

Technical Change and the Demand for Skills during the Second Industrial Revolution: Evidence from the Merchant Marine, 1891-1912*

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August 31, 2005

Abstract

Using a large, individual-level wage data set, we examine the impact of a major technological innovation—the steam engine—on the demand for skills in the merchant shipping industry. We find that the technical change created a new demand for engineers, a skilled occupation. It had a deskilling effect on production work—moderately skilled able-bodied seamen were replaced by unskilled engine room operatives. On the other hand, able-bodied seamen, carpenters and mates employed on steam vessels earned a premium relative to their counterparts on sail vessels, and this appears partly related to skill. (JEL J23, J31, N31, O30)

* We thank Daron Acemoglu, Josh Angrist, David Autor, Eli Berman, Jonathan Guryan, Peter Meyer, Peter Mieszkowski, and seminar participants at Rice/UH, Cornell, 2004 SOLE meetings, IZA and 2004 NBER Summer Institute Labor Studies Workshop for helpful comments and discussion.

I. Introduction

Today, the returns to education in the United States are much greater than they were fifty years ago despite an enormous increase in the relative supply of educated workers (Acemoglu, 2002, Figure 1). Residual inequality, after controlling for observables like education and age, has also shown a notable rise over this period (Juhn, Murphy and Pierce, 1993; Acemoglu, 2002). It is widely accepted that skill-biased technical change (SBTC), in conjunction with a slowdown in the growth rate of the supply of skilled workers, underlies this evolution of the wage structure (Katz and Murphy, 1992; Autor, Katz and Krueger, 1998, Card and Lemieux, 2001).

However, recent scholarship has argued that the simplest formulations of SBTC, in which technological advances raise the relative demand for skilled workers in every task, overlooks some richer implications of technical change for the demand for skills. Acemoglu (1999) has shown that search frictions in the labor market can induce firms to eliminate jobs in the middle of the skill distribution in response to an increase in the supply of skilled labor, replacing these jobs with vacancies for both highly skilled and unskilled workers. Evidence from the Current Population Survey indicates that this had indeed been happening in the 1980s and early 1990s (Acemoglu, 1999, Table 2). Similarly, Autor, Levy and Murnane (2003) found that computer technology has been substituting for labor in tasks that can be routinized, and these tasks are not undertaken by the least skilled.

An analogous situation exists for the Second Industrial Revolution at the end of the 19th century. While there has long been a broad consensus that technological change in this period was skill-replacing, researchers with an eye for detail have argued for a more nuanced interpretation. Braverman (1974), Hounshell (1984), Goldin and Katz (1998) and others have described how skilled artisans were in many instances replaced by a combination of unskilled

operatives and highly skilled engineers and managers. Unfortunately, the empirical evidence for the 19th century is very sparse, and support for the idea that the real story is more nuanced than conventional wisdom admits comes only as a byproduct of conflicting evidence.¹

Our understanding of the impact of technological change on the demand for skills during the 19th century is undoubtedly constrained by an almost complete absence of individual-level wage data. In this paper, we exploit a unique data set from the merchant shipping industry collected during a period of dramatic technical change—steam-powered vessels were quickly displacing sail-only vessels on the oceans—to address this question. The data set is not only large, but also high quality. Data on individual workers, including their wages, come from crew lists which served contemporaneously as binding employment contracts. We linked these data to official vessel registry records, which contain technological details of each ship, most notably its form of propulsion. Our data set is the earliest example of matched employee-employer information that we are aware of, containing detailed characteristics of workers, all their co-workers, and the technology with which they worked.

II. Background

A. The Steam Engine

Thomas Newcomen invented the first steam engine to see commercial success in 1712, but its mass and inefficiency restricted its use to pumping water out of mines. James Watt's improved design, first patented in 1769, made the steam engine sufficiently compact and fuel efficient to open the door to a wider set of applications. Indeed the steam engine has been

¹ For example, Atack, Bateman and Margo (2004), using establishment-level data from manufacturing censuses from 1850 to 1890, find that larger establishments (e.g., new factories) paid lower average wages than smaller establishments (e.g., traditional artisanal shops), which is consistent with a deskilling effect of technical change. In contrast, Meyer (2002), using Weeks report data on manufacturing establishments covering 1860 to 1880, finds that wage inequality increased more in industries experiencing rapid technical change, which is consistent with SBTC.

characterized as a general-purpose technology (Crafts, 2004; Rosenberg and Trajtenberg, 2004). The steam engine enabled the conversion of heat energy to mechanical energy, and so any industry that needed portable power might find the steam engine useful. In this paper, we focus on the application of the steam engine to transoceanic transport.

