alternative measures: the number of inventions relevant to the textile sector, and the total number of patents in England, weighted by their importance. The number of inventions relevant for the textile industry, was constructed by Griffiths, Hunt and O'Brien (1992), who took into account all the known inventions that had a potential application to textiles, both patented and not. Because this series exists in increments of five years (e.g., 1710, 1715, 1720, etc.) we are left to fill in the intervening years in order to complete the panel for which we have apprenticeship

[31] Economic historians (Feinstein 1981; Crafts 1985; Harley 1982; Crafts and Harley 1992; and Antras and Voth 2003) have managed to develop estimates of TFP based on both primal and dual approaches however these only go back to as far as the last quarter of the eighteenth century.

data. We undertake a number of ways to do this, one of which is to take the number of inventions in year t and assume that one-fifth of this number is created each year. For example, if five inventions are recorded in 1720, we assume that one occurred in each of 1716 - 1720. Then, we calculate the three-year moving average of inventions. None of the results we present are particularly sensitive to this specification (alternative variants to filling in the panel are available upon request). In addition, we perform an analysis of the data when it is collapsed into five-year time periods and obtain similar results.

The second variable that we use is the annual number of patents weighted by the *Woodcroft's Reference Index* (an index constructed by Nuvolari and Tartari (2011) that aims at capturing the significance of a patent by the number of citations it has in the contemporary technical literature). While this series of patents, weighted by their importance, does not fully correct the biases in the patent series, it does allow, to a large extent, to correct some of the downward bias in the number of patents by giving larger weights to the more significant inventions. In addition, it allows us to capture the effect of inventions in general and not only of those relevant for the textile industry.

Of our initial sample of 50,200 apprenticeship contracts, just over 1 percent have missing or invalid information, which leaves us with 49,574 contracts. After collapsing the data to the occupation-year level, the data are a panel of 3,513 observations from 75 occupations between 1710 and 1772.[32] Table 1 lists descriptive statistics for our sample.

