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SPINNING THE WEB:
THE IMPACT OF ICT ON TRADE IN INTERMEDIATES AND TECHNOLOGY DIFFUSION

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ABSTRACT

This paper studies how information and communication technology (ICT) improvements affect trade along the value chain and international technology diffusion. We examine the impact of a revolutionary technology, the roll-out of the global telegraph network, on the 19th century cotton textile industry. First, we show that connection to the telegraph disproportionately increased trade in intermediate goods relative to final goods. We document that this was due to differences in codifiability; that is, the extent to which product specifications could be communicated at a distance using only words (and thus by sending telegrams) as opposed to inspecting a sample of the product. Second, adoption of the telegraph also facilitated international technology diffusion through the complementary mechanisms of importing machinery and acquiring knowledge of the production process and local demand through importing intermediates. These results shed light on how ICT facilitates the formation of global value chains and the diffusion of frontier technology.

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An Online Appendix is available at
https://drive.google.com/file/d/18s_Qz6EOlMb_RtsQqTQ_F6xhbueTNGHf/view

1 Introduction

This paper is motivated by the observation that economic integration across countries has become more complex. Global value chains that require the careful coordination of production across large distances now span the globe (Feenstra, 1998), with trade in intermediate goods accounting for a significant share of total global trade (Miroudot et al., 2009). In addition, some authors have argued that as parts of the production process were offshored from high-wage to low-wage countries, "Northern" technology also followed, allowing some initially poor countries to develop at previously unprecedented rates (Baldwin, 2016). Dramatic improvements in information and communication technology (ICT) are widely believed to be a driver of the increasingly complex nature of integration in the global economy (Baldwin and Martin, 1999; Baldwin, 2016). According to this argument, the reduction of the cost and the type of information that can be exchanged makes possible the coordination of complex tasks at a distance (Grossman and Rossi-Hansberg, 2008; Leamer and Storper, 2001).

This paper aims to deepen our understanding of the forces driving trade in intermediates and technology diffusion by examining the effect of a revolutionary information communication technology, the roll-out of the global telegraph network in the second half of the nineteenth century, on the cotton textile industry. In particular, we estimate the effect of communication time improvements on imports of intermediate and final goods in the industry as well as on the subsequent adoption of frontier technology.

The setting serves as an ideal testing ground for these questions for a number of reasons. First, estimating the causal effect of ICT on economic outcomes is notoriously difficult as investment in communication technology is generally systematically related to economic fundamentals. In the case of the global telegraph network, we exploit the fact that the technology took decades to develop and mature, leading to significant variation in the year the telegraph was adopted in different countries. We use one factor, variation in the ruggedness of the submarine terrain, that made laying the cable more or less challenging in a particular location to isolate exogenous variation in the timing of a successful cable connection (Company, 1915). This was a factor that contemporaries were initially unaware of, and later was difficult to account for, given that the sea floor could not be mapped in detail at the time.

Second, standard trade data sources make it difficult to distinguish between intermediate inputs and final goods, making it challenging to analyze how factors such as ICT affect trade along the value chain. The cotton textile industry provides a rare exception where it is possible to definitively separate the stages of production. Cotton textile manufacturing is a fairly simple, linear value chain comprised of three stages of production (spinning, weaving, finishing). The output of each stage is typically delineated separately in trade data: yarn, plain cloth, and finished cloth. The first two categories, yarn and plain cloth, are intermediate inputs, whereas finished cloth is the final good. Moreover, owing to a number of major technological breakthroughs, Britain completely dominated trade in cotton textiles for the vast majority of the 19th century at all stages of the production process. Taking these factors together, it is possible to recover the global supply chain using only bilateral British product level trade data.

Third, the historical setting makes it possible to study long run impacts of ICT and trade in intermediate inputs on technology diffusion, which is highly relevant but not feasible with contemporary data.

Our empirical analysis consists of two parts. First, we ask how communication time affected imports of cotton textiles at different stages of the production chain. We find that communication time improvements had a larger trade enhancing effect on intermediate inputs than on finished goods. According to our preferred specification, a 1% fall in communication time increased imports of yarn by 0.27%, by 0.13% for plain cloth, and by 0.03% for finished cloth, though this latter effect is not statistically significant.

To shed light on the mechanism driving these findings, we exploit the rich historical evidence to understand how merchants conducted trade at a distance both prior to and after the introduction of the telegraph. We show how before the introduction of the telegraph, buyers and sellers exchanged information about product attributes at a distance by sending letters and product samples using the fastest method of transportation. The introduction of a telegraph connection between the buyer and seller dramatically affected the time it took to exchange information specified in words, but had no effect on the time it took to exchange information that could not be expressed in words, such as product samples.

In this paper, we use the term *codifiability* to refer to the extent to which attributes of a product can be specified in words as opposed to inspecting a sample of the product. We use a telegraph codebook developed for trading cotton textiles to gauge the extent to which communication was in line with what we would expect given the differences in the codifiability of our product categories. Yarn was a standardized product categorized based on its fineness, and the telegraph used this standard classification in the order process. Plain cloth, while not standardized, could be codified by providing information on a handful of characteristics, such as measurements and weaving patterns. While more complicated and hence more costly, the telegraph was used to specify these characteristics when ordering plain cloth. For the final good, finished cloth, no instructions were provided using the telegraph. Specifying an order for finished cloth remained reliant on the exchange of product samples even after the telegraph was put in place, as this part of the production process was non-codifiable. In light of this evidence, the extent to which imports increased along the value chain in response to the introduction of the telegraph was systematically related to the codifiability of the product.

Second, we turn to examining the long-run effects of ICT on trade in intermediate inputs. We show suggestive evidence that imports of yarn increased up to 10 years after the introduction of the telegraph, but after that, the effect began to decline. We find no similar non-monotonicity on imports of plain or finished cloth. A natural explanation for this pattern is that over time, yarn importing countries started to develop their own mechanized industries. Our estimates show that countries that had been connected to the telegraph for a longer period of time at the end of the 19th century had larger growth in mechanized cotton spinning capacity, suggesting that ICT facilitated the adoption of frontier technology.

The historical evidence emphasizes two complementary mechanisms that allowed the transmission of technology from Britain (Farnie, 2004). The spinning machinery itself was imported from Britain, the world's leading machinery manufacturer. But having machinery alone was not sufficient; to successfully operate modern cotton mills, managers needed to have knowledge about the whole system of the production process and local demand conditions. As merchants accumulated this knowledge from importing yarn, cotton mills appointed them as their managers. Imported machinery together with knowledge acquired through imported intermediates made possible the diffusion of technology. We find evidence for these mechanisms in the data. Using data on trade in mechanized spinning machinery, we show that countries that achieved a telegraph connection sooner imported more machines from Britain in the long-run. In addition, by matching names of local and British merchants from trade directories to the names of managers from a directory of cotton mills for Bombay, we also find that 28-46% of managers were indeed merchants, providing suggestive evidence of the knowledge transfer mechanism.

The paper is related to several strands of the literature. To the best of our knowledge, we provide the first causal estimates of ICT's impact on trade along the value chain. The paper shows evidence in support of the argument that ICT has been an important factor facilitating the formation of global value chains by disproportionately increasing trade for codifiable intermediate inputs (Baldwin and Martin, 1999; Grossman and Rossi-Hansberg, 2008; Baldwin, 2016).

Codifiability of tasks or product specifications is one mechanism that has been argued to facilitate offshoring and fragmentation of production in the contemporary setting (Leamer and Storper, 2001; Autor et al., 2003). In this respect, the paper is most closely related to Fort (2016), who shows that codifiability of product specifications are associated with a firm's willingness to contract for manufacturing services either domestically or internationally. In addition, Startz (2017) finds that in the contemporary setting in which ICT is far more sophisticated, Nigerian merchants expend significant resources in order to travel to the source country and purchase products through face-to-face interaction with the seller, suggesting that specifying product specifications at a distance remains difficult.

A number of papers have studied how information and search in general affect trading patterns (Rauch, 1999; Rauch and Trindade, 2002; Startz, 2017) and some papers have examined the impact of ICT on trade (Freund and Weinhold, 2004; Portes and Rey, 2005; Fink et al., 2005; Allen, 2014; Steinwender, 2018). The paper contributes to this literature by providing causal estimates of the impact of ICT on trade along the value chain, allowing us to speak to how ICT impacts the composition of trade.

In terms of ICT's effect on technology diffusion through the imports of intermediates, the paper is related to a recent literature that has shown that better access to (high-quality) imported inputs has a positive effect on firm productivity (Amiti and Konings, 2007; Topalova and Khandelwal, 2011). The results in this paper suggest that importing intermediates may allow firms to learn about the production process for these inputs in the long-run, allowing countries to move into new parts of the value chain using frontier technology, facilitating technology diffusion through importing as discussed in Keller (2004).

The paper is structured as follows. The next section discusses features of trade in the 19th century cotton textile industry that are key for our empirical strategy. Section 3 introduces the main datasets used in the empirical analysis. Section 4 contains the empirical analysis. Section 5 concludes.

2 Trade in cotton textiles in the 19th century

Cotton textile manufacturing is a fairly simple, "snake" production chain comprised of the following three stages: First, raw cotton fibers are twisted into yarn in a process called spinning. In the second step, yarn is woven into cloth in a process called weaving. Finally, cloth is finished by bleaching, dyeing, embroidering or printing patterns on the cloth. In what follows, we refer to the products produced at each stage of the production process as *"yarn"*, *"plain cloth"* and *"finished cloth"*. Yarn and plain cloth are intermediate inputs, whereas finished cloth is the final product of this industry. Figure 1 provides examples of products at each stage of the value chain. Below, we discuss features of trade in cotton textiles during the 19th century that are important for the empirical analysis.

2.1 British dominance of the industry with technology diffusion

Cotton manufacturing was a leading industry during the First Industrial Revolution owing to a number of key innovations forged in Britain in the late 18th and early 19th century.[1] These innovations reduced the prices of machine spun yarn and woven cloth dramatically, as shown in Figure A.1. Importantly for our setting, this led to Britain becoming the largest producer and exporter of cotton textiles for most of the 19th century.

Table 1 provides data on the value of exports of yarn and cloth for the most important cotton textile exporters for 1871 to 1880, the last decade of our sample period in the trade data. As is apparent from the table, Holland, Germany, and France, the most important cotton textiles exporters behind Britain, each exported under 4% of Britain's value. This aspect is helpful for our

[1] Appendix A.1.1 discusses the various innovations in cotton textile manufacturing in detail. Crafts (1985) estimates that cotton textiles accounted for 25% of British TFP growth between 1780 and 1860. The importance of the industry for global trade is well reflected by the fact that cotton textiles were also the most traded good during the age of industrialization (Riello, 2013).

analysis, as we only observe bilateral trade flows between Britain and the rest of the world, but not total imports of cotton textiles in a specific country. However, given Britain's dominance of trade in the industry, we do not expect unobserved imports from other countries to confound our analysis.