The potential benefits of steam power to water transportation were tremendous. With steam propulsion, a vessel could make progress in its journey even when the wind and current were unfavorable. Thus time to destination was shorter on average and less variable. Steamship companies could publish scheduled routes and promise delivery times. Steam was quickly adopted for river, lake and coastal transport. However, it took a long time before steam became the preferred technology for transoceanic transport. This was because early steam engines required too much fuel for long voyages and thus could not compete with sail. Even in the mid-19th century, daily coal consumption of ocean-going steam vessels was around one hundred tons, meaning much valuable cargo space was usurped for coal storage.

It was not until the mid-1880s, after numerous improvements had been made to the steam engine and the building of steam ships, that steam became more attractive than sail for transoceanic transport.² Ship owner W.B. Forwood wrote in 1891: “[T]he steamer of today can travel five times as far upon the same coal consumption as the steamer of 40 years ago.”³ The world tonnage of sail-powered merchant vessels reached a maximum in 1880, even as world tonnage of merchant vessels grew (Gardiner and Greenhill, 1993, table 1). After the mid-1880s, merchant shipping companies were phasing out sail vessels and adding steam vessels to their fleets. In 1860, only 12% of the world merchant tonnage was steam (some was for inland waterway and coastal trade); the steam share had increased to 46% by 1890 and 76% by 1910.

² Some key improvements included screw propulsion, steel hulls and boilers, and triple expansion engines. See Gardiner and Greenhill (1993).

³ Quoted in Tyler (1939, p. 371).

The Atlantic Canadian ocean-going fleet, which is the source of our data, was slower to adopt steam technology, but caught up quickly. Steam-powered vessels accounted for only 11% of all ocean-going vessels in 1890, but 67% by 1910.

B. The Organization of Production in Steam and Sail

The introduction of steam power created a new group of workers who worked below deck. Both the engineers and engine room operatives spent their work time in the engine room, isolated from the rest of the crew. Engineers attained their positions only after extensive training, including through apprenticeships and technical college. Certification required meeting the training standards as well as passing written and oral exams. The engine room operatives provided unskilled manual labor under the management of the engineers. The most numerous of these engine room operatives were the trimmers, who carried coal from the storage areas to the boiler areas, and the firemen, who shoveled coal into the boilers to generate steam.

Most occupations on sail vessels carried over to steam vessels. The master was in charge of the voyage, assisted by one or more mates. The mates transmitted the master's orders to the non-engine-room workers, commanded a share of the seven round-the-clock watches each day, had responsibility for the cargo, kept the log-book detailing the journey, and made navigational measurements. The mates were capable of performing the physical tasks any able-bodied seaman was, although they rarely had to do them. The majority of the masters and mates had attained their high status only after spending years as able-bodied seamen and passing examinations administered by the government. The mariners—in order of experience, they were the bosuns, able-bodied seamen, ordinary seamen and boys/apprentices—were the production workers on the deck. They undertook a wide variety of tasks under the direction of the mates. This included handling the sails, steering, standing watch, maintaining the appearance and structural integrity

of the ship, and handling lines for docking and departing.

Among the ranks that survived the transition from sail to steam, the nature of the skills involved could have changed. On sail vessels, as one mariner recalled, “three quarters of [one’s] waking time is devoted to fondling rope”⁴ and there were many ropes to learn. Locating and handling the rigging was a skill arduously learned before promotion from ordinary to able-bodied seaman (this took several years at least). These skills did not completely lose their value on steam vessels, as even at the close of the 19th century steam vessels continued to be equipped with sails.⁵ However, considering steam vessels could complete journeys without sails and (as we find below) hired only half as many mariners, they likely valued a different mix of skills.

III. A Framework for Understanding the Impact of the Steam Engine

In this subsection, we discuss the theoretical implications of switching from sail to steam technology using a simple production model. The switch from steam to sail was similar to the movement from the artisanal shop to the factory described in Goldin and Katz (1998) and we adapt their model for the discussion here. In their model, production has two stages. In the first stage, skilled labor (H) and raw capital (K) are used to make usable machines (K*):

$$(1) \quad K^* = \min(\lambda_i^H H, \lambda_i^K K) \quad i=\text{SAIL, STEAM}$$

In the second stage, unskilled labor (L) and K* are used to make the final product (Q):

$$(2) \quad Q = A_i (L)^{\alpha_i} (K^*)^{(1-\alpha_i)} \quad i=\text{SAIL, STEAM.}$$

The Leontief form of the first stage is chosen to highlight the strong complementarity

⁴ Quoted in Sager (1989, p. 133).

