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# Language standardization and the Industrial Revolution

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## Abstract

Why did the countries with the highest literacy rates fail to contribute to the innovations of the Industrial Revolution? Recent empirical research shows that people tend to mistrust those perceived to speak with an accent. Here the hypothesis of a link between language, trust and innovation is tested with a new data set comprising 201 urban regions and 117 important innovations between 1700 and 1850. In the three states that contributed almost all of these innovations (Britain, France and the USA), rising literacy was merely the first step toward the formation of large networks of people speaking standardized languages. These networks proved particularly important for advances requiring collaboration. Elsewhere, where language standardization was delayed, innovation also came later.

**JEL classifications**: N11, N13, O15.

## 1. Introduction

*It is easily possible to doubt whether they are speaking English or some foreign language.*

—Grammarian Alexander Gil writing in 1619 of those speaking English regional dialects

This paper extends recent research in linguistics and social psychology to revisit one of the puzzles of the Industrial Revolution; namely the absence of a close relationship between education and productivity growth rates (Mitch, 1999, pp.255–6). During the 17th and 18th centuries, literacy rates rose especially rapidly in the Protestant states of Northern Europe. By 1800 male literacy in northern Germany, the Netherlands and Scandinavia, measured by signature rates, ranged from 70% to over 90% (Reis, 2005, p.202). Theoretical models of endogenous growth suggest that these societies should have been the first to experience rapid technological change (see the review by Romer, 1994). Yet measured by rates of innovation, these regions contributed little before 1850. Instead, for a century and a half after 1700, virtually all of the important technical innovations were developed in Britain, its American offshoots and northern France, where literacy rates were considerably lower than in northern Europe.[1]

This paper offers a possible explanation for the apparent orthogonality of education and productivity growth in the West before 1850. In a word, literacy was merely a first step toward creating standardized language networks. These expanding networks made possible the trust that allowed people from different regions to innovate cooperatively. The argument is based on three propositions. First, because industrial technologies were growing in complexity, cooperation between individuals with different skill sets was increasingly important.[2] Think, for example, of Scottish engineer James Watt and English entrepreneur Matthew Boulton. Second, cooperation between individuals required that they write and speak the same vernacular language. Had Watt and Boulton been born a century earlier, they would have had difficulty communicating with each other. However, by the second quarter of the 18th century, grammar and spelling texts used in both England and southern Scotland were insisting on standardized ways of spelling and pronouncing the English language for boys 'who are to be put to Trades' (Cohen, 1977, p.48, pp.81–2; Frank, 1994, p.55). Third, there was some minimum size for a language network that would allow it to generate cooperative innovations such as the Boulton and Watt steam engine. In the first decade of the 18th century, England, Scotland and Wales had a combined population of 5.4 million (Maddison, 2001, p.247), while the population of France north of a line from St Malo to Geneva was over 10 million. In comparison, the United Provinces had a population of only 1.5 million, while Denmark had only 0.7 million. Although the states that comprise present-day Germany had a population of 16 million (Maddison, 2001, p.241), they as yet had no standard language. Arguably, if network effects are taken into account, these and other continental states were either too small or linguistically too heterogeneous to generate novelty.

Previous studies have offered several plausible explanations for the burst of innovation that occurred during the Industrial Revolution. The dominant approach has emphasized the supply side. North (1990, p.3) stressed the importance of institutions ('humanly devised constraints that shape human interaction'). Similarly, Acemoglu and Robinson (2012, p.82) pointed to the emergence of 'inclusive' political institutions as the keys to Britain's economic success. A corollary suggested by Mokyr (2002, p.34) was that the innovating society must have an ideology that favours new ways of practical thinking ('the expansion of useful knowledge'). Also on the supply side, Landes (1998, p.219) emphasized Britain's individualistic culture, while Clark (2007, p.11) argued that Britain's industrial lead had a genetic/cultural component due to high fertility rates of the 'economically successful'.

Allen (2009), in contrast, proposed a demand-side approach to innovation, suggesting that institutions and ideology were not enough. New technologies, he argued, were developed through the response of entrepreneurs to the opportunities signalled by changes in factor prices. In the case of 18th-century Britain, the rising costs of labour and conventional

1 In 1800, the male literacy rate in England was only about 60% (Cressy, 1980, p.177) and in France 50% (Houdaille, 1977, p. 68). If slaves and Native Americans are included, American literacy levels were probably even lower than those in England (Graff, 1991, p.252).

2 In 18th-century Britain, as Jacob (1997, pp.105–8) has explained, technological cooperation was typically the result of partnership between a self-educated engineer and an unrelated industrial entrepreneur.

sources of energy led skilled artisans and their backers to develop new processes that replaced labour with machinery and charcoal, wind and water with coal (Crafts, 2010).[3]

There are several problems, however, with these explanations. Relying on differences between *nations* as a whole they cannot explain why even in the innovating countries, development of new technologies tended to be confined to a small number of *regions*. As will be shown below, some three-quarters of the important innovations cited by historians of technology were developed in three narrow bands of territory in England, northern France and the USA. Other regions in the West with similar institutions and factor prices, or higher levels of literacy failed to innovate during the century and a half prior to 1850.