Though Britain dominated trade in the industry, its primacy in terms of production was not quite as overwhelming. Mechanized technology diffused worldwide, particularly during the second half of the 19th century, as Figure 2 shows. Moreover, in the weaving industry, traditional hand-loom weaving often survived British import competition, particularly in lower-wage regions such as India and the Ottoman Empire (Beckert, 2014; Roy, 2010). The presence of domestic manufacturing (mechanized or not) in a wide variety of locations around the world implies that imports were often in competition with domestic production. This is helpful in terms of our analysis, as it means that there was indeed scope to trade intermediates across international borders as many regions around the world possessed absorptive capacity in the form of a cotton manufacturing industry. Furthermore, the presence of technology diffusion in mechanized production provides scope for us to examine the extent to which ICT facilitated technology diffusion.

2.2 The importance of trade in intermediate inputs

Crucially for the empirical analysis, in which we estimate the effect of communication time improvements at different stages of the value chain, there was significant trade in intermediate inputs in the cotton textile industry. Figure 3 shows the share of yarn, plain and printed cloth exported by Britain to the world between 1845 to 1880, our sample period. It is striking that about 70% of total trade is in one of the intermediate stages, yarn or plain cloth, while the final good, finished cloth, accounts for only about 30% of trade.[2] This is a particularly interesting point to note, as it offers a portrait of 19th century trade that is substantially different to how the pattern of trade during the first wave of globalization is often represented: as consisting of mainly trade in raw materials and finished goods.[3]

2.3 Codifiability affects the usefulness of the telegraph for exchanging information

In the case of 19th century cotton textiles, timely information about distant markets was crucial. Much like the apparel industry today, cotton textiles in the 19th century was an industry characterized by rapidly changing product cycles (Llorca-Jana, 2012). Prints and patterns in fashion would change from one season to the next, meaning that merchants needed to specify attributes of the particular type of product that was in fashion in a particular market at any given time.

[2]The importance of trade in intermediate goods can be seen both in terms of quantities and values traded.

[3]For example, Baldwin (2006) highlights trade in intermediates as a distinguishing feature of the second wave of globalization.

The historical evidence points to fluctuating demand as affecting a significant proportion of the market. Llorca-Jana (2012, p. 108) quotes a Latin American based merchant advising that "care must be taken that every fresh parcel is composed of different and newest patterns to the preceding as if parcel after parcel arrive of the same patterns and designs our dealers will soon get tired of them."[4] Novelty, however, was not sufficient, as demand was not only volatile, but also highly market-specific; "(...) goods must be manufactured entirely for these markets to make anything by them." (Llorca-Jana, 2012, p. 96).[5]

It should also be noted that fluctuating demand affected not only the final good, but also the intermediate products, yarn and plain cloth. The type of finished cloth that could be produced was determined in part by the type of yarn and plain cloth that was used in its production. Llorca-Jana illustrates this point as follows; "The principal cause of your loss in these first shipments arises according to our opinion from the change in demand for cloths that has latterly taken place in our markets [Chile]. When you commenced your consignment, the advices received were very favourable for star cloths ... but before the goods came out a change had taken place and the principal demand was on good and middling cloths." (Llorca-Jana, 2012, p. 98).[6]

In light of the evidence above, when ordering cotton textiles at a distance, the attributes of the product needed to be specified. This was easier for some, and more difficult for other product categories. Yarn was a standardized product classified according to a metric, its count.[7] This attribute determined the fineness of the yarn that was spun, and was straightforward to specify in words.

In contrast, plain cloth was not standardized, meaning that there was no shorthand terminology that had the same meaning to all parties. Instead, a number of product characteristics such as the weaving pattern, the length and width of the cloth, and the count and color of yarn used had to be specified.

Finished cloth was the most difficult to specify in words. A particular piece of finished cotton cloth was specified by the count of yarn used, the type and measurements of cloth woven and the technique or pattern that it was finished with. A cursory look at the intricate printed design shown for finished cloth in Panel C of Figure 1 should go a long way in convincing the reader of the inherent difficulty in specifying, using only words, the product in question.

Llorca-Jana (2012) describes the difficulties in specifying orders for finished cloth in words by merchants in South-America in the 19th century in the following way; "Even if agents in the Southern Cone could establish with certainty the sort of goods that would be in most demand, they still had great 'difficulty of specifying, in words, and at a distance of several thousand miles and

[4]GFDP, Hughes to Garrett (London). Buenos Aires, March 8, 1843, quoted in Llorca-Jana (2012).

[5]UGD/28/1/2, Wylie to Daglish (Glasgow). Buenos Aires, December 23, 1809, quoted in Llorca-Jana (2012).

[6]HPEL, Volume 6, Huth to Waterhouse (Leeds). London, November 6, 1830, quoted in Llorca-Jana (2012).

[7]Count was a measure of density. It was the number of hanks (840 yd or 770 m) of skein material that weigh 1 pound (0.45 kg). Under this system, the higher the number, the finer the yarn.

several months, exactly what was wanted'.[8] Very often British manufacturers got it wrong, as seen in this extract (...) 'Your ideas with respect to the dresses ... have been sadly disappointed ... [and] it is another proof, out of great many which the writer has seen, of the great risk in sending fancy goods to a foreign market, when not selected by a person who knows exactly the article wanted, as it appears the plainest written description which can be given, is seldom correctly understood.'[9]" (Llorca-Jana, 2012, pp. 98-99). To overcome the inherent difficulty of communicating attributes of the finished cloth in words, the standard practice was to send product samples (Llorca-Jana, 2012).

Given the need for timely information, it is unsurprising that the telegraph was rapidly adopted by textile traders. Moreover, as a way of minimizing telegraph charges, specific codes were developed for traders of cotton textiles, and published in telegram code books.

However, according to the historical evidence, the telegraph was differentially useful for exchanging information about product specifications at a distance at different stages of the production chain. In this paper, we use the term *codifiability* to refer to the extent to which attributes of a product can be specified in words as opposed to inspecting a sample of the product. This definition is key, as the introduction of the telegraph dramatically reduced communication time for exchanging words, but not for exchanging physical product samples, implying that the telegraph may have had a differential effect on products depending on their codifiability.

We examine the extent to which instructions about product specifications were communicated using the telegraph depending on product type by examining the telegraph codes which were developed specifically to trade cotton textiles. Figure 4 shows excerpts from the telegraph code published in "Liddel's The 'Economic' Telegram Code for Piece Goods and General Business".

The first column shows the code that specifies the count of yarn. Consistent with the discussion above, as yarn was standardized and therefore a highly codifiable product, we see the code numbers corresponding to the count of yarn.

The second column shows examples of how the telegraph was used to order plain cloth. Several characteristics described above were in fact communicated using the telegraph. For example, "buy for us a trial lot one pick less in the weft" instructs the exporting merchant about the type of weave that is demanded, "send samples of this made of heavier yarns" instructs the exporting merchant about the type of yarn that should be used in the cloth, while the last photo shows a table that buyers can use to specify measurements. However, it is also clear that it was more costly to specify plain cloth compared to yarn, as more product attributes needed to be communicated in a non-standardized way.

Finally, the third column shows product specifications related to finished cloth. In stark contrast to plain cloth, we find no instructions to the exporting merchants about how the finishing should be done. Conversations about finished cloth were restricted to discussing product samples. For example; "We cannot give the following patterns – we are sending substitutes for approval". Note

[8]Smail (1999) p. 83 quoted in Llorca-Jana (2012).

[9]UGD/28/1/7, Wylie Cook to Daglish (Glasgow). San Luis de Potosi, June 22, 1834 quoted in Llorca-Jana (2012).

how there are no details given about the substitute pattern. Instead, the telegraph was used to negotiate prices and quantities, and other terms and conditions of delivery – everything however, always subject to inspection of a product sample. (Farnie, 2004, p. 38) writes, "Mail advices became restricted to the dispatch of samples, general discussion, hypothetical inquiry, advice, admonition and complaint".

The telegraph improved communication technology by dramatically reducing the time it took to exchange information expressed in words, which is more relevant for products that are codifiable. In the case of cotton textiles, the telegraph made it easiest to order yarn, followed by plain cloth, while the impact on ordering finished cloth was smallest. In the empirical analysis we therefore expect the telegraph to have had the largest effect on yarn, followed by plain, and then printed cloth, if the mechanism by which the telegraph affected trade is via codifiability.

3 Data

Our empirical analysis estimating the effect of communication time on imports of different product categories is based on a number of novel datasets constructed from primary sources for the years 1845 to 1880. This time period covers the initial roll-out of the global telegraph network. 1851 marks the year the first underwater telegraph was put in place (between Britain and France). By 1880, most countries were connected to the telegraph. The data sets include: 1) Bilateral British exports at various parts of the cotton textile value chain that we digitized manually from handwritten customs records, 2) "communication times" and "mail shipping times" (measured in days) between Britain and the countries in our dataset for each year using data from the Lloyd's List, and 3) the year in which a country was first connected to the global telegraph network using data on submarine cables from Wenzlhuemer (2013), supplemented with the most important international overland connections from a variety of country-specific sources.

With respect to the second data set, we collected data on communication and mail shipping time relative to Britain from the Lloyd's List, a daily London-based publication which printed the most up to date shipping information for ports worldwide.[10] We used optical character recognition (OCR) technology to convert images into text files and text matching tools to extract information on the dates of ship movements in foreign ports, and the date the information about this ship movement was published in London. We then compute the difference between these dates, which measures how fast information traveled, i.e., the information lag.[11] We define communication time as the minimum information lag across all observations in a port*year, and mail shipping time as the median information lag. We are able to track communication and mail shipping times separately

[10] Our method follows Kaukiainen (2001) who collected communication times for a number of ports at decadal intervals from the Lloyd's List between 1820 and 1870.

[11] As the overland telegraph network was well-developed within Britain by 1850, it is reasonable to assume that the information lag relative to production regions in Britain, i.e., Lancashire, was very similar to that of London.

as even once the telegraph was adopted for a given port, both forms of technology were used to communicate information to London.[12]

To estimate the effect of communication technology on the development of the domestic mechanized cotton spinning industry in the long run, we use data up to WW1. Data on mechanized spinning capacity, measured as the number of mechanized spindles normalized by population, is only observed for a sufficiently large number of countries before the roll-out of the global telegraph network (1845) and once the network is well-established (1880, 1890, 1900, 1910), using a variety of sources based on Farnie (2004) and Beckert (2014).

To shed light on the mechanism, we use bilateral exports of textile machinery from Britain for the years 1878-1914 using firm level data on the number of spindles exported to firms around the world by British machine producers, which were the dominant exporters of capital equipment (Saxonhouse and Wright, 2010), collected by Saxonhouse and Wright (2004). Appendices A.3 - A.4 contains a more detailed discussion of the construction of each data source in addition to the variables that are used in the robustness checks.

4 Empirical analysis

In this section we estimate the effect of ICT on trade along the value chain and the development of the domestic industry in technological follower countries. We first discuss how the introduction of a revolutionary information communication technology, the telegraph, affected communication times around the globe. As the roll-out of the telegraph is potentially endogenous to trade potential of different countries, we discuss our identification strategy based on the ruggedness of the submarine terrain. We then present the estimation results.

4.1 The impact of the telegraph on communication times

It is hard to overstate the impact that telegraphy had on the speed at which information expressed in words traveled. Prior to the development of telegraphy, information was able to travel only at the speed of the fastest mode of transportation. This meant that even when frontier technology such as steamships and railways were used to deliver information, the speed of communication was painfully slow.