⁵ The sails might be stored during a voyage, and the sail plan tended to be less complicated than that for sail vessels. See Gardiner and Greenhill, 1993, Chapter 8.

between skilled labor and capital and is not necessary for the results.⁶ On merchant ships, additional skilled labor was not useful without additional capital; human capital alone does not move ships across oceans, and providing an engine, sail or even oar makes a big difference. Conversely, additional capital was not useful without the additional skilled labor to install and maintain it. On steam vessels, the K was the steam engine, boilers to create steam, and coal to fuel the boilers. Skilled workers, in the form of engineers, “were required to tend the machinery, ensure that it was operating properly, undertake repairs, start, stop and reverse the engines when arriving or leaving port, and supervise the firing of the boilers” (Griffiths, 1997, p.132). The 1862 amendment to the Merchant Shipping Act required all steam vessels to carry certified engineers, “the number depending upon the power of the ship’s machinery” (Griffiths, 1997, p.134). On sail vessels, the K was the masts, spars, sails and ropes. Skilled workers, in the form of able-bodied seamen, handled ropes to achieve desired positions of the masts, spars and sails. The K in all sections of the large vessel had to be manipulated throughout the journey. Sails left unmanned could impede a journey.

Technical change (switching from sail to steam technology) can be expected to change the demand for skilled labor in several ways. First, steam employed more raw capital and less skilled labor in the production of usable capital, K^* . On steam vessels, one skilled worker such as the engineer could be responsible for making a large amount of K usable for production. In contrast, on sail vessels, one unit of K^* encapsulated lots of time spent by skilled seamen working with relatively small amounts of K. One can view this as factor-augmenting technical change where steam technology increased the productivity of skilled labor in the production of

⁶ The two production functions can take a more general constant elasticity of substitution form, and similar results would hold so long as the elasticity of substitution between skilled labor and capital is lower than the elasticity of substitution between unskilled labor and the capital-skilled labor aggregate. See Goldin and Katz (1998), footnote 16.

usable capital, $\lambda^H_{STEAM} > \lambda^H_{SAIL}$. The skilled labor required to produce a unit of K^* on steam is $1/\lambda^H_{STEAM}$ which is less than the skilled labor required on sail, $1/\lambda^H_{SAIL}$. Interestingly, in this case, skill-augmenting technical change which increases the productivity of skilled labor is also “skill-replacing” due to the low elasticity of substitution (we assumed Leontief technology) between skilled labor and capital in the first stage. In other words, steam enables the engineer to take the place of many able-bodied seamen. Of course, it may not be entirely plausible to classify both the engineer and the able-bodied seamen in one category as “skilled labor.” Rather than enhancing existing skills, it may be more appropriate to view steam technology as creating demand for a new skill—the ability to install and maintain steam engines—which engineers possessed.

Technical change also affected the production of output, Q , which we might think of as miles of safe and timely passage in the ocean. Steam technology was more intensive in the use of unskilled labor, L , so that $\alpha_{STEAM} > \alpha_{SAIL}$. Tasks that were previously performed by the capital-skilled labor aggregate were now performed by unskilled labor. On steam vessels, many unskilled workers were used to keep the steam engine running continuously. They carried coal to the boiler and shoveled coal into the boiler. On sail vessels, there were fewer unskilled workers. Less experienced mariners like the ordinary seamen and boys/apprentices might perform the simplest aspects of handling ropes to make the ship sail. It was the skilled mariners, through the K^* , that did most of the work. Overall, the skilled share of total employment, $H/(H+L)$, in the merchant shipping industry will fall despite the capital-skill complementarity provided that α_{STEAM} is sufficiently higher than α_{SAIL} .

IV. Data

We use data on vessels and crew members compiled by the Atlantic Canada Shipping Project at Memorial University at Newfoundland in the late 1970s and published in electronic form by the Maritime History Archive in 1998. Information on vessels are in the vessel registry database, which covers the universe of vessels listed in the shipping registries of ten major Atlantic Canadian ports from 1787 to 1936.⁷ For a subset of the vessels, researchers also compiled information from crew agreements. Crew agreements served as both immigration documents (as the ships traveled from country to country) and binding employment contracts.⁸ They contain each crew member's name, date and place of birth, wages and rank (occupation) among other variables. Researchers recorded individual-level data from the crew agreements for about 30% of the vessels registered in four ports (Saint John, New Brunswick, Yarmouth and Halifax).⁹ For all the vessels registered in these four ports, they recorded data on the voyages taken, including intended destination and duration.