What did these particular regions of Britain, France and America have that other regions in the West lacked? Section 2 presents an original data set composed of 117 important innovations identified by the urban regions where they were developed. Following the first proposition stated above, the approach here departs from earlier studies in distinguishing between cooperative innovations and non-cooperative innovations (NCIs).[4]

A second difficulty overlooked in most previous research is the effect of communication on strategic behaviour, that is, situations where the outcome for each individual depends on the actions of other agents. Smith (2010) observed that there are several ways in which communication through language may facilitate cooperation. If information is costless, 'cheap talk' may allow individuals with convergent interests to coordinate their strategies (Farrell and Rabin, 1996). Language also permits information concerning the reputation of individuals to circulate in groups (Smith, 2010, pp.236–7); for example, the network of Maghribi traders studied by Greif (2006, pp.58–61) shared a common written medium that seems to have been unique to their community.[5] Finally, in large groups, if acquiring the capacity to speak and write the standard language has a cost that is negatively correlated with an individual's competence, players can credibly signal their capacities to one another by investing in formal education (Spence, 1973).

Recent research in social psychology and linguistics provides support for the importance of language in building trust. When two strangers meet, empirical studies have shown, the crucial issue for each person is whether the other can be trusted (Wojciszke *et al.*, 1998; Fiske *et al.*, 2007). Experiments by Lev-Ari and Keysar (2010) indicate that one of the measures people use to evaluate trustworthiness is accent. The stronger one's accent, the less credible one sounds. Moreover, annoyance with accents applies not only to those using a second language but also to those speaking variants of the same language (Sumner and Samuel, 2009). 'Just as the colour of one's skin or education level might, however unjustly, influence our behaviour, voice cues activate the same social biases and influence behaviour in a similar manner' (Sumner, 2015, p.239). As Anderson (2006, p.48) affirmed, in the modern period the process of language standardization has been extremely important in

3 Human capital adds another dimension to the story, one with both demand- and supply-side aspects, linking education levels to growth in productivity (Galor *et al.*, 2009, p. 144).

4 Allen (1983) studied 'collective invention' among 19th-century American iron and steel firms that shared the results of successful technological refinements with local rivals; however, all were price takers and there was no explicit research and development.

5 According to Goitein (1973, p. 4), the letters to which Greif refers were written in Arabic, but 'not classical Arabic nor a simple vernacular but a semiliterary language' with Hebrew characters, often interspersed with 'Hebrew words and phrases'.

widening the boundaries of people's 'imagined community'. Section 3 discusses the relationship between cooperation and language standardization.

A third difficulty with previous discussions of the Industrial Revolution is neglect of the process of innovation. Over 60 years ago Ashton ([1948] 1962, pp.13–5) proposed that innovation occurred through the combination of apparently unrelated ideas. Metcalfe's Law and its extensions suggest that the number of interactions in a network increases more than proportionally to the number of nodes (Briscoe *et al.*, 2006).[6] If these insights are valid, it is important to model explicitly the number of potential connections between individuals in a society.

To verify the effects of network size, following the third proposition, Section 4 proposes a model of collaboration between potential innovators in two cities. The probability of successful innovation depends on the population of each city and on the distance between them. An empirical version of this model is then expanded to include the institutional, factor-price and human-capital explanations of innovation as special cases. The results in Section 5 along with the methodological discussion in Section 6 help explain why literacy rates were unrelated to productivity growth before 1850. Literacy was a necessary first step, but rapid innovation required that the vernacular language then be standardized among large networks of people.

## 2. Cooperating to innovate

The introduction proposed an approach to innovation during the Industrial Revolution that emphasized the effect of language standardization on willingness to cooperate. Consider now a data set that allows comparison of this linguistic approach with those of previous studies.

Table 1 presents 117 important innovations identified by leading historians of technology. The principal source for this sample is an extensive study by a panel of experts headed by Maurice Daumas (1979), published in French in 1968. To avoid possible bias, each of the innovations selected also had to be mentioned by at least one comparable more recent study from outside France.[7] This methodology has the advantage of including important technologies never patented, such as Smeaton's breast wheel and Trevithick's high-pressure engine, while excluding numerous others that may have been patented but were never developed.