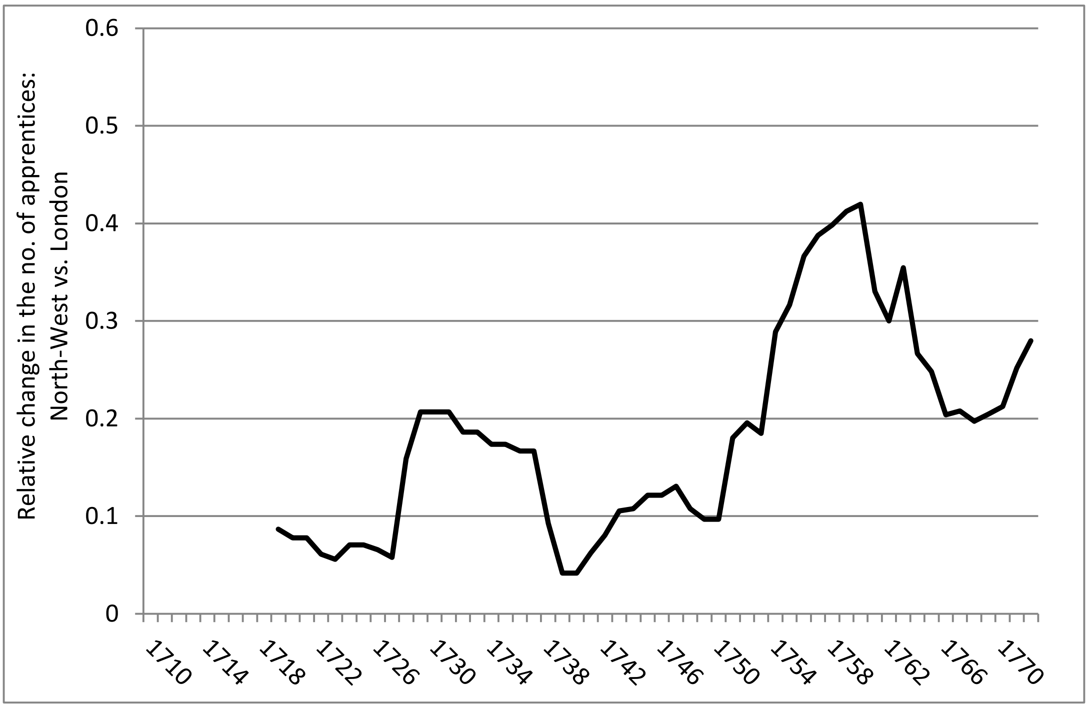
## 4. Econometric Analysis

Our hypothesis is that the main effect of the wide spread technological changes was to trigger an expansion in the development, production, and maintenance of machinery and other skill-intensive products and processes. This expansion

[32] Observations from years prior to the activation of the tax in 1710 and from the last two years for which the index was compiled were not complete and were therefore dropped. Years with less than 100 entries were considered as missing and dropped in the analysis. These are 1727, 1734 and 1739.

increased the demand for skilled workers, particularly in the highly skilled mechanical occupations.[33]

**Figure 3: Number of apprentices in machinery: The North-West vs. London**




Source: Stamp tax registers. See text.

Notes: The relative change in the number of apprentices is calculated as the ratio of the indexes measuring the change in the number of apprentices in machinery occupation relative to the average in the years 1710–1720 (100=average 1710-20) in each area.

The technological changes that were taking place were also reflected in a general expansion in industrial production, which we control for in our regression analysis. The effect of this process on the demand for machinery workers is clear when looking into the north-west part of the country, which experienced the fastest rise in industrial production during this period. As can be observed in Figure 3, although a dominant share of apprenticeships took place in London, as technological change

[33] Musson and Robinson (1960) claim that the tremendous growth in the Lancashire cotton industry gave rise to an equally rapid development of mechanical engineering and that the rise in machine manufacturing required skilled mechanical labor as well and contributed to the increased demand for these workmen who were already required in the cotton mills.

became more intense the number of apprentices in the machinery occupations in the North-West relative to the London area increased dramatically.

It seems that the demand for workers with mechanical skills increased with the emergence of a factory based system, which also employed many unskilled workers (particularly women and children). According to S. D. Chapman (1972, p.54): "The mill owners' problem can only be understood by examining the recruitment of skilled workers (machine builders, millwrights and mule spinners) separately from that of the unskilled machine minders who formed the majority of labor force in Arkwright-type mills. The fundamental difficulty in obtaining skilled men was simply the consequence of the rapid growth of the cotton industry, which made artisans with relevant skills very much at a premium. Local newspaper advertisements, memoirs, private correspondence and high wage rates all bear testimony to the acute shortage of craftsmen whose skills could be applied to textile machine building or to the installation of water wheels and transmission systems."