We matched the individual-level data from the crew agreements to the vessel-level data, enabling us to identify the technology on which each worker worked.¹⁰ A vessel makes multiple voyages over its lifetime, and we matched the individual-level data to voyage-level data as well; the voyage is probably the unit most comparable to a firm. A nice feature our data set is that when we have data for one individual, we also have data for every co-worker on that voyage,

⁷ Ship owners of the British Empire were required by law to register their vessels with the customs officer in their home port, and so the database should accurately reflect ships with home ports in Atlantic Canada.

⁸ Most notably, a failure on the part of the employee to fulfill the terms of his contract was a *criminal* offense. The crew list also protected the employee by laying out the responsibilities of the employer. However, most failures by the employer to meet his obligations constituted a civil offense.

⁹ Although all the individuals in the sample served on vessels registered in Canadian ports, they are not necessarily Canadian. Merchant vessels picked up workers at their various ports of call, and Canadian merchant vessels can be thought to be drawing from the same labor supply as merchant vessels registered in other countries. Over fifty nationalities are represented in the sample.

¹⁰ We define a vessel's technology based on the "type of vessel" variable. Researchers placed each vessel into one of seventeen categories, five of which represent vessels equipped to undertake transoceanic voyages. Of these five categories ("ocean-going vessels"), four are sail-only vessels (barquentine, barque, brig and ship), while the fifth identifies steam-powered vessels (steam/sail).

which enables us to measure the composition of the workforce on each voyage for which we have wage data. This is useful for analyzing the organization of production.

For greater comparability across observations, we restricted the sample to international voyages; the domestic coastal trade may have faced different labor market constraints.¹¹ We therefore eliminated individuals on voyages with Canada as both the country of embarkation and country of intended destination, or on voyages less than six months in intended duration, or on small vessels not intended for ocean-going trade. Furthermore, to make the measured wages more comparable, we only included workers paid on a monthly basis in British sterling, U.S. dollars or Canadian dollars.¹² Using exchange rates from Officer (2001), we converted all monthly wages to British sterling. These wages were then converted to 1900 prices using the British consumer price index from McCusker (2002).

Wage data exist from 1861 to 1912. We focus on the period 1891 to 1912, when we have observations on both technologies. Prior to 1891, there are too few observations of individuals working on steam vessels, not only because steam vessels accounted for a modest proportion of the ocean-going fleet, but also because steam vessels were under sampled.¹³ Thus the sample we use has about 20,000 observations, of which nearly 4,000 are for individuals working on steam vessels. It covers 564 voyages by sail vessels and 111 voyages by steam vessels.

V. Results

Table 1 shows the occupational composition of the crew of the average sail voyage and average steam voyage. While total crew size was similar between sail (32) and steam (35), there

¹¹ Some of the domestic voyages pertained to the fishing and whaling industries. Also, employer-employee relationships on domestic voyages were generally more personal than on international voyages (Sager, 1989).

¹² In practice, few workers were paid at a different frequency or in a different currency.

¹³ For more details on the data, see the working paper version of this paper, Chin, Juhn and Thompson (2004).

were striking differences in how it was distributed across occupations. Most dramatically, able-bodied seamen were 70% of the sail crew but only 24% of the steam crew. This 46 percentage point decrease was entirely offset by the addition of workers in the new engine room aboard steam vessels. The steam crew had an average of 16 workers in the engine room, 4 engineers and 12 engine room operatives. It should be noted that able-bodied seamen were not the only skilled manual workers experiencing lower demand after the switch to steam. The sail maker occupation became all but obsolete. Thus, consistent with the model in section III, in the process of technical change, artisans were replaced by a combination of unskilled and highly-skilled workers, and the skilled share of total employment declined.

Columns 5-8 of Table 1 report the average wage and wage bill share by occupation and technology. The average wage was over 40% higher on steam vessels than on sail vessels. Mirroring earlier findings with employment share, the wage bill share of able-bodied seamen fell from 60% to 18% switching to steam, as the wage bill share of the engineers and engine room operatives rose from nil to 52%.

Interestingly, wages paid to both the skilled and unskilled constituents of the engine room were higher than wages for the able-bodied seamen. The higher wages for engine room operatives undoubtedly reflected a compensating differential for the unpleasant work environment in the engine room. The engine room was placed on the lowest level of the ship and made as compact as possible to save space for cargo and steerage, resulting in a dark, poorly ventilated and intensely hot workplace. Sager (1993, p. 44) reports that in the British merchant marine, 100 firemen and trimmers committed suicide in 1893 and 1894: “Driven mad by the heat, they would throw themselves overboard.” The environment for engineers was little better. “Work was hot and often dangerous, many engineers suffering injury through coming into

contact with operating machinery or being scalded while repairing some part of the steam plant” (Griffiths, 1997, p. 133). We must, therefore, conclude that part of the high wage for engineers was a compensating differential. But considering engineers earned more than twice the engine room operatives, much of their wage would have been a premium for skills gained after extensive training and for which remunerative opportunities also existed on land.