A detailed study of each innovation by Dudley (2012, chs 2–4) indicated that 54 of these technologies involved collaboration between two or more principals. An example is the partnership for the water frame by wig-maker Richard Arkwright and clock-maker John Kay, the former specializing in conception and marketing and the latter in technical development. Since in the 54 cases, each partner contributed services that could not readily be

6 From the 6th to the 13th centuries AD, China, generally with one or two states, was considerably more innovative than Europe divided into multiple units. Moreover, between 1200 and 1500, an increased rate of European innovation coincided with the formation of larger political units (Mokyr, 1990, chs 2, p. 9). Inter-regional barriers to mobility and trade fell as strong centralized monarchies appeared in England, France, Spain, and Portugal, while some territorial consolidation also occurred in Italy and Germany.

7 The other studies were Paulinyi (1989), Mokyr (1990), and Cardwell (1991) along with the online edition of the *Encyclopedia Britannica*.

**Table 1.** 117 important innovations, 1700–1849

| Country | 1700–1749 | 1750–1799 | 1800–1849 |
|---|---|---|---|
| Denmark | | | Galvanometer (Oersted, 1819; Copenhagen) |
| France | Loom coded with perfo-rated paper (Bouchon, 1725; Lyon)<br>Loom coded with punched cards (Falcon, 1728; Lyon) | Steam-powered wagon (Cugnot, 1770; Paris)<br>Automatic loom (Vaucanson, 1775; Paris)<br>Single-action press (Didot, Proudon, 1781; Paris)<br>Two-engine steamboat (Jouffroy d'Abbans, 1783; Lyon)<br>Hot-air balloon (Montgolfier, 1783; Paris)<br>Parachute (Lenormand, 1783; Montpellier)<br>Press for the blind (Haüy, 1784; Paris)<br>Chlorine as bleaching agent (Berthollet, 1785; Paris)<br>Sodium carbonate from salt (Leblanc, d'Arcet, 1790; Paris)<br>Visual telegraph (Chappe, 1793; Paris)<br>Vacuum sealing (Appert, 1795; Paris)<br>Paper-making machine (Robert, Didot, 1798; Paris)<br>Illuminating gas from wood (Lebon, 1799; Paris) | Automatic loom with perfo-rated cards (Jacquard, Breton, 1805; Lyon)<br>Wet spinning for flax (de Girard, 1815; Avignon)<br>Electromagnet (Arago, Ampère, 1820; Paris)<br>Water turbine (Burdin, 1824; Saint-Étienne)<br>Single-helix propeller (Sauvage, 1832; Le Havre)<br>Three-color textile printing machine (Perrot, 1832; Rouen)<br>Water turbine with adjust-able vanes (Fourneyron, 1837; Besançon)<br>Photography (Daguerre, Niepce, 1838; Paris)<br>Multiple-phase combing machine (Heilmann, 1845; Mulhouse) |
| Germany | Porcelain (Tschirnhaus, 1707; Dresden) | Lithography (Senefelder, 1796; Munich) | |
| Great Britain | Seed drill (Tull, 1701; Oxford)<br>Iron smelting with coke (Darby, Thomas, 1709; Birmingham)<br>Atmospheric engine (New-comen, Calley,1712; Birmingham)<br>Pottery made with flint (Astbury, 1720; Birmingham) | Crucible steel (Huntsman, 1750; York)<br>Rib knitting attachment (Strutt, Roper, 1755; Birmingham)<br>Achromatic refracting tele-scope (Dollond, 1757; London)<br>Breast wheel (Smeaton, 1759; York) | Machines for tackle block production (Brunel, Maudslay, 1800; London)<br>Illuminating gas from coal (Murdock, Watt Jr., 1802; Birmingham)<br>Steam locomotive (Trevithick, Homfray, 1804; Plymouth) |

(continued)

**Table 1**. Continued

| Country | 1700–1749 | 1750–1799 | 1800–1849 |
|---|---|---|---|
| | Quadrant (Hadley, 1731; London)<br>Flying shuttle (Kay, 1733; Manchester)<br>Glass-chamber process for sulphuric acid (Ward, White, D'Osterman, 1736; London)<br>Spinning machine with rollers (Wyatt, Paul, 1738; Birmingham)<br>Stereotyping (Ged, 1739; Edinburgh)<br>Lead-chamber process for sulphuric acid (Roebuck, 1746; Birmingham) | Bimetallic strip chronometer (Harrison, 1760; London)<br>Spinning jenny (Hargreaves, 1764; Manchester)<br>Creamware pottery (Wedgewood, Wieldon, 1765; Birmingham)<br>Cast-iron railroad (Reynolds, 1768; Birmingham)<br>Engine using expansive steam operation (Watt, Roebuck, 1769; Glasgow)<br>Water frame (Arkwright, Kay, 1769; Birmingham)<br>Efficient atmospheric steam engine (Smeaton, 1772; Newcastle)<br>Dividing machine (Ramsden, 1773; London)<br>Cylinder boring machine (Wilkinson, 1775; Birmingham)<br>Carding machine (Arkwright, Kay, 1775; Birmingham)<br>Condensing chamber for steam engine (Watt, Boulton, 1776; Birmingham)<br>Steam jacket for steam engine (Watt, Boulton, 1776; Birmingham)<br>Spinning mule (Crompton, 1779; Manchester)<br>Reciprocating compound steam engine (Hornblower, 1781; Plymouth)<br>Sun and planet gear (Watt, Boulton, 1781; Birmingham) | Compound steam engine (Woolf, Edwards, 1805; London)<br>Winding mechanism for loom (Radcliffe, 1805; Manchester)<br>Arc lamp (Davy, 1808; London)<br>Food canning (Durand, Girard, 1810; London)<br>Rack locomotive (Blenkinsop, Murray, 1811; Bradford)<br>Mechanical printing press (Koenig, Bauer, 1813; London)<br>Steam locomotive on flanged rails (Stephenson, Wood, 1814; Newcastle)<br>Safety lamp (Davy, 1816; London)<br>Circular knitting machine (M. I. Brunel, 1816; London)<br>Planing machine (Roberts, 1817; Manchester)<br>Large metal lathe (Roberts, 1817; Manchester)<br>Gas meter (Clegg, Malam, 1819; London)<br>Metal power loom (Roberts, Sharp, 1822; Manchester)<br>Rubber fabric (Hancock, Macintosh, 1823; London)<br>Locomotive with fire-tube boiler (Stephenson, Booth, 1829; Manchester)<br>Hot blast furnace (nielson, Macintosh, 1829; Glasgow)<br>Self-acting mule (Roberts, Sharp, 1830; Manchester) |

(continued)

**Table 1**. Continued

| Country | 1700–1749 | 1750–1799 | 1800–1849 |
|---|---|---|---|
| | | Indicator of steam engine power (Watt, Southern, 1782; Birmingham)<br>Rolling mill (Cort, Jellicoe, 1783; Portsmouth)<br>Cylinder printing press for calicoes (Bell, 1783; Glasgow)<br>Jointed levers for parallel motion (Watt, Boulton, 1784; Birmingham)<br>Puddling (Cort, Jellicoe, 1784; Portsmouth)<br>Power loom (Cartwright, 1785; York)<br>Speed governor (Watt, Boulton, 1787; Birmingham)<br>Double-acting steam engine (Watt, Boulton, 1787; Birmingham)<br>Threshing machine (Meikle, 1788; Edinburgh)<br>Single-phase combing machine (Cartwright, 1789; York)<br>Machines for lock production (Bramah, Maudslay, 1790; London)<br>Single-action metal printing press (Stanhope, Walker, 1795; London)<br>Hydraulic press (Bramah, Maudslay, 1796; London)<br>High-pressure steam engine (Trevithick, Murdoch, 1797; Plymouth)<br>Slide lathe (Maudslay, 1799; London) | Lathe with automatic cross-feed tool (Whitworth, 1835; Manchester; Manchester)<br>Planing machine with pivoting tool-rest (Whitworth, 1835; Manchester)<br>Even-current electric cell (Daniell, 1836: London)<br>Electric telegraph (Cooke, Wheatstone, 1837; London)<br>Riveting machine (Fairbairn, Smith, 1838; Manchester)<br>Transatlantic steamer (I. K. Brunel, Guppy, 1838; Bristol)<br>Assembly-line production (Bodmer, 1839; Manchester)<br>Multiple-blade propeller (Smith, Currie, 1839; London)<br>Steam hammer (Nasmyth, 1842; Manchester)<br>Iron, propeller-driven steamship (Brunel, Guppy, 1844; Bristol)<br>Measuring machine (Whitworth, 1845; Manchester)<br>Multiple-spindle drilling machine (Roberts, 1847; Manchester) |
| Italy | | | Electric battery (Volta, 1800; Como) |
| Switzerland | | Massive platen printing press (Haas, 1772; Basel)<br>Stirring process for glass (Guinand, 1796; Berne) | |

(continued)

**Table 1**. Continued

| Country | 1700–1749 | 1750–1799 | 1800–1849 |
|---|---|---|---|
| United States | | Continuous-flow production (Evans, Ellicott, 1784; Philadelphia)<br>Cotton gin (Whitney, Green, 1793; Philadelphia)<br>Machine to cut and head nails (Perkins, 1795; Boston) | Single-engine steamboat (Fulton, Livingston, 1807, New York)<br>Milling machine (North, 1818; New York)<br>Interchangeable parts (North, Hall, 1824; New York)<br>Ring spinning machine (Thorp, 1828; Boston)<br>Grain reaper (McCormick, Anderson, 1832; Philadelphia)<br>Binary-code telegraph (Morse, Vail, 1845; New York)<br>Sewing machine (Howe, Fisher, 1846; Boston)<br>Rotary printing press (Hoe, 1847