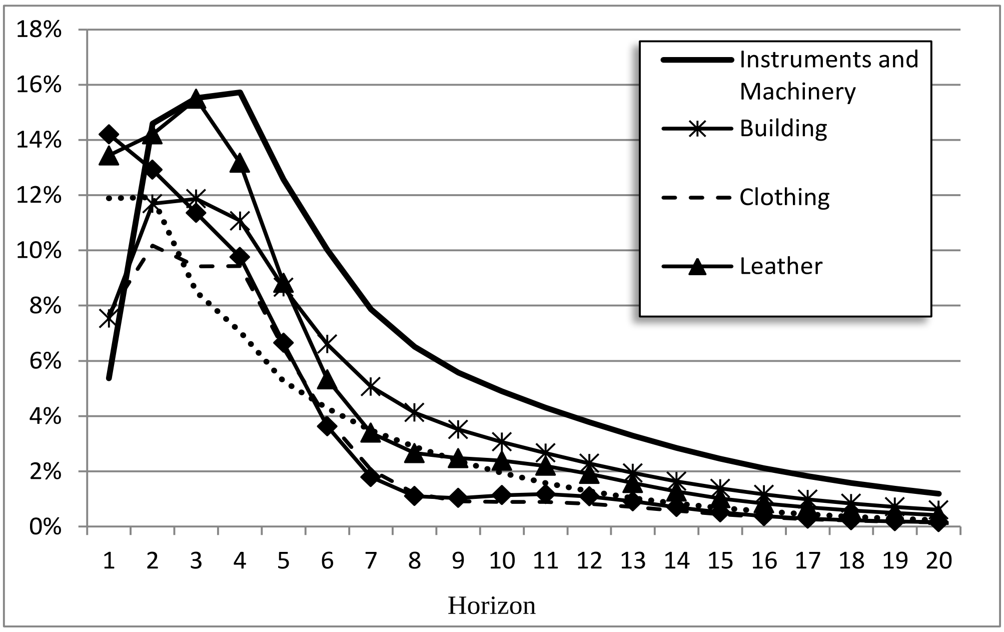
**4.1 VAR Analysis**

Figures 4 and 5, illustrate the results of a Vector Autoregression (VAR) analysis that tests the short-run and long-run response of the number of apprentices to technological changes using weighted patents, *wri*.[34] The figures depict the estimated impulse responses of inventions and the number of apprentices in different occupational categories to a positive one standard deviation unanticipated technology shock. However, it is also clear from Figure 5 that inventions impacted the various occupations differentially. It increased the number of apprentices as whole but had the strongest impact on apprentices in the highly skilled mechanical occupations, mainly in instrument and machine making. This group of occupations, which consists mainly of wrights (wheelwrights, millwrights, clock makers, etc.), was the most relevant for machine making. According to Musson and Robinson (1960)

[34] Figures A1 and A2 in the appendix present the same analysis for technological shocks measured using innovations in textile.

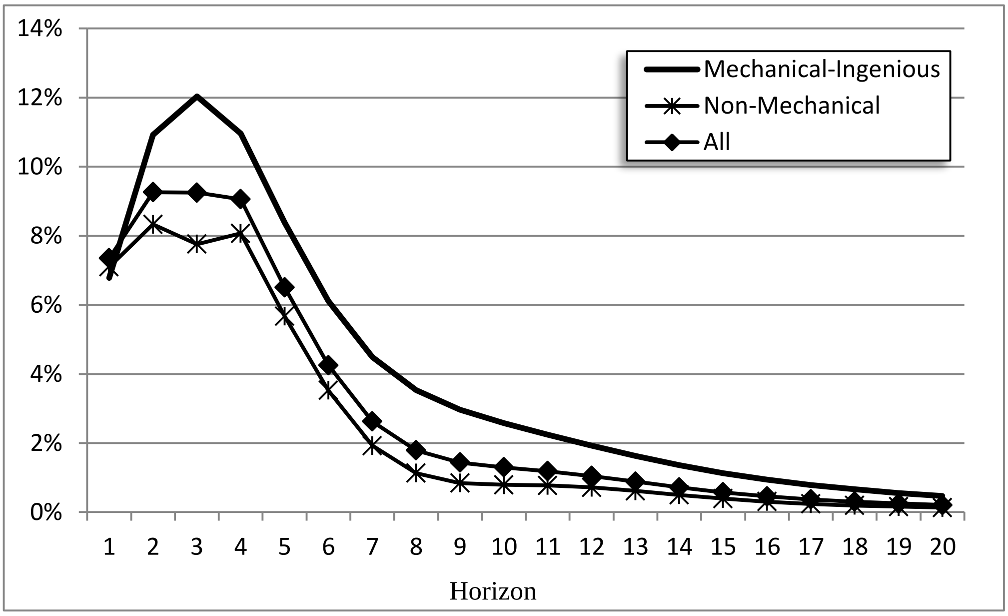
before the Industrial Revolution machines were constructed by specialized wood and metal workmen, but mill wrights were of particular importance in this business.[35]

**Figure 4: The Differential Impact of Inventions on Occupational Groups**




Notes: The VAR was estimated via a cholesky decomposition with the technological variable ordered first. Technological shocks are measured using the weighted annual number of patents (Nuvolari and Tartari, 2011).