The new-skill-demanding (addition of engineers) and skill-replacing (fewer able-bodied seamen and no more sail makers, but addition of engine room operatives) aspects of the switch from sail to steam is reminiscent of the hollowing out of the skill distribution observed in recent data (Acemoglu, 1999), and can be expected to impact the wage structure in the merchant shipping industry. Figure 1 plots the 90th and 10th percentile wages by technology. The 90th percentile wage was higher in steam, but the 10th percentile wage was similar between steam and sail. Consequently, wage inequality was greater in steam than in sail. Over this period, the average 90/10 ratio was 2.1 in sail and 2.9 in steam. At the aggregate industry level, we would therefore expect to observe a large rise in inequality as steam gradually displaced sail, holding all else constant. If we subtracted out the compensating differential, then we would see that as a result of technical change, jobs were being created at the top and bottom of the wage distribution, and being lost in the middle.

The new-skill-demanding aspect of technical change alone accounts for one-third of the increase in mean wage and two-thirds of the increase in wage inequality associated with steam. If engineers were excluded from the sample, the steam premium (i.e., the positive mean wage differential in steam) would decrease from 43% to 26%, and the average 90/10 ratio would decrease from 2.9 to 2.35.

Columns 5-6 of Table 1 document a substantial wage premium associated with steam

within some occupations that survive the transition. For example, mates earned 25% more on steam than did their counterparts on sail and able-bodied seamen on steam earned 21% more. Considering firms hired from the same pool of workers, why did steam vessels pay more for a same-ranked worker than sail vessels? Three broad sets of explanations for the steam premia are as follows. First, observable characteristics of workers (e.g., age, education and country of birth) might have differed between steam vessels and sail vessels. Second, the work environment faced by workers might have differed, perhaps requiring a compensating differential. Third, there may have been unobserved differences in worker quality. The richness of our data enables us to decompose the steam premium into these three categories. This is a useful exercise because it can shed light on whether the steam premia were related to skill, and if so, what type of skill.

Table 2 reports the steam premium that remains after we control for various measures of worker characteristics and work environment in a regression framework. In Column 1, we control for a quadratic in worker age and year dummies.¹⁴ To this specification, we add a dummy for being able to sign one's name (a rough measure of literacy) in Column 2, a full set of country of birth dummies (another rough skill proxy, since where the worker grew up affects his quantity and quality of schooling, training and work experience) in Column 3, some voyage and vessel characteristics in Column 4 and all of the preceding controls in Column 5.

For bosuns, cooks/stewards and ordinary seamen, there is no significant difference in wages between the two technologies once year dummies are added. For mates, the steam premium of 12% observed in Column 1 is half explained by country of birth dummies (Column 3) and half by voyage and vessel characteristics (Column 4). It is plausible that the former is

¹⁴ Only a small fraction of the difference between the raw steam premium implied by Columns 5 and 6 of Table 1 and the adjusted steam premium in Column 1 of Table 2 is due to the addition of the age quadratic (which we might consider a measure of experience). The bulk is due to the addition of year of embarkation dummies. Since macroeconomic conditions are fluctuating leading up to World War I, it is perhaps not surprising that adjusting for year of embarkation makes such a difference.

related to skill.¹⁵ The latter may represent a combination of a skill premium, a compensating differential and an efficiency wage.¹⁶

In contrast, significant unexplained steam premia remain for able-bodied seamen and carpenters. For able-bodied seamen, we are particularly confident that the steam premium is not related to compensating differentials. This is not only because controlling for vessel and voyage characteristics failed to eliminate the steam premium. This is also because of the *absence* of a steam premium for ordinary seamen. Ordinary seamen and able-bodied seamen worked and lived side by side, and differed only in their experience and skill. Since there is no steam premium for ordinary seamen, it would be hard to maintain that changes in the work environment underlie the steam premium for able-bodied seamen.

A plausible explanation for the steam premium for able-bodied seamen is that it reflects a reward for unmeasured quality of the worker. The number of able-bodied seamen on a steam vessel was typically less than half the number on a sail vessel of similar size, possibly increasing the range of responsibilities and tasks performed by any single able-bodied seaman. In a normal voyage by a steam vessel, the skills of the able-bodied seaman might only marginally affect the success of the voyage. However, in a voyage where the steam engine broke down or the coal supply got depleted, the steam vessel would have to revert to sail technology, and the skills of

¹⁵ Steam vessels were more likely to hire British mates, and British mates tended to be paid more, such that when we control for country of birth dummies the steam premium decreases. In our sample, 40% of mates on steam vessels were British, compared to only 23% in sail vessels. In contrast, the proportion of able-bodied seamen that were British is similar between the two technologies (21.1% for sail and 21.6% for steam). The British merchant marine was the earliest adopter of the steam engine, the most widespread user of formal apprenticeships, and the pioneer in professionalizing the service (Burton, 1990), and so the greater tendency to hire British mates on steam can likely be interpreted as related to skill.

¹⁶ The regression results suggest that part of the premium for mates in steam vessels was from having responsibility over a larger cargo (as measured by gross tonnage of the vessel). While at sea, the mates had to ensure the security of the cargo. When the vessel stopped at a port, a mate had to stay behind at the vessel to watch the cargo; the rest of the crew could go pursue the diversions on the land. In our sample, the steam vessels had much higher gross tonnage than sail vessels, and since mates were paid more when gross tonnage increased (the coefficient for gross tonnage is positive and significant), when we omit gross tonnage from the regression we get a higher steam premium.

the able-bodied seamen would be pivotal. It is difficult to handle the whole ship's sails with only a few co-workers. Less specialization is possible. Additionally, it takes some flexibility to adapt the rigging skills learned in a sail vessel to a steam vessel, as the latter sometimes used different sail plans. In other words, among the able-bodied seamen, demand for narrowly-defined, job-specific skills may have been usurped by a demand for general ability.

For carpenters, we can only conjecture about their sizable steam premium. Despite their name, carpenters were expected to be able to work with both wood and iron, the latter being a skill with increasing opportunities on land.¹⁷ Perhaps on steam vessels the ratio of iron to wood work was higher, demanding more skilled carpenters.

We pursued further the question of whether the steam premium reflected unobserved worker quality by exploiting the panel dimension of our data.¹⁸ Unfortunately we observe few individuals who switched between sail and steam—only 24, accounting for 69 observations—so these panel data results must be viewed as merely suggestive.¹⁹ In a regression with individual fixed effects, we still find a sizable though insignificant steam premium.²⁰ We also do not find evidence that these switchers had higher unobserved qualities, since they come from the middle of the residual wage distribution in sail.²¹ Similar to the findings related to industry wage premia (Krueger and Summers, 1988; Murphy and Topel, 1990), the preceding suggests that the steam

¹⁷ Meyer (2002, Figure 2a) compares the daily wages of U.S. wood workers to metal workers from 1855 to 1880. Until 1870, the two groups had similar wages. Afterwards, metal workers received higher wages.

¹⁸ Our data allow us to create a limited panel, matching observations with the same surname, first name, birth year, country and city of birth. To increase sample sizes, we include all years 1861-1922 in this exercise. We start with 168,177 observations which are from 155,492 distinct individuals. The process allows us to identify a substantial panel consisting of 21,948 observations and 9,263 individuals with two or more observations.

¹⁹ Chari and Hopenhayn (1991), whose model has been found consistent with the data used here (Thompson, 2003), predict that no one switches technologies.

²⁰ The coefficient for working on a steam vessel is 0.1418 log points and its robust standard error is 0.10. Additional controls were a quadratic in age, year dummies, and vessel and voyage characteristics as in Table 2, Column 5.

²¹ For each occupation, we examined the percentile position of switchers in the residual wage distribution in sail. The switchers who are mates came from the 46th percentile of the residual distribution and those who were able-bodied seamen came from 56th percentile. We refer the reader to Table 7 of the working paper version of this paper for more detail.

premium may reflect an interaction between worker and workplace characteristics. The absence of a compensating differential for ordinary seamen suggests that the premium did not purely reflect workplace characteristics. The able-bodied seamen possessed a combination of skills valued on steam vessels which distinguished them from those who worked on sail. On the other hand, the same seaman earned a reward for his skills on steam that he would not have earned otherwise in sail.

VI. Discussion

Not much is known about the evolution of the wage structure at the end of the 19th century and beginning of the 20th century because individual-level wage data that are collected consistently over time are not available until the second half of the 20th century. Yet, this is a critical juncture in our economic history. Many of today's modern economies began industrialization then; the modern wage structure has its roots at the turn of the century. We have taken advantage of a data set on merchant mariners to learn about the impact of technical change on the demand for skill and on the wage structure in the merchant shipping industry.

The switch from sail to steam had some elements that were skill-biased and other elements that were skill-replacing. On the skill-biased side, the adoption of steam created a new highly-skilled occupation aboard the ship, the engineer. Also, able-bodied seamen, mates and carpenters employed on steam earned a premium relative to their counterparts on sail, part of which appears to be a reward for skill. On the skill-replacing side, moderately skilled able-bodied seamen were replaced by less skilled engine room operatives for production work. Also, steam made the sail maker occupation obsolete. Overall, the switch from sail to steam seems to be deskilling when one considers the number of skilled and unskilled workers employed by the typical firm.

Since wage inequality was higher on steam vessels than sail vessels, then as steam displaced sail during the turn of the century, the wage structure in the merchant shipping industry as a whole must have widened. The widening is largely attributable to changes at the top of the distribution—mates were paid more on steam than sail, and engineers were paid even more than mates. There was little change at the bottom of the distribution.

The steam engine was applied to many other industries—it was a key force behind the First Industrial Revolution—and the empirical findings here should have relevance for these other industries. A few caveats are in order, however. First, land-based firms could have gotten away with hiring fewer engineers, since they can pay for an engineer when a machinery problem arises. Ships had to staff in anticipation of their problems; once at sea, they would be unable to get additional help. Thus the number of skilled jobs created by steam in other industries might be fewer than predicted from the example of the merchant shipping industry. Second, in contrast to the land-based firms, the merchant shipping industry crossed country borders: the crew came from all over the world. The impact of steam on a particular country's wage structure therefore depends on what types of workers the country supplies. Britain, which supplied a disproportionate share of the engineers in steam vessels, gained more skilled jobs than any other country, and so technical change might appear more skill-biased for Britain than other countries. Finally, part of the steam premium that we observed could have been temporary, owing to the shortage of qualified engineers.

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TABLE 1. Composition of the crew: sail voyages vs. steam voyages

	Employment		Employment Share (%)		Average Wage (£ 1900)		Wage Bill Share (%)	
	Sail (1)	Steam (2)	Sail (3)	Steam (4)	Sail (5)	Steam (6)	Sail (7)	Steam (8)
1-mate	2.0	2.5	6.9	7.3	7.32	9.15	13.9%	12.2%
2-bosun	1.1	0.5	3.9	1.4	5.51	5.13	5.6%	1.2%
3-able-bodied seamen	22.6	9.0	70.0	24.4	3.50	4.22	60.2%	18.1%
4-ordinary seamen	2.4	0.9	7.0	2.9	2.35	2.71	4.8%	1.5%
5-cook/steward	1.6	2.5	5.6	7.7	6.51	6.17	10.0%	8.9%
6-carpenter	0.8	0.6	2.4	1.9	5.36	5.43	3.5%	2.0%
7-sailmaker	0.1	0.0	0.2	0.0	3.86	--	0.3%	0.0%
8-engineer	0.0	3.9	0.0	12.3	--	10.64	0.0%	24.3%
9-engine room operatives	0.0	12.0	0.0	33.5	--	4.56	0.0%	27.9%
10-other	1.2	2.9	3.9	8.5	1.48	2.43	1.7%	3.8%
Total Crew	31.8	34.7	100.0	100.0	3.93	5.54	100.0%	100.0%

Notes: Data on individuals with years of embarkation 1891-1912 were used, encompassing 564 voyages by sail vessels and 111 voyages by steam vessels. Each voyage was equally weighted. Columns 5-8 are calculated using individuals with non-missing wages. The data set contains 70 different occupation codes, which we have aggregated as follows:

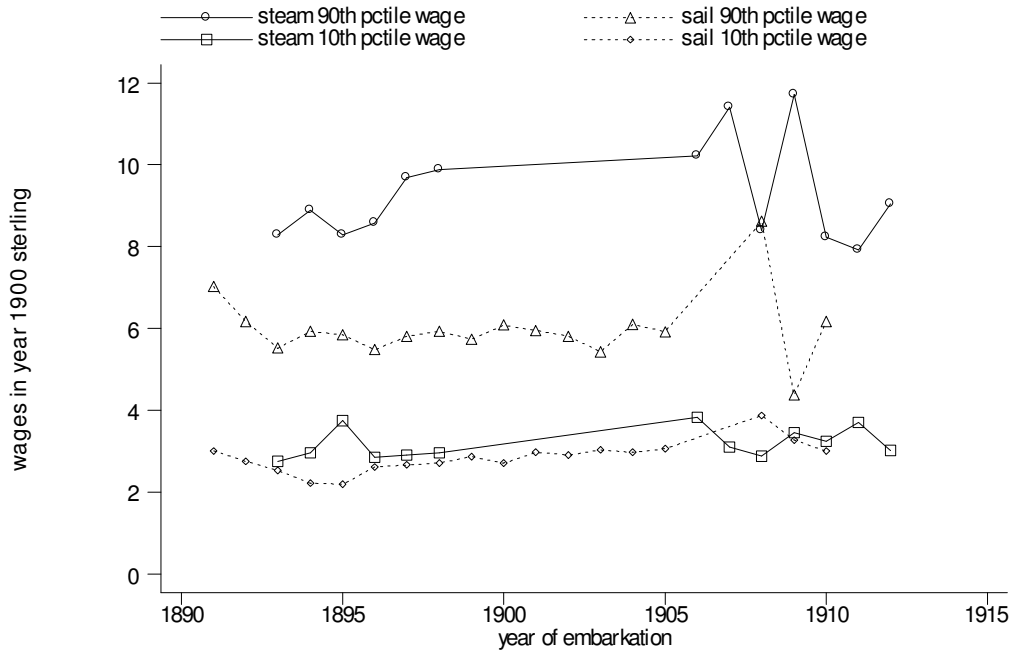
<i>Aggregate occupation:</i>	<i>Includes:</i>
1-mate	First Mate, Second Mate, Third Mate
2-bosun	Bosun, Bosun/Mate
3-able-bodied seamen	only one occupation
4-ordinary seamen	only one occupation
5-cook/steward	Cook, Steward, Cook/Steward
6-carpenter	Carpenter, Carpenter/Bosun, Carpenter/AB, Carpenter's Mate, Second Mate/Carpenter
7-engineer	Engineer, Second Engineer, Third Engineer, Fourth Engineer
8-sailmaker	Sailmaker, AB & Sailmaker, Bosun & Sailmaker
9-engine room operatives	Leading Fireman, Fireman, Bosun & Lamp Trimmer, Fireman & Trimmer, Donkey Man, Trimmer (Steamer), AB & Lamp Trimmer, AB & Trimmer, Oiler & Greaser
10-other	All other occupations, predominantly Boy, Stewardess, Apprentice, Stowaway and Assistant Steward

TABLE 2. Regression-adjusted cross-technology differences in wages by occupation

		Difference in <i>log wage</i> for steam, regression-adjusted for				
		<i>Specification in column 1 plus:</i>				
		age quadratic and year dummies	literacy proxy	country of birth dummies	voyage characteristics	all previous controls
		(1)	(2)	(3)	(4)	(5)
Mate	Log difference:	0.1221 ***	0.1232 ***	0.0634 **	0.0558	0.0352
	Standard error:	(0.029)	(0.029)	(0.029)	(0.034)	(0.034)
	No. observations:	1,337	1,337	1,327	1,258	1,249
Bosun	Log difference:	-0.0022	-0.0140	-0.0143	-0.0522	-0.0560
	Standard error:	(0.059)	(0.060)	(0.059)	(0.071)	(0.067)
	No. observations:	659	659	651	637	629
Able-bodied seaman	Log difference:	0.1674 ***	0.1677 ***	0.1676 ***	0.2157 ***	0.2203 ***
	Standard error:	(0.026)	(0.026)	(0.026)	(0.028)	(0.028)
	No. observations:	12,448	12,448	12,232	12,062	11,852
Ordinary seaman	Log difference:	-0.0781	-0.0723	-0.0300	-0.0151	0.0318
	Standard error:	(0.109)	(0.105)	(0.103)	(0.100)	(0.092)
	No. observations:	1,315	1,315	1,281	1,290	1,256
Cook/ steward	Log difference:	0.0002	-0.0044	-0.0254	-0.0006	-0.0361
	Standard error:	(0.032)	(0.032)	(0.035)	(0.047)	(0.052)
	No. observations:	1,094	1,094	1,083	1,033	1,024
Carpenter	Log difference:	0.1743 ***	0.1690 ***	0.1585 ***	0.2309 ***	0.2190 ***
	Standard error:	(0.032)	(0.033)	(0.039)	(0.065)	(0.061)
	No. observations:	485	485	478	463	456

Notes: Data on men aged 16 to 60 with years of embarkation 1891-1912. Each cell comes from a separate regression. Robust standard errors are in parentheses. Single, double, and triple asterisks denote 90%, 95% and 99% level of confidence, respectively. Voyage characteristics are crew size (quadratic), whether embarking from home country, whether discharging at home country, gross tonnage, year ship was constructed, and intended duration (quadratic).

FIGURE 1. Wages by technology



Notes: Raw statistics computed from sample of 19,773 men aged 16 to 60 (16,218 from sailing vessels and 3,555 from steam vessels). Year-technology cells with fewer than 25 observations have not been graphed.