Our newly collected data on communication time enables us to provide evidence for the astonishing reductions in communication time brought about by the telegraph. Figure 5 plots communication times (pink lines) for three ports relative to London (Madras, New York and Constantinople). Communication time fell gradually in the lead-up to a telegraph connection, reflecting transportation technology improvements. However, there is a sharp drop in communication times at the vertical lines which indicate the year the port was connected to London via the telegraph. For

[12] More details on the data collection and extraction are provided in Appendix A.4.

comparison, we are also able to examine mail shipping times, which track the number of days it took to ship mail (i.e., letters, newspapers, and product samples) between London and the port in question using the fastest mode of transportation.[13] Communication and mail shipping time fell in parallel up to the year of connection to the telegraph. This reflects the fact that prior to the telegraph, information could only travel as fast as the quickest mode of transportation. Once a port was connected to the telegraph network, however, there was stark divergence between the two, as communication time dropped to within a couple of days, while mail shipping time continued on its previous trend.

Figure 6 shows heat-maps for communication times around the world during our sample period. Communication lags relative to Britain are shown for every decade between 1850 and 1880. In 1850, most of the world is colored in red or orange, meaning it takes several weeks to communicate between London and these countries. Communication time increased with distance, reflecting the fact that it was still determined by the fastest mode of physical transportation. By 1880, most major ports were within instantaneous communication with Britain. Distance now had very little role to play in determining communication times.

4.2 Identification strategy

Figure 7 shows the first telegraph links via which countries in our sample were connected to the worldwide telegraph network.[14] We define a country as having a connection to the global telegraph network if it has an active (terrestrial and/or submarine) connection to London. As is apparent from this figure, it took decades for all countries to be connected to the worldwide telegraph network.

Investments in ICT infrastructure, such as the laying of submarines telegraph cables, may be systematically related to trade potential or economic development. This poses an empirical challenge when estimating the effect of communication technology on our outcomes of interest. In the case of the roll-out of the global telegraph, we exploit the fact that entrepreneurs faced significant technological challenges and setbacks in laying submarine cables. Our identification strategy relies on one geographic aspect of laying submarine cables that introduced quasi-random variation in the difficulty of establishing a submarine connection; the ruggedness of the underwater terrain. A rugged sea-floor made laying a telegraph cable particularly difficult as the cable would break if it became suspended between two peaks (Company, 1915). Laying a cable across a rugged sea bed also meant that the cable had to be longer, which made the transmitted signal weaker and noisier, because automatic signal re-transmission had not yet been invented. It also made the cable heavier, which put more strain on it, making it easier to break during the cable laying process, or afterwards, when it chafed against sharp rocks as the cable moved with the currents.

Given the state of contemporary technology, mapping the sea floor in any meaningful detail

[13] This was not generally the mode of transportation taken for shipping merchandise.

[14] Our data end in 1899. At this point in time, only a handful of countries (almost all of which are small islands) in our sample are unconnected.

was impossible. The lack of understanding implied that progress was made through trial and error. To illustrate the extent to which contemporaries were initially unaware of the ruggedness of the submarine terrain along a given connection, it is instructive to compare the elevation profile of the ocean floor along the Atlantic cable route in Figure 8 with the description the New York Times gave based on the soundings that had been taken; "[the telegraphic plateau] extends in a *continuous ledge* from Cape Clear, in Ireland, to Cape Race in Newfoundland; the greatest depths being in mid-ocean whence it *ascends imperceptibly* to the shore on either side."[15] Contemporaries were aware neither of the steep drop in elevation on both side of the Atlantic, nor the significant amount of ruggedness along what they called the telegraphic plateau, that modern data shows in Figure 8. This was problematic, as the amount of slack cable that should have been laid depends crucially on getting the elevation changes right. In fact, it took five attempts over the course of almost a decade to establish the first successful transatlantic telegraph connection.[16]

Our identification strategy isolates exogenous variation in the year a country was connected to the telegraph by using variation in the ruggedness of the submarine terrain to predict the year of the first successful connection to a given country. To measure ruggedness of the submarine terrain, we use the Riley measure of local ruggedness as proposed by Riley et al. (1999) and first used in the economics literature by Nunn and Puga (2012). As a robustness check, we also construct a second measure, *normalized cable length*, defined as the ratio between 3-dimensional and 2-dimensional distance along the shortest path. This measure naturally captures one way in which historical accounts claim ruggedness mattered; the amount of "slack" that is needed because of underwater peaks and troughs.

We operationalize both ruggedness measures as follows. The nodes that make up a given connection between a country c and London are taken from the global telegraph network that we constructed (Figure 7). This is the shortest path along which a country was first connected to London, using any combination of overland and submarine connections.[17] To locate the actual path along which ruggedness will be measured, we take the two endpoints of all submarine connections and find the shortest sea-route between them. Note that the actual cable might have been laid on a different route. We prefer to use the shortest distance route, as ex ante this is the most economical (longer cables were costlier) and hence exogenous, while the path of the actual cable may be endogenous if routes were changed after difficulties were experienced. The Riley measure of ruggedness and the normalized cable length measure are then calculated along this route.

Calculation of the *Riley measure* proceeds as follows. To calculate ruggedness in a representative area around the shortest path, we take a 25km buffer along both sides of the shortest route. Within this area, we then calculate a measure of local ruggedness as proposed by Riley et al. (1999). This

[15]"The Atlantic Cable. Successful Completion of the Great Work", *The New York Times*, July 30, 1866 (own emphasis).

[16]Appendix A.1.2 discusses additional historical evidence regarding the difficulty of laying submarine cables.

[17]Construction of the global telegraph network is discussed in detail in Appendix A.4.

measure is designed to capture local changes in the terrain. This is well-suited to our purposes, as it was precisely local variation in elevation that was difficult to map for contemporaries, yet crucially important for the success of a given link. As knowledge about laying submarine cables advanced, depth was measured at a few points along a proposed route, giving an approximation of large changes in elevation. However, it was not possible to map the more local aspects of ruggedness, which is the type of terrain variation that our measure utilizes.

Ruggedness is defined at a point in space. The measure is the square root of the sum of the squared differences in elevation between a point and its eight neighbors (ie. the point to the north, north-east, east, south-east, south, south-west, west and north-west).[18] We calculate this measure of ruggedness for each cell within the 25km buffer. Following the methodology in Nunn and Puga (2012), we take the mean of the ruggedness measure (defined at the level of individual cells) along the 25km buffer of the given connection (edge), which we denote as R_i (mean ruggedness for edge i). In the majority of cases, a connection between London and a country was made up of multiple edges. We define the ruggedness of a connection in our dataset as the maximum across all edges that form a particular connection. This captures the idea that the edge with the largest ruggedness measure will be the binding constraint for establishing the full telegraphic connection to that place. Normalized cable length is calculated as the ratio between 3-dimensional and 2-dimensional distance along the shortest path (including only submarine edges).

We predict the year a country is first connected to London based on these ruggedness measures using a linear probability model. This yields non-integer predictions, which we round to the nearest integer. We need integer predictions of the year of connection to the telegraph, as we will use this instrument in a panel regression where it will take the value of one in years including and after a predicted connection, and zero otherwise.

Figure 9 and Table 2 show the scatterplot and the estimates from the linear prediction model.[19] As the figure shows, ruggedness seems to be a better predictor of year of connection for early years, while the relationship seems weaker from about 1880. This is consistent with ruggedness of the submarine terrain mattering most at the earlier phases of the roll-out when the technology was still being developed.

One concern is that longer connections may be more likely to feature areas of large elevation changes, meaning that distance to London may be correlated with these measures. For this reason, we use only the variation in ruggedness not explained by distance to London when predicting the year of the telegraph connection, as shown in Column (2) of Table 2. Another concern is that ruggedness may be correlated with shipping time, for example, because submarine ruggedness may be correlated with currents affecting ship speed. However, we can test for this in our data. Column

[18]More formally, let e_{rc} denote elevation at the point located in row r and column c of a grid of elevation points. The terrain ruggedness index at point rc is calculated as $\sqrt{\sum_{i=r-1}^{r+1} \sum_{j=c-1}^{c+1} (e_{ij} - e_{rc})^2}$.

[19]Note that we use the full dataset of connection up to 1899 for this prediction, as we need to have a predicted year of connection for those countries that are not connected to the telegraph by 1880.

(3) of Table 2 shows that this is not a concern; ruggedness does not predict mail shipping time.[20]

4.3 The effect of communication technology on imports along the value chain

As we have seen in previous sections, the telegraph was rapidly adopted by cotton textile merchants to facilitate the exchange of information at a distance in an industry characterized by rapidly fluctuating demand. In this section, we ask whether communication time improvements differentially affected trade at different parts of the value chain. We estimate the elasticity of imports to changes in communication time separately by product category using the following specification;

$$E[imp^i_{ct}|C_{ct}] = \exp\{\beta^i * \ln C_{ct} + \lambda_c + \gamma_t\} \quad (1)$$

imp^i_{ct} denotes quantity imported of product category i (yarn, plain cloth, finished cloth) in country c at time t. C_{ct} denotes communication time as defined in the previous section. λ_c and γ_t are country and time fixed effects, respectively. The parameters of interest are β^i, which capture the elasticity of imports of product category i with respect to changes in communication time. We use Poisson pseudo-maximum likelihood (PPML) to estimate the equation following the extensive literature showing PPML to be a consistent and relatively efficient estimator for gravity equations featuring a large number of zeros and a multiplicative estimating equation (Santos Silva and Tenreyro, 2006; Head and Mayer, 2013).[21] We examine quantity imported as opposed to the value of imports so as to not confound price and volume effects. Standard errors are clustered at the level of countries to account for country level serial correlation in the error terms.

The endogeneity concern in equation (1) is that communication time between two locations is partially determined by ICT investments, which may be related to the trading potential between those locations. On one hand, countries that traded intensively with each other had larger incentives to invest in faster communication infrastructure. On the other hand, political considerations may have resulted in larger investments in infrastructure for more peripheral or conflict-ridden regions where trading potential was lower.[22]

As discussed in the previous section, we address these concerns by using the variation in telegraph connections that is predicted based on ruggedness. We transform the predicted telegraph year into a binary variable that takes the value of zero in years preceding a predicted connection, and one thereafter. However, the telegraph had a differential effect on the communication times of different countries: While communication time to France was reduced only by 1 day, communi-

[20]Mail shipping time is averaged across 1845 to 1850, i.e., before any country was connected to the telegraph network.

[21]Estimation of the relationship using ordinary least squares does not yield similar results. The reason in this particular case seems to be because of heteroscedasticity in the error term rather than differential shares of zeros, because non-linear least squares, which is a less efficient method to deal with heteroskedasticity yields similar results to PPML and diagnostic tests suggested by Head and Mayer (2013) also point to PPML being the preferred specification. Appendix A.2 contains a more in depth discussion of these issues.

[22]Headrick (1981) discusses in detail the extent to which the telegraph was a tool for empire building of the British.

cation time to Australia was reduced by several weeks. To exploit this cross-sectional variation in communication time reductions, we interact our predicted telegraph dummy with the log average reduction in the communication time of a country's neighbor. Neighbors are defined according to sea-distance between the ports used for each country. We use the neighbor with the largest number of observations among the three closest neighbors of a country. The log drop in communication time is defined as the log of the difference in communication time across all years pre- and post-telegraph (excluding the year of the telegraph connection). We use the communication time drop of the neighboring country rather than the country itself in order to avoid potential reverse causality: If a country was more important in terms of trade or trade potential, its communication times before the telegraph might have been influenced, e.g., by using faster mail ships instead of slower sail ships before the telegraph.