**Figure 5: The Differential Impact of Inventions On Occupational Types**




Notes: The VAR was estimated via a Cholesky decomposition with the technological variable ordered first. Technological shocks are measured using the weighted annual number of patents (Nuvolari and Tartari, 2011).

[35] Musson and Robinson 1960, pp. 210-211.

**4.2 Regression Analysis**

We first establish that technological change in the eighteenth century had a positive effect on the number of apprentices in England.

$$(1) \qquad \ln(apprentices)_{i,t} = \alpha \ln(apprentices)_{i,t-1} + \beta_1 Inventions_{t-1} + X'\delta + \gamma_i + \varepsilon_{i,t} \,,$$

where each observation represents an occupation *i* in year *t*. The dependent variable of interest is the logarithm of the number of new apprentices. The lagged value of this variable is included on the right-hand side to capture persistence in quantities. *Inventions* are measured both by the inventions relevant for textile and by the weighted patents. We are primarily interested in how an additional invention affected the number of those entering apprenticeships in the subsequent period ($\beta_1$).

The *X* matrix contains our control variables: cotton exports, industrial production, nominal wages of day laborers, population, the number of war recruits, death rates and consumer prices.[36] We add occupational fixed effects ($\gamma_i$) to control for unobserved time-constant occupational characteristics that may be correlated with our variables of interest. Because our control variables vary only over time and not over occupation, we cannot additionally add year fixed effects to our regression. Errors were clustered at the year and occupational level. Finally, we also estimated the model in Equation (1) in 5-year intervals in order to smooth through the year-to-year noise in our variables.

In the next stage, we extend the baseline model in (1) to examine whether the differential effect of technological change on the highly skilled (non-routine) mechanical occupations--as we observe in Figure 5--is statistically significantly attributable to a differential impact of technological change on these occupations. In this vein, we estimate the following model:

[36] The main wars of this period were the Spanish Succession 1701-1714, the Austrian Succession 1740-1748, and the Seven Years' War 1756-1763.

$$(2) \quad \ln(apprentices)_{i,t} = \alpha_0 \ln(apprentices)_{i,t-1} + \alpha_1 Inv_{t-1} + \alpha_2 (Inventions * mech\_nr)_{t-1} + X^{'}\vartheta + \upsilon_i + \mu_{i,t}$$

Where - *mech_nr* stands for mechanical, non-routine occupations (binary), which were measured using both Campbell's classification of ingenuity and our independent classification.

The estimates of the model in Equation (1) are presented in Tables 2a and 2b, in which the model was estimated in one-year and five-year intervals, respectively. Consider first Table 2a. In columns (1)-(4) inventions are measured using the textile series. Column (1) presents the estimates of Equation (1) where we regress the log number of apprentices on inventions. Taking the result from column (1), an additional invention is correlated with roughly four percent more apprentices in the next year in every occupational group, on average. This implies a total of about 210 apprentices per year, given the mean number of apprentices per year, per occupation of 70. This effect increases to about six percent when we add the additional controls in column (2). The effects of the control variables are all as expected.

As discussed in Section 2, cotton manufacturing in England began expanding at about the same time as the number of inventions increased and may potentially confound our results. As column (3) shows, cotton exports also had a positive and significant effect on the number of apprentices. Yet, the coefficient on inventions remains positive and significant. Using a non-dynamic setting (column 4) changes our coefficient of interest by little.[37] In columns (5)-(7) we repeat the estimations performed in columns (1)-(2) and (4), replacing our invention measure with the weighted patents series and obtain consistent results. The positive and statistically significant result on patents shows that our results are robust to an alternative

[37] A problem that arises with fixed effects model in the context of a dynamic panel data, in a "small T, large N" context is a correlation between the lagged dependent variable on the right-hand side, $\ln(apprentices)_{i,t-1}$, and the error term (because the demeaning process which subtracts the individual's mean value of y and each X from the respective variable). This problem diminishes here due to the long time dimension (T) in our panel. We therefore do not employ the Arellano–Bond GMM estimator developed to deal with this type of endogeneity (Arellano and Bond, 1991), which is also biased in the presence of a long time dimension.

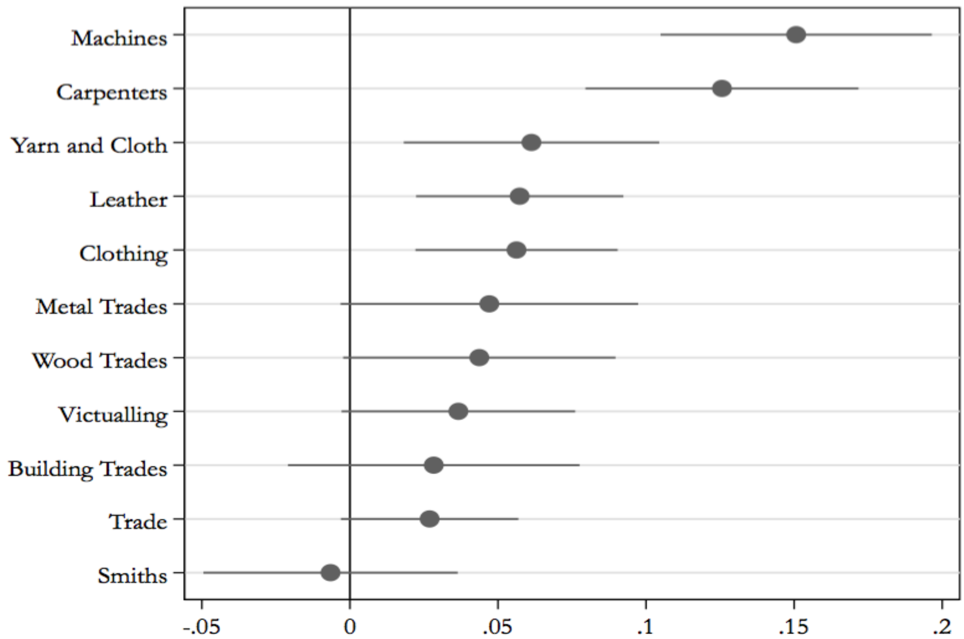
measure of technological change. Each one unit increase in the weighted patent series is correlated with about 21-32 additional apprentices per year.

Table 2b presents the results of the same regressions as in Table 2a using 5-year intervals to smooth through the yearly noise that may arise from the year-by-year estimation. Because this decreases the time dimension of our panel, it is possible that we now introduce a correlation between the lagged dependent variable on the right-hand side, $\ln(apprentices)_{i,t-1}$ and the error term. Therefore, we also employ the Arellano–Bond GMM estimator developed to deal with this type of endogeneity (Arellano and Bond, 1991). Columns (1)-(5) present the results using the inventions in textile series and columns (6)-(10) present those using the weighted patents series. Here, based on columns (1)-(2), an additional invention during the 5-year period (inventions are summed over the period) is correlated, on average, with a yearly 2 percent increase in the number of apprentices in every occupational group over the subsequent 5 years.

The Arellano-Bond estimation in column (4) gives a coefficient of roughly 6 percent on invention. Interestingly, the lagged dependent variable is no longer statistically significant at conventional levels. Reestimating the model in column (5) without this lagged dependent variable in a standard OLS model gives a coefficient of roughly 5 percent on invention. The results from Table 2b are overall broadly consistent with those from Table 2a with some variation in the estimated coefficients. Our preferred estimates are those from column (4) of Table 2a and column (5) of Table 2b—both reflecting roughly a 5 percent increase in the number of apprentices, on average, per occupation for each one unit increase in inventions. Again, the results on weighted patents in columns (6)-(10) are qualitatively similar.