While there is no first stage defined in GMM similarly to that in the linear 2SLS case, it is still important to assess the strength of relationship between the endogenous variable, communication time, and each instrument, because weak instruments can invalidate the GMM estimates. In Table 3, we therefore report the equivalent first stages from an OLS regression with two-way fixed effects. It is reassuring to see that both instruments are highly statistically significant and have the expected sign.

Estimation of a Poisson regression model with endogenous regressors is done using generalized method of moments (GMM), following Windmeijer and Santos Silva (1997) and implemented using Stata's `ivpoisson` command. It has been known since Neyman and Scott (1948) that non-linear regressions with fixed effects may suffer from the incidental parameters problem. Fernández-Val and Weidner (2016) have shown that, for the case of exogenous or predetermined regressors, Poisson models do not suffer from the incidental parameters problem. However, it may well be a concern for the IV Poisson model. If both N and T are relatively large, as is the case in our data with 72 countries and 36 years, the bias arising from the incidental parameters problem is unlikely to be large. However, to gain a better sense of the potential size of the bias, we implement a panel jackknife bias correction that has recently been proposed in the literature (Hahn and Newey, 2004; Fernández-Val and Weidner, 2016; Cruz-Gonzalez et al., 2017).

4.3.1 Baseline Results

Table 4 contains summary statistics for quantities and values imported for each group of products across the sample period. The table also splits the sample according to years before and after the telegraph was put in place in. This provides a first assessment of the extent to which the effect of the telegraph is apparent in the raw data without imposing additional structure. As can be seen, both in terms of quantities and in terms of import values, the percentage increase in imports after the telegraph was put in place is largest for yarn, followed by plain and finished cloth. We now turn to estimating the effect of interest; the elasticity of imports with respect to communication time.

Table 5 presents the baseline results. Panel A reports the coefficients for the effect of communication time on yarn, plain and finished cloth in the different columns, using country and year fixed effects.[23] We see a clear pattern: A 1% decrease in communication time increases the quantity of yarn imported by 0.183% (s.e. 0.041), plain cloth by 0.097% (s.e. 0.029), while there is no statistically significant effect on finished cloth (the point estimate is effectively zero; 0.006).

In order to explore which components of the time series and cross-sectional variation used are important for our results, Table A.2 explores alternative regressors. Results using only (time series) variation from the telegraph dummy are similar, but less precise, which is to be expected as the cross-sectional variation in communication time drops is not exploited, which adds a lot of noise to the estimation. Results using the telegraph dummy interacted with the average communication time drop of a country yield similar results to those in Panel A (though the interpretation of the estimated coefficients are different). The importance of the cross-sectional variation motivates our inclusion of a plausibly exogenous component of it (the closest neighbor's drop in communication time) in the instrument.

Panels B and C of Table 5 report the IV estimates based on the Riley measure and the normalized cable length, respectively. The estimated coefficients decrease in size as we move from yarn to plain and then to finished cloth, consistent with our previous results. The coefficients are very similar across the two IVs. Comparison of the coefficients between the Poisson specification and IV estimates shows that while the IV estimates are marginally larger, the two are fairly similar and statistically indistinguishable. This is suggestive of the fact that the timing of successful telegraph connections is predominantly determined by exogenous factors such as ruggedness of the submarine terrain.

In terms of magnitudes, e.g. in panel B, a 1% drop in communication time is predicted to increase quantity imported by 0.272% (s.e. 0.076) for yarn, 0.128% (s.e. 0.065) for plain cloth, and by 0.030% (s.e. 0.066; not significant) for finished cloth. To gain a better sense of the economic effect of the telegraph, we scale the elasticities by the average drop in communication time caused by the telegraph. Based on this, introduction of the telegraph increased imports of yarn by 10.6%, of plain cloth by 5.0% and of finished cloth by 1.2%, though this latter effect is statistically indistinguishable from zero, consistent with the historical evidence that trading finished cloth required the physical shipping of samples, which could not be done via telegraph.

The difference between the estimated effect on yarn and the effect on plain cloth is statistically different, as we show in Table A.3, which presents the pooled baseline and IV specifications. The difference between the effect on plain and finished cloth is statistically different in the Poisson specification, but not in either IV specification.

[23]Results without fixed effects are shown in Table A.1.

4.3.2 Robustness

We explore the robustness of our results along a number of dimensions. First, Table 6 examines robustness of the results for various subsamples of the data. The robustness checks are based on the instrument that uses the Riley measure of ruggedness. We use this as our baseline instrument as this measure has been used previously in the literature. All results are similar when we use normalized cable length as reported in Table A.4.[24] Panel B reports results for the sample that excludes years during the American Civil War (1861-1865), when the supply of raw cotton to the British textile industry was severely disrupted because of the blockade of the raw cotton exporting Southern states (Hanlon, 2015). Comparison with the baseline IV results show virtually no change in the size of the coefficients and their statistical significance.

Panel C estimates the effects of interest by excluding British colonies from the sample. It is likely that trade with colonies was more regulated thus restricting the impact of communication time on trade. Indeed, the gradient of the effect across product categories is larger when British colonies are dropped, suggesting that our results hold (and are even stronger) in contexts that resemble competitive markets more closely.

Panel D includes time-varying product level ad-valorem tariffs from Tena-Junguito et al. (2012) for the subset of countries for which they are available. The coefficients of interest remain similar in both magnitude and significance, confirming that our identification strategy is robust. Tariffs enter with the expected negative sign, though they are only statistically significant for finished cotton cloth.

Panel E includes controls for GDP for the countries for which they are available using data from the Maddison Project Database (Bolt et al., 2018) and from Fouquin and Hugot (2016). The point estimates for the coefficients of interest retain their pattern, however, the estimated effect on yarn is somewhat larger and plain cotton cloth is no longer different statistically from zero. The reason for this does not seem to be the effect of including GDP, but rather the different (and substantially smaller) subsample on which this specification is estimated. The coefficients of interest are virtually identical when the sample is restricted to the same subsample and the control for GDP is omitted.

Panel F shows the estimated effect on import values. Interestingly, the magnitudes of the effect are smaller and insignificant, even though the same gradient of the effect across product categories is present. This suggests that unit values decreased as the quantity imported increased.

Table A.6 contains the panel jackknife bias correction to assess the size of bias arising from the incidental parameters problem. The effects on yarn and finished cloth are basically unchanged, but the effect on plain cloth is slightly reduced, turning it marginally insignificant. Reassuringly, the gradient of the effect across product categories is unchanged.

[24] It should be noted that the effect on plain cloth is not always statistically significant when normalized cable length is used as the instrument.

4.3.3 Discussion of mechanism

The results presented above show that communication time improvements driven by connection to the telegraph network had a larger effect on more codifiable product categories, i.e., when buyers and sellers could specify and order at a distance using only words instead of needing to exchange product samples.

Are there other mechanisms besides codifiability that could explain the empirical findings? In the cotton textile industry, codifiability is correlated with upstreamness, as more codifiable products are located further upstream, and it is also correlated with the degree of product differentiation, as less differentiated products are more codifiable. We explore a range of alternative mechanisms, starting with a discussion of mechanisms that yield the opposite prediction to what we find in our empirical section: contracting frictions, search frictions, and demand volatility.

First, better communication technology may have facilitated search or reduced contracting frictions, e.g., by increasing trust (Nunn, 2007). Contracting frictions are expected to be larger in product categories that are less standardized, as the hold-up problem is less severe for these products. Similarly, search frictions are expected to be larger in more downstream, more differentiated product categories. If better communication increased contract enforcement or reduced search frictions, we would therefore expect to see the pattern across products to be the opposite of what we find, so this is unlikely to be an alternative mechanism.

We explored the extent to which search or contracting frictions are empirically relevant in our setting by collecting data on the number of international merchant houses active in a particular country in the cotton goods trade. International merchant houses with representatives in both the exporting and importing countries were common during the 19th century, solving contract enforcement problems for a significant proportion of trade (Chapman, 1992). Moreover, as the buyer and seller for these transactions interacted repeatedly, search would not seem to play an important role for these relationships. In Panel A of Table 7, we explore whether our effect is indeed weaker or insignificant for those countries where international merchant trading houses were widespread, by adding an interaction term between the coefficient of interest and the number of international merchants. The effect on the interaction term is very small and not large enough to offset the pattern across product categories that we see, suggesting that contract enforcement or search are unlikely to be the driving force behind the different estimated elasticities.[25]

Second, notice that in order for faster communication time to have any effect on imports, demand must be fluctuating (if there were no changes to local market conditions, information about them would not matter as the market conditions would already be known). Communication time could have a different effect on product categories along the value chain, if demand volatility varied across those categories. Upstreamness implies that inputs are transformed into a variety of outputs at

[25] Table 7 uses the Riley ruggedness measure as the instrument, the results with the cable length instrument are shown in Table A.5.

every stage of the production chain. For example, in the case of the cotton textile industry, the same unit of yarn can be turned into different types of plain cloth, and the same unit of plain cloth can be turned into innumerable different varieties of printed cloth. Because of this, the more aggregate demand at the level of the input of each stage would then have a *lower* coefficient of variation than the output of that stage, and this holds throughout the production chain. Since communication time should be expected to be most valuable at stages for which demand volatility is largest, we would expect the telegraph to have the largest trade enhancing impact at the more downstream stages, contrary to what we find.

We now turn to discussing mechanisms that yield predictions that are in line with what we find empirically. In fact, the mechanism that is arguably the most difficult to rule out is a fairly generic one. Assume demand elasticities are larger further upstream for an unspecified reason. In this case the same 1% decrease in price will increase yarn imports by more than imports of finished cloth.

However, note that this effect should hold for *any* reduction in trading frictions. To test for this, we can exploit the fact that data from the Lloyd's List also yields shipping time for mail and product samples, and explore whether the effects are similar when a different trading friction decreases. Panel B of Table 7 shows that while the estimated coefficients for mail shipping time are not statistically different from zero, the point estimates *increase* in magnitude as we move further downstream, which is precisely the opposite of what we find for communication time. This suggests that the main driver of the effect of communications times is not the generic effect of a reduction in trading frictions.

Interestingly, however, our preferred mechanism — codifiability — *is* highly consistent with mail shipping time having the opposite effect: Reductions in mail shipping time, which are also used for mailing samples, are most relevant for the non-codifiable information, i.e., for finished cloth.

4.3.4 Codifiability and trade in intermediates

The previous sections showed that communication time improvements disproportionately increased trade for products further upstream as these were more codifiable. In order to understand the extent to which this mechanism has the potential to shed light on how ICT affects the formation of global value chains more generally, in this section, we explore the extent to which codifiability and position in the value chain are related.

It seems reasonable to expect codifiability to decrease as we move down the value chain, because — as we described in the case of cotton textiles —, when specifying the attributes of a product further downstream, it is necessary to specify all inputs that are used and their transformations up to that point. This naturally leads to the prediction that codifiability should decrease as we move downstream, though it is clearly possible to find counterexamples.

We correlate a widely used measure of position in the value chain with a proxy for codifiability as follows. Antràs et al. (2012) define upstreamness as an industry's relative product line position (or its average distance from final use). We correlate this measure with the Rauch classification of products. Rauch classifies products according to whether they are traded on an organized exchange (we assign these a value of 3), whether they have a reference price published in a trade journal (assigned a value of 2), or neither (1). These categories are commonly interpreted as the degree of differentiation of a product, however, this measure also captures our notion of codifiability well; products which are traded on an organized exchange must have easily codifiable attributes that are standardized such that they mean the same to all parties. Products that are reference priced also need to be easily specified along a small number of dimensions. Finally, products that are neither traded on organized exchanges, nor are reference priced will likely have attributes that are more difficult to specify.[26]

Column 1 in Table 8 shows the full sample, while column 2 drops all product categories from the Rauch classification that are primary products.[27] It is important to make sure the correlation is not driven exclusively by primary products, as the location of production is determined to a large extent by natural resource endowments. In both specifications, codifiability and upstreamness are strongly correlated.

An important point to bear in mind is that the Rauch measure captures aspects of product categories beyond their codifiability; Rauch (1999) focuses on the extent to which search at a distance will affect products differentially, while Nunn (2007) highlights the differing extent to which the products are vulnerable to hold-up problems. Disentangling the multitude of different factors that undoubtedly affect the Rauch classification of these product categories is beyond the scope this paper. The point is simply that the correlation between upstreamness and the Rauch measure suggests that the mechanism via which communication time affects trade along the value chain in this paper, the positive relationship between codifiability and upstreamness, also seems to be present more generally in the data.

Finally, it should also be noted, that for ICT to facilitate the formation of global value chains, codifiability does not need to be monotonically decreasing along the value chain. It does not even need to be the case that all intermediates along the value chain are more codifiable than the final good. All that is necessary is that intermediate inputs are generally more codifiable than final goods. If this latter holds true, in response to ICT improvements, trade in intermediate goods should increase more than trade in final goods. Moreover, all else equal, firms will have a higher incentive to offshore the production of more codifiable inputs, while less codifiable inputs

[26] The I-O classification system and the SITC codes for which the Rauch classification is available are matched following the methodology in Nunn (2007). When more than one SITC code matches with the same I-O code, we take the average of the Rauch classification. Admittedly, this imposes cardinality on the Rauch measure which it does not have. However, the results are robust to using the minimum or maximum of the Rauch measure for all products that belong to the same I-O classification which do not rely on cardinality.

[27] In particular, all SITC codes belonging to "Crude materials, inedible, except fuels" and "Mineral fuels, lubricants and related materials" are dropped.

are produced in-house or are sourced from geographically proximate suppliers.

4.4 The effect of communication technology on technology adoption

The previous section established that communication technology improvements disproportionately increased imports of intermediate goods, and in particular imports of yarn, in destination markets. In this section, we explore how imports of intermediate goods evolved in the long run, and in particular, how this is related to the adoption of frontier technology in the upstream part of the value chain, cotton spinning.

4.4.1 Dynamic effects of communication time on imports

We begin the empirical analysis by exploring the dynamic effects of communication time on importing at different parts of the cotton textile value chain. Table 9 estimates the effect of the telegraph on imports of yarn, plain and finished cotton cloth separately for the period within 5 years of the introduction of the telegraph, between 6-10 years of the introduction of the telegraph and more than 10 years after the introduction of the telegraph.[28]

For yarn, the effect of the telegraph is non-monotonic across time. In particular, imports of yarn increase within 5 years of the introduction of the telegraph, and increase further between 6-10 years after the connection is put in place. However, after 10 years the effect falls by a sizable magnitude (although the reduction in the effect is only statistically significant in the Poisson specification and not in the IV Poisson specification). For plain and finished cloth, the estimated effects do not show the same pattern. The estimated additional effect of the telegraph within 6-10 and after 10 years is typically very small for these goods, never statistically significant and does not display the same non-monotonicity as yarn.[29]

4.4.2 Effect of telegraph on adoption of mechanized spinning

One natural explanation for this decline in imports of British machine-spun yarn after 10 years is that over time, yarn importing countries started to develop their own mechanized industries. In fact, the historical literature has emphasized a link between importing yarn and the subsequent development of a domestic mechanized spinning industry. For example, Farnie (2004, pp. 574) writes; “The role of yarn exports has never achieved due recognition in historiography [...] The

[28] The corresponding specification without interaction terms allowing for heterogeneous effect over time is estimated in Panel C of Table A.2.

[29] The specification presented in Table 9 estimates the effect on a subsample of the data that drops all observations more than 20 years before or after the telegraph connection is achieved. This is in order to estimate the dynamic effects for comparable time horizons across countries. Table A.7 estimates an alternative specification that includes the full sample of observations 1845-1880. The estimated coefficients are similar in magnitude, though in this case, the effect on yarn within 5 years of the telegraph is not statistically significant, while the effects within 6-10 years and after 10 years are highly significant.

trade in yarn became more influential than the trade in cloth in one key respect. It stimulated the establishment of spinning mills overseas and so fostered the spread of industrialization abroad."

We test this hypothesis using data on worldwide spinning capacity. These data are only available for the first and last years of our sample period, i.e., 1845 and 1880 (and several decades thereafter), so we begin by asking whether mechanized spinning capacity increased the longer a country was connected to the telegraph network, using our ruggedness measure as an instrument for years since adoption of the telegraph:

$$\frac{S_{c,1880} - S_{c,1845}}{POP_{c,1845}} = \beta_t * YRS_{c,1880} + \epsilon_c \tag{2}$$

where $S_{c,1880} - S_{c,1845}$ denotes the growth in spindles in country c between 1845 and 1880 normalized by the population of a country in 1845, $POP_{c,1845}$. We use levels of the dependent variable because of the large number of zeros in the data.

$YRS_{c,1880}$ denotes years since the introduction of the telegraph for country c in 1880. For countries that are not yet connected in a particular period t, we set $YRS_{ct} = 0$. In order to account for the potential endogeneity of the telegraph connections, we use the same identification strategy as before, with two simplifications: As we are now estimating a cross-sectional regression, we can use the ruggedness measures directly as instruments. Moreover, we can also directly control for the effect of distance (rather than taking out that variation from the predicted telegraph year).

Table 10 begins the analysis by estimating the effect of a telegraph connection on growth in normalized mechanized spinning capacity for 1880. Column (1) reports the first stage in order to asses the strength of the instrument. The instrument is highly significant and of the expected sign; a more rugged submarine terrain leads to a later connection to the network. This will also be apparent from the first stage KP F-statistics, which are consistently high across all specifications. Columns (2) and (3) show the OLS and 2SLS specifications, respectively. Both estimates are positive and highly statistically significant; countries that had been connected to the telegraph for a longer period of time in 1880 had higher growth in mechanized spinning capacity. Consistent with the previous section, the OLS and 2SLS coefficients are only marginally different, in line with our contention that the timing of a successful telegraph connection was mainly driven by exogenous factors.

We assess the robustness of these results to the inclusion of a number of controls across columns (4) to (8). The coefficient of interest remains stable and highly significant across all specifications. Column (4) includes a control for distance to London, motivated by the fact that our instrument is correlated with distance to London and also that the diffusion of technology may follow a gravity equation (Keller and Yeaple, 2013). Distance enters with the expected negative sign, though it is not statistically significant. Countries may have used tariff policy as a way to protect what was seen as a strategic industry in the 19th century. For this reason, columns (5) to (7) add cotton yarn, plain cotton cloth and finished cotton cloth ad-valorem tariffs measured in 1845, respectively. There is no clear pattern in terms of the estimated effect of these tariffs, however, only finished cotton cloth tariffs are statistically significant. Finally, one concern is that more developed countries may have achieved a telegraph connection sooner and also developed their mechanized cotton spinning industries to a greater extent. In the absence of GDP per capita data for the majority of our sample in pre-telegraph years, we proxy for development using urbanization rates measures in 1850 from Pascali (2017). Urbanization enters with the expected positive sign, though it is not statistically significant.

While spindle data is not available for more years within our baseline sample period, it does become more readily available after 1880. In particular, we were able to collect decadal mechanized spinning capacity for the years 1890, 1900 and 1910. Table 11 estimates our baseline specification using growth of spindles over these longer time horizons, $\frac{S_{c,t}-S_{c,1845}}{POP_{c,1845}}$, where $t \in \{1890, 1900, 1910\}$. Distance to London is always included as a control as our ruggedness instrument is weakly correlated with distance to London. The results hold independent of the time span used; if anything, the magnitude may grow over time (with the exception of 1890, where our sample size is reduced).[30]

Column (5) reports the result from a placebo test that asks whether the year of connection to the telegraph predicts mechanized spinning capacity in 1845 (normalized by population); before the telegraph was introduced. The coefficient of interest is defined as the year of connection to the telegraph in this specification, as "years since connection to telegraph" would be zero everywhere. This is simply a rescaling of our regressor of interest. Reassuringly, the coefficient of interest is not statistically different from zero. This is also the single specification in which distance to London is of the expected sign and highly statistically significant. One potential concern with the strength of this placebo is that the ban on British exports of spinning machinery was lifted in 1843, implying that technology diffusion may have been limited before this point in time. However, as Saxonhouse and Wright (2010) point out, prior to the lifting of the ban, a license system was in place between 1824-1843 allowing some exports of textile machinery.

4.4.3 Potential mechanisms

The historical evidence emphasizes two complementary mechanisms that facilitated the diffusion of mechanized spinning technology from Britain throughout the world (Farnie, 2004). On the one hand, spinning machines were imported from Britain, the world's leading machinery manufacturer. But having machinery was not sufficient; in order to successfully operate modern cotton mills, managers needed to have knowledge about the whole system of the production process and local demand conditions. Through their experience in importing yarn and distributing it to local weavers, merchants were well placed to accumulate this type of knowledge, making them well suited to managing the newly established cotton mills. Farnie (2004, pp. 120) writes: "British merchant

[30] As our sample size is relatively small and data coverage is not complete across years, we estimate the effect for each year on the largest sample for which data are available.

houses 'were the principal innovators in India' [...] In Bombay, almost from the start, local merchant houses were appointed managers of the new cotton-spinning mills. [...] Management of the Bombay cotton spinning mills by managing agents who were invariably merchant houses remained the prevailing pattern". Moreover, " (...) merchant houses were well-placed to distribute the yarn and cloth produced by their mills." (Jeremy, 2004, p. 120).

In the following, we present empirical evidence for both mechanisms. First, we use data on imported spinning machinery from Britain to test for the relevance of imports of capital from the technology frontier, Britain. As annual imports represent flows of technology, our dependent variable is defined as total machinery imports for the time period 1878 to 1914. This yields an estimate of the stock of mechanized imported spindles per country. Column (6) of Table 11 uses this imported mechanized spindle stock measure (normalized by population) as the dependent variable. The coefficient is positive and significant, as in columns (1) to (4). This suggests that importing machinery from Britain played an import role in technology diffusion. Table A.8 provides the same set of robustness checks used in Table 10, all of which are consistent with this finding.

To assess whether merchant houses were systematically involved in the management of cotton spinning firms, we use directories for both cotton mill managers (in 1925) as well as merchants (for 1886-87) for Bombay, which was where most of the Indian cotton spinning industry was located. We matched the names of managers to the merchant directory, and depending on the strictness of the matching criteria of the name, we in fact find that 28 to 46% of managers had been merchants previously.[31] Note that half of these matched merchants are British, and half were local merchant houses, so no particular merchant origin explains this pattern. While we were only able to collect data for India for this exercise, we do not believe that the link between merchants and local mechanized cotton spinning firms is limited to this specific country. For example, Jeremy (2004) discusses a similar mechanism for the case of Russia and China.

Taking together the empirical and historical evidence presented in this section, establishing a connection to the telegraph network had a positive effect on the development of a domestic mechanized cotton spinning industry. While far from conclusive, this section provides evidence that technology diffusion through the imports of capital equipment from Britain was complemented with learning through importing intermediates.

5 Conclusion

This paper has examined how a revolutionary ICT, the telegraph, affected trade along the value chain in cotton textiles and the subsequent adoption of frontier technology in the industry. This setting allows us to isolate exogenous variation in the time at which a country was connected to the global telegraph network. Moreover, the fact that distinct stages of the production process

[31] Note that this is plausibly an underestimate, as the merchant directory and firm list are 40 years apart.

are delineated in the trade data, coupled with British dominance in trade, presents us with a rare opportunity to recover the global value chain.

In the first part of the empirical analysis, we find that imports from the technological leader, Britain, increased disproportionately for more upstream products. These were products that were easier to codify. This finding is in line with the literature that has argued that ICT facilitates the formation of global value chains by making it easier to communicate product specifications at a distance. While understanding the extent to which codifiability is systematically related to the position in the value chain is outside the scope of this paper, we have shown suggestive evidence that upstreamness and codifibaility may be related more generally. However, as discussed in the paper, the conditions under which ICT facilitates the formation of global value chains seem to rely on even weaker assumptions about the relationship between codifiability and position in the value chain. In particular, if intermediate inputs are generally more codifiable than final goods, trade in the former should increase disproportionately in response to ICT improvements. Moreover, all else equal, firms will have a higher incentive to offshore the production of more codifiable inputs, while less codifiable inputs are produced in-house or are sourced from geographically proximate suppliers.

In the second part of the analysis, we exploit the fact that the historical setting allows us to examine dynamic effects. We show that over time, imports of yarn began to decline relative to their initial increase after connection to the telegraph. This suggests that importing countries may have moved into this part of the value chain themselves. Indeed, we find that ICT affected the diffusion of frontier technology and show suggestive evidence that this took place through the complementary mechanisms of capital imports and knowledge transfer acquired through importing intermediates.

Though we have highlighted the similarities between the 19th century cotton textile industry and the contemporary setting, it is also clear that there are important differences. The prevalence of multinational activity is one feature of the current environment that we believe may affect both the formation of global value chains and the complex nature of trade and international technology diffusion within these value chains. Understanding how MNC activity interacts with these forces is far from trivial. For example, recent work suggests that even though multinationals account for a large fraction of US imports and exports, only the very largest multinationals engage in trade between parent and affiliate (Ramondo et al., 2016). One explanation may be that only the largest multinationals find it profitable to invest in the type of within firm ICT system that makes possible the building of cross-country supply chains. In addition, the literature has found evidence on technology transfer within the boundaries of the multinational firm (Branstetter et al., 2006; Keller and Yeaple, 2013; Bilir and Morales, 2016), suggesting that MNC activity may facilitate knowledge transfer. The aim of this paper is to focus on a setting in which it is possible to isolate the key forces we are interested in (ICT, trade along the value chain and international technology diffusion). We view understanding how other forces such as MNC activity interact with the factors considered in this paper as a fruitful avenue for future research.

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A Tables

Table 1: World exports of cotton goods and yarn, by country

	Exports of cotton goods and yarn	
	Value exported 1876-1880	Ratio relative to British 1876-1880
Great Britain	68,457	
Holland	2,818	0.041
Germany[1]	2,727	0.040
France	2,616	0.038
United States	2,008	0.029
Belgium	770	0.011

Notes: British exports are declared value. There are no recorded exports of cotton goods and yarn from Russia, Austria, Spain or Italy. Source: Ellison (1886, p. 113).
[1] German exports are estimates.

Table 2: Prediction of first successful telegraph connection based on Riley ruggedness

VARIABLES	(1) Telegraph year	(2) Telegraph year	(3) Mail shipping time
Riley ruggedness	0.029***	0.026***	-0.011
	(0.004)	(0.004)	(0.010)
Distance to London		0.000***	0.007***
		(0.000)	(0.000)
Observations	73	73	63
R-squared	0.499	0.531	0.648

Notes: Estimation via linear probability model. Riley ruggedness defined as the maximum Riley measure across all submarine edges that make up a connection. Distance to London is the natural logarithm of great circle distance to London. Robust standard errors in parentheses. Notation for statistical significance; *** p<0.01, ** p<0.05, * p<0.1.

Table 3: First stage equivalent

VARIABLES	(1) ln(comm time)	(2) ln(comm time)
(Pred tele Riley)*	-0.297***	
(comm time change neighbor)	(0.046)	
(Pred tele cable length)*		-0.296***
(comm time change neighbor)		(0.044)
Observations	2,150	2,150
R-squared	0.557	0.557
Number of countries	72	72

Notes: OLS specification for the pseudo-first stage. ln(commtime) defined as the natural logarithm of communication time (in days) to London. Regressors: (Pred tele Riley)* (comm time change neighbor) is a binary variable that takes the value of one including and after the predicted year of connection based on the Riley measure interacted with the closest neighbor's drop in communication time after connection to the telegraph. (Pred tele cable length)* (comm time change neighbor) is a binary variable that takes the value of one including and after the predicted year of connection based on the normalized cable length measure interacted with the closest neighbor's drop in communication time after connection to the telegraph. Year and country FEs included. Standard errors clustered by country in parentheses. Notation for statistical significance; *** p<0.01, ** p<0.05, * p<0.1.

Table 4: Summary statistics

	All	**Before telegraph**	**After telegraph**	**Change**	**Change in %**
Num. observations (country*year)	2,684	1,884	800		
Quantities					
Yarn, million pounds[1]	2.33	0.78	5.99	5.21	668
Plain cloth, million yards	21.73	12.25	44.05	31.80	260
Finished cloth, million yards	10.72	7.45	18.41	10.95	147
Values (000's of £'s)					
Yarn	138.23	40.09	369.34	329.24	821
Plain cloth	300.73	172.97	601.60	428.62	248
Finished cloth	203.20	138.96	354.51	215.54	155

Notes: "Before telegraph" includes all country*year observations prior to achieving a connection to the telegraph network. "After telegraph" includes all country*year observations including and after achieving a connection to the telegraph network. On average, 1 pound of yarn yields 5 yards of cloth (Ellison, 1886).

Table 5: Baseline specifications

VARIABLES	(1) Yarn	(2) Plain cloth	(3) Finished cloth
Panel A. Baseline, no IV			
ln(comm time)	-0.183***	-0.097***	0.006
	(0.041)	(0.029)	(0.044)
Observations	2,150	2,150	2,150
Nr of countries	72	72	72
Panel B. Riley measure * comm time drop			
ln(comm time)	-0.272***	-0.128**	-0.030
	(0.076)	(0.065)	(0.066)
Observations	2,150	2,150	2,150
Nr of countries	72	72	72
Panel C. Normalized cable length * comm time drop			
ln(comm time)	-0.269***	-0.110*	0.007
	(0.077)	(0.065)	(0.064)
Observations	2,150	2,150	2,150
Nr of countries	72	72	72

Notes: ln(commtime) defined as the natural logarithm of communication time (in days) to London. The instrument in Panel B is a binary variable that takes the value of one including and after the predicted year of connection based on the Riley measure interacted with the closest neighbor's drop in communication time after connection to the telegraph.The instrument in Panel C is a binary variable that takes the value of one including and after the predicted year of connection based on the normalized cable length measure interacted with the closest neighbor's drop in communication time after connection to the telegraph. Year and country FEs included. Standard errors clustered by country in parentheses. Notation for statistical significance; *** p<0.01, ** p<0.05, * p<0.1.

Table 6: Robustness

VARIABLES	(1) Yarn	(2) Plain cloth	(3) Finished cloth
Panel A. Baseline IV (Riley measure)			
ln(comm time)	-0.272***	-0.128**	-0.030
	(0.076)	(0.065)	(0.066)
Observations	2,150	2,150	2,150
Nr of countries	72	72	72
Panel B. Drop Civil War			
ln(comm time)	-0.265***	-0.128*	-0.036
	(0.076)	(0.069)	(0.080)
Observations	1,845	1,845	1,845
Nr of countries	72	72	72
Panel C. Drop British colonies			
ln(comm time)	-0.401***	-0.212***	0.067
	(0.122)	(0.073)	(0.107)
Observations	1,632	1,632	1,632
Nr of countries	55	55	55
Panel D. Control for tariffs			
ln(comm time)	-0.282***	-0.125**	-0.047
	(0.069)	(0.055)	(0.062)
tariff rate	-0.430	-0.041	-0.020***
	(0.276)	(0.293)	(0.001)
Observations	1,096	1,096	1,096
Nr of countries	36	36	36
Panel E. Control for GDP			
ln(comm time)	-0.428**	-0.076	0.153
	(0.195)	(0.093)	(0.094)
ln(GDP)	0.082	-0.680***	-0.757***
	(0.417)	(0.173)	(0.258)
Observations	920	920	920
Nr of countries	38	38	38
Panel F. Import values			
ln(comm time)	-0.158	-0.076	0.005
	(0.104)	(0.067)	(0.066)
Observations	2,150	2,150	2,150
Nr of countries	72	72	72

Notes: ln(commtime) defined as the natural logarithm of communication time (in days) to London. The instrument used across all specifications is a binary variable that takes the value of one including and after the predicted year of connection based on the Riley measure interacted with the closest neighbor's drop in communication time after connection to the telegraph. Controls: ad-valorem product specific tariffs from Tena-Junguito et al. (2012), current price annual (log) GDP values from Bolt et al. (2018) and Hugot and Dajud (2016). Appendix A.3 contains a detailed discussion of the construction of each variable. Year and country FEs included. Standard errors clustered by country in parentheses. Notation for statistical significance: *** p<0.01, ** p<0.05, * p<0.1.

Table 7: Mechanism

VARIABLES	(1) Yarn	(2) Plain cloth	(3) Finished cloth
Panel A. Interaction with international merchants			
ln(comm time)	-0.335***	-0.230***	-0.094
	(0.095)	(0.059)	(0.065)
ln(comm time)*	-0.001	0.023**	0.020**
number int merchants	(0.020)	(0.010)	(0.009)
Observations	2,019	2,019	2,019
Nr of countries	68	68	68
Panel B. Control for mail shipping time			
ln(comm time)	-0.306***	-0.127*	-0.014
	(0.092)	(0.068)	(0.068)
ln(mail ship time)	0.201	-0.074	-0.212
	(0.148)	(0.123)	(0.142)
Observations	2,150	2,150	2,150
Nr of countries	72	72	72

Notes: ln(commtime) defined as the natural logarithm of communication time (in days) to London. The instrument used across all specifications is a binary variable that takes the value of one including and after the predicted year of connection based on the Riley measure interacted with the closest neighbor's drop in communication time after connection to the telegraph. Controls: international merchants defined as the number of British merchant houses that have an affiliate merchant house in the destination market, mail shipping time defined as the natural logarithm of mail shipping time (in days) to London. Appendix A.3 contains a detailed discussion of the construction of each variable. Year and country FEs included. Standard errors clustered by country in parentheses. Notation for statistical significance; *** p<0.01, ** p<0.05, * p<0.1.

Table 8: Correlation between upstreamness and codifiability

VARIABLES	(1) Upstreamness	(2) Upstreamness
Rauch class.	0.720***	0.669***
	(0.095)	(0.094)
Observations	291	291
R-squared	0.191	0.179
Sample	Full	Exc. Raw materials

Notes: Upstreamness measure represents poistion in the value chain as defined in Antràs et al. (2012). Rauch classification as defined in Rauch (1999). Column (1) includes the full sample that can be matched. Column (2) excludes all raw materials; in particular, all SITC codes belonging to "Crude materials, inedible, except fuels" and "Mineral fuels, lubricants and related materials" are dropped. Robust standard errors in parentheses. Notation for statistical significance; *** p<0.01, ** p<0.05, * p<0.1.

Table 9: Dynamic effects

VARIABLES	(1) Yarn	(2) Plain cloth	(3) Finished cloth
Panel A. Poisson			
(Tele dummy)*(change comm time)	0.104**	0.059	-0.013
	(0.052)	(0.040)	(0.044)
(Tele dummy)*(change comm time)*	0.154***	0.038	0.004
(>5 yrs after tele)	(0.051)	(0.044)	(0.034)
(Tele dummy)*(change comm time)*	-0.196**	0.022	0.012
(>10 yrs after tele)	(0.092)	(0.040)	(0.066)
Panel B. IV poisson (Ruggedness IV)			
(Tele dummy)*(change comm time)	0.240**	0.080	0.039
	(0.112)	(0.092)	(0.086)
(Tele dummy)*(change comm time)*	0.199***	0.001	-0.007
(>5 yrs after tele)	(0.042)	(0.029)	(0.046)
(Tele dummy)*(change comm time)*	-0.110	0.049	-0.002
(>10 yrs after tele)	(0.093)	(0.038)	(0.086)
Panel C. IV poisson (Cable length IV)			
(Tele dummy)*(change comm time)	0.242**	0.073	-0.048
	(0.121)	(0.075)	(0.092)
(Tele dummy)*(change comm time)*	0.195***	0.020	0.003
(>5 yrs after tele)	(0.044)	(0.039)	(0.042)
(Tele dummy)*(change comm time)*	-0.117	0.046	-0.038
(>10 yrs after tele)	(0.096)	(0.036)	(0.096)
Observations	1,757	1,757	1,757
Number of countries	68	68	68

Notes: Tele dummy is a binary variable that takes the value of one including and after the year of connection to the telegraph and is zero otherwise. (>5 yrs after tele) is a binary variable that takes the value of one 6 years and after the telegraph connection is established and is zero otherwise. (>10 yrs after tele) is a binary variable that takes the value of one 11 years and after the telegraph connection is established and is zero otherwise. Change in comm time is the drop in communication time after connection to the telegraph. The instrument in Panel B is a binary variable that takes the value of one including and after the predicted year of connection based on the Riley measure interacted with the closest neighbor's drop in communication time after connection to the telegraph. The instrument in Panel C is a binary variable that takes the value of one including and after the predicted year of connection based on the normalized cable length measure interacted with the closest neighbor's drop in communication time after connection to the telegraph. Observations more than 20 years before/after telegraph connection is achieved are dropped. Year and country FEs included. Standard errors clustered by country in parentheses. Notation for statistical significance; *** p<0.01, ** p<0.05, * p<0.1.

Table 10: Impact of telegraph on technology adoption

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VARIABLES	Years since telegraph	Growth mechanized spindles						
Riley ruggedness	-0.023***							
	(0.003)							
Years since telegraph		2.282***	2.346***	2.108***	2.551***	2.153**	2.668***	2.385***
		(0.613)	(0.612)	(0.721)	(0.875)	(0.847)	(0.930)	(0.881)
Distance to London				-3.012				
				(4.337)				
Yarn tariff (1845)					-2.808			
					(13.038)			
Plain cloth tariff (1845)						7.514		
						(10.880)		
Printed cloth tariff (1845)							-0.388*	
							(0.209)	
Urbanization rate (1850)								128.179
								(351.868)
Observations	67	67	67	67	32	32	32	46
Specification	First stage	OLS	2SLS	2SLS	2SLS	2SLS	2SLS	2SLS
First stage KP F-stat			59.25	32.10	30.29	27.62	35.53	43.63

Notes: Column (1) contains the first stage specification, Column (2) contains the OLS specification and Columns (3)-(8) contain 2SLS specifications. Growth mechanized spindles is defined as the change in mechanized spindles 1845-1880 normalized by country population in 1845. Years since telegraph measured as years since first telegraph connection. Countries as yet unconnected to the telegraph are set to zero. The instrument is the Riley measure of ruggeddness. Controls: Distance to London is the natural logarithm of great circle distance to London, ad-valorem tariffs for cotton yarn, plain cotton cloth and finished cotton cloth measured in 1845 from Tena-Junguito et al. (2012), urbanization rate measured in 1850 from Pascali (2017). Appendix A.3 contains a detailed discussion of the construction of each variable. Robust standard errors in parentheses. Notation for statistical significance; *** p<0.01, ** p<0.05, * p<0.1.

Table 11: Impact of telegraph on technology adoption - 2SLS, all years

	(1)	(2)	(3)	(4)	(5)	(6)
	Growth mechanized spindles				Mech. spindles	Imported spindles
VARIABLES:	1880	1890	1900	1910	1845	1878-1914
Years since telegraph	2.108***	1.157*	3.696**	4.717**		3.138*
	(0.721)	(0.615)	(1.502)	(2.249)		(1.871)
Telegraph year					-0.812	
					(0.778)	
Distance to London	-3.012	-4.644	-8.189	-17.823	-9.871***	-18.840***
	(4.337)	(4.142)	(9.271)	(12.524)	(3.705)	(6.121)
Observations	67	62	70	73	73	73
Specification	2SLS	2SLS	2SLS	2SLS	2SLS	2SLS
First stage KP F-stat	32.10	20.36	23.53	25.27	25.27	64.00

Notes: Dependent variable in Columns (1) - (4) is the change in mechanized spindles between 1845 and 1880, 1890, 1900 and 1910, respectively, normalized by country population in 1845, Column (5) uses the level of mechanized spindles in 1845 normalized by population, Column (6) uses the sum of imported spinning machinery (measured in spindles) over 1878 to 1914 normalized by population to get a proxy of the stock of imported machinery in the long run. Years since telegraph measured as years since first telegraph connection. Countries as yet unconnected to the telegraph are set to zero. Telegraph year is the year of connection to the telegraph. Distance to London is the natural logarithm of great circle distance to London. The instrument for both Years since telegraph and Telegraph year is the Riley ruggedness measure. Robust standard errors in parentheses. Notation for statistical significance; *** p<0.01, ** p<0.05, * p<0.1.

B Figures

Figure 1: Cotton textile value chain

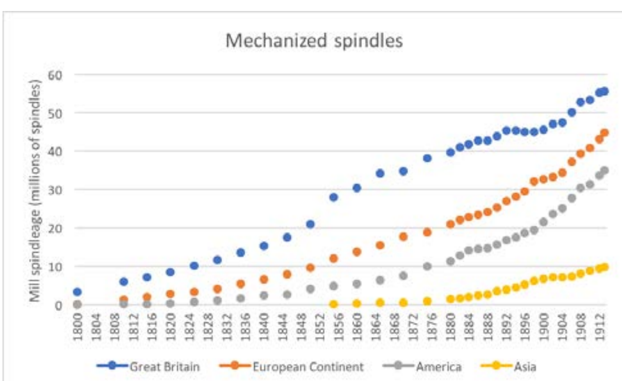
(a) Cotton yarn

(b) Plain cotton cloth

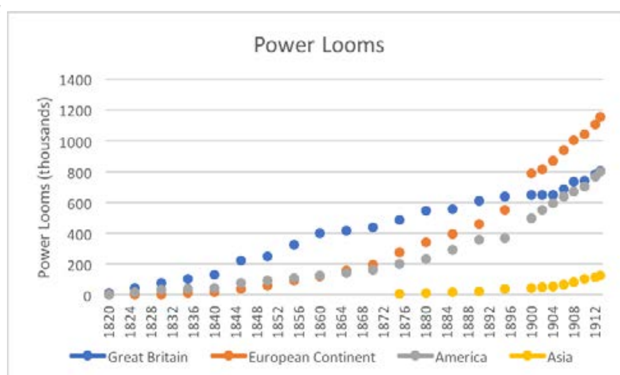
(c) Finished cotton cloth

Notes: Images from www.globaltextiles.com, www.aliexpress.com, www.vam.ac.uk (left to right).

Figure 2: Worldwide mechanized production capacity. Source: Farnie 2004, pp. 23-25

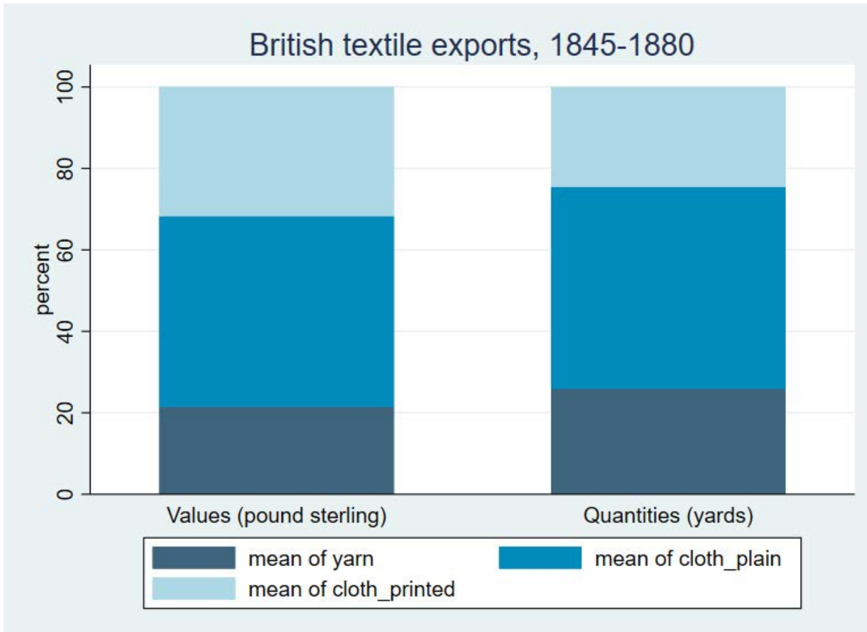


(a) Mechanized spindles, 1800-1930



(b) Power looms, 1820-1929

Figure 3: British cotton textile exports, by product category, (average 1845-1880)



Notes: For quantities chart, 1 pound of yarn yields on average 5 yards of cloth (Ellison, 1886)

Figure 4: Excerpts from *"Liddel's The 'Economic' Telegram Code for Piece Goods and General Business"*

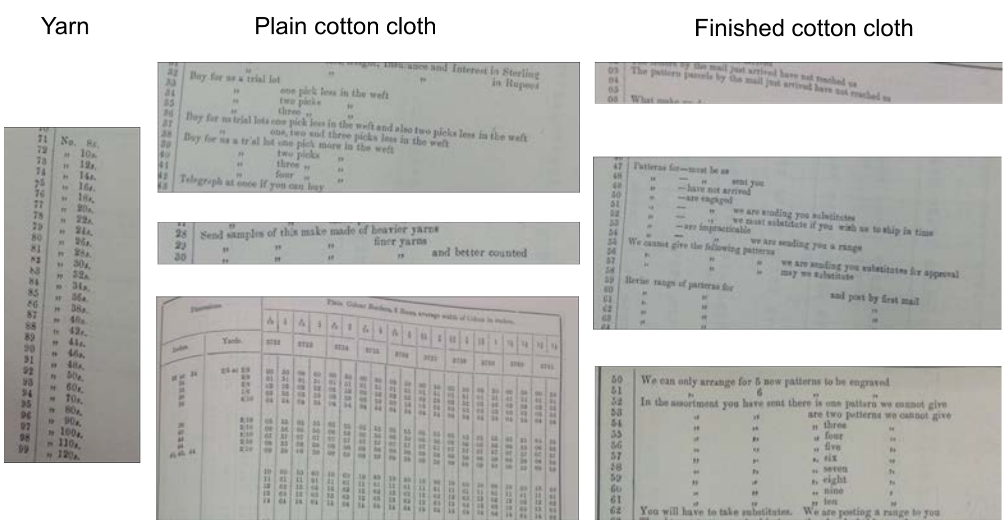
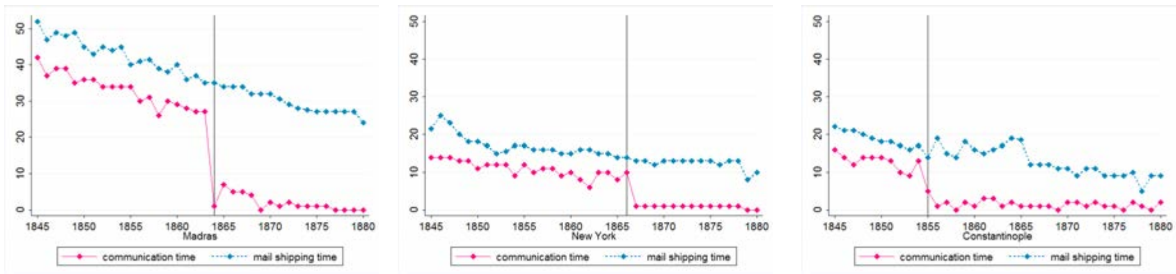


Figure 5: Communication and mail shipping times relative to London (in days)



(a) Madras (b) New York (c) Constantinople

Figure 6: Global communication times in days to London by decade, 1850-1880

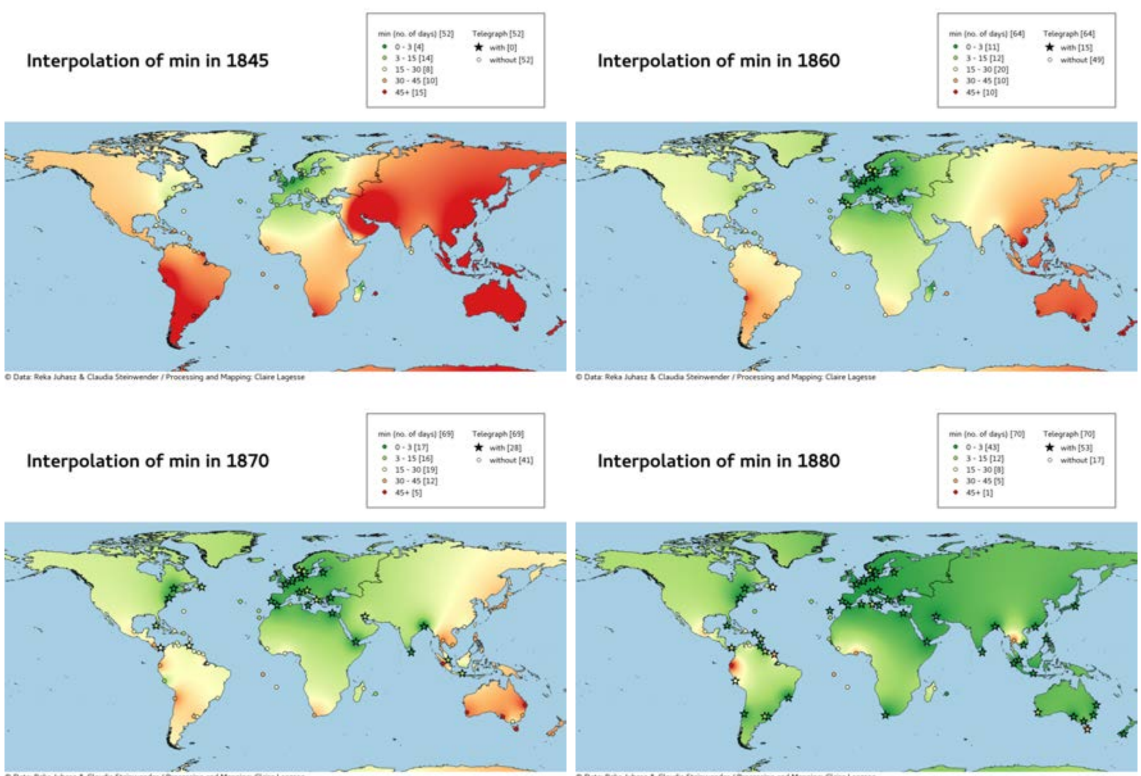


Figure 7: Year of first successful connection to London via telegraph, 1850-1899

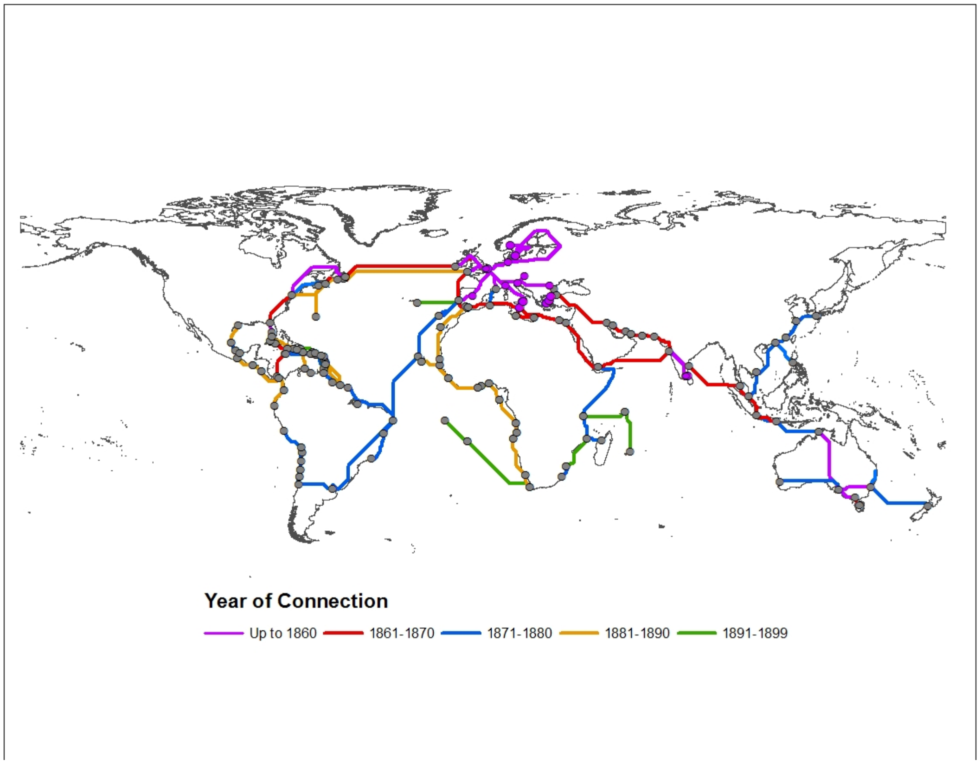


Figure 8: Ruggedness of "telegraphic plateau" (transatlantic telegraph)

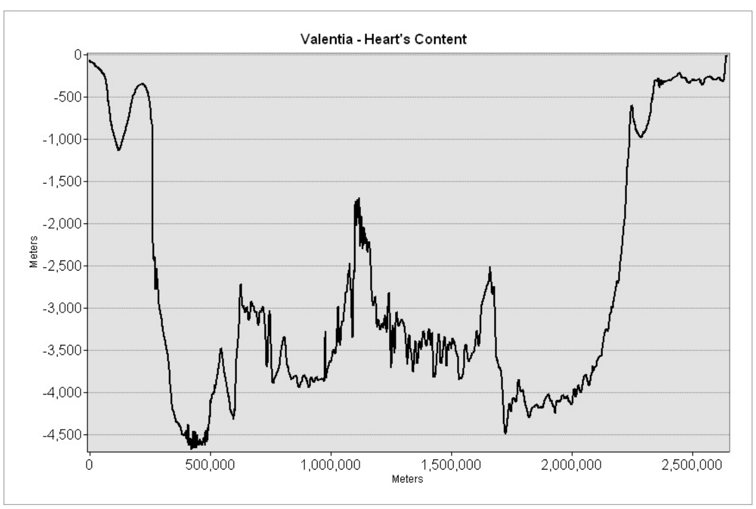
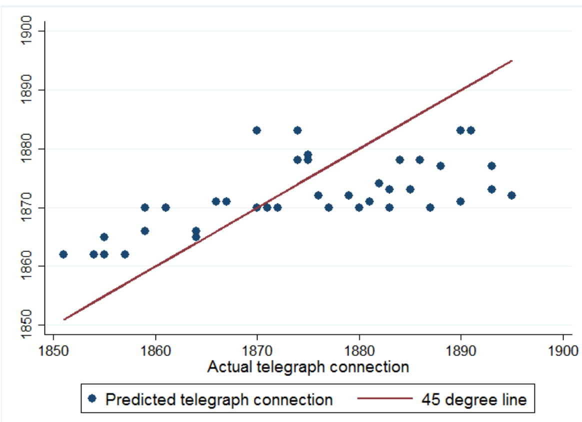
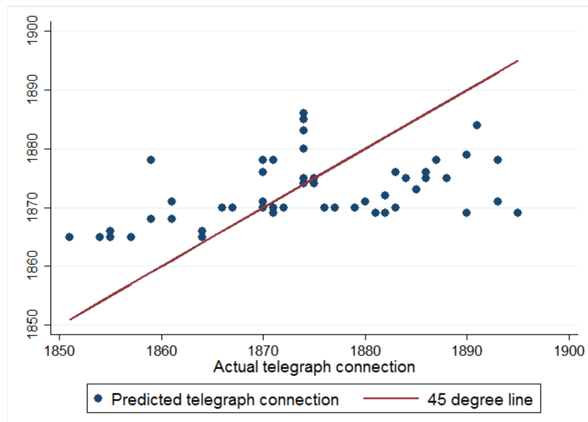


Figure 9: Predicted versus actual year of first successful telegraph connection



(a) Riley ruggedness



(b) Normalized Cable Length