The differential effect of inventions on apprenticeship in different sectors can be observed in Figure 6, where we graphically present the coefficients on the interaction of inventions with binary indicators for different sectors (omitting the services sector for which the coefficient is significantly not different from zero) from a regression analysis in which we regress log apprentices on our benchmark specification from Table 2a column (3). The Figure shows that while many sectors experienced a statistically significant growth in the number of apprenticeships in response to inventions, the effect in machinery trades and carpenters was particularly strong.

**Figure 6: The Differential Effect of Invention on Apprentices in Various Sectors (base category = services)**




Notes: The differences are the estimated coefficients on the interaction of inventions and an occupational dummy, where the omitted category is services.

For example, while we cannot reject the null hypothesis that apprenticeships in the service, smiths, trade and building sectors did not respond to inventions, the clothing, yarn and leather producing sectors experienced approximately 6.5-7 percent growth in apprenticeships and the machine sector experienced a 16 percent growth (both statistically significant from zero at the 5 percent level).

The response of the machine sector is not surprising as it includes the occupations of wrights, lock smiths, clock makers and other specific machine makers. These are occupations that are directly relevant to the machinery production and maintenance and are therefore expected to be in demand when technological changes take place. Nevertheless, other mechanical occupations may have been experiencing growing demand as well, given the limited supply of relevant workmen in the short run and the fast expansion of the machinery sector. We next look at the interaction of invention with mechanical ingenious/non-routine occupations as well as with other ingenious/non-routine occupational categories.

Table 3 presents the estimates for the model in Equation (2), in which we expand our baseline FE regression from column (3) of Table 2b, focusing on occupational characteristics that were more likely to be impacted by technological change. We maintain the five-year interval analysis as in Table 2b.[38] In column (1) we interact the inventions variable with a binary indicator for highly skilled mechanical occupations using Campbell's ingenuity classification. As in Table 2b, the lagged dependent variable is not statistically significant at conventional levels (column 2). We therefore estimate the regression in a non-dynamic setting in columns (3)-(4) and find that inventions are associated with a five percent increase in the number of apprentices in all the occupations and an additional 10 percent increase in the ingenious, mechanical occupations. This shows that apprenticeships in occupations with both qualities (mechanical and non-routine) experienced much higher demand than others with at most one of the qualities. This latter result is robust to replacing ingenuity with the non-routine classification (column 4). The results using the *wri* series as a proxy for technological changes are presented in columns (5)-(8) and produce similar results.

Thus far, we have shown that inventions are strongly correlated with an increase in the absolute number of apprentices entering all occupations, on average, and, particularly those entering the highly skilled mechanical occupations. The question is whether there was an increase also in the share of those entering apprenticeship out of their cohort. We address this question in Table 4 by regressing the logarithm of the number of (new) apprentices divided by the number of the fifteen year-old youths as a left hand side variable.[39]

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[38] The results of the one-year interval analysis are presented in Table A2 of the Appendix.

[39] In this one case we exclude population and death rates as control variables. The number of 15 year olds was calculated on the basis of the number of births and size of the cohorts 0-4 and 5-14 in Wrigley and Schofield (1981), Tables A2.3, pp. 496-502 and Table A3.1, pp. 528-9.)

As the results in Table 4 show, the effect of technological change in this case is smaller, yet it remains significant and positive. According to the results in column (4), an additional invention increases the share of those in an apprenticeship out of the cohort of the fifteen year-olds by about 1 percent and the share of those in the mechanical occupations involving “ingenuity” by an additional percent. These results confirm that the number of apprentices and mainly that of the highly-skill mechanical apprentices was growing relative to the population of potential apprentices.

## 5. Conclusion

Was the first Industrial Revolution de-skilling? Marx and Engels told us so, but their assessment - and the judgement of economists for the last 200 years - has not been based on detailed quantitative data. In this study, we explore one new dimension of skill demand - apprenticeships - and show that they responded positively to increases in invention. Because education in the pre-industrial world worked differently - with a much greater emphasis on "learning on the job" - these findings present an important challenge to the established view that Britain's Industrial Revolution did not raise skill demand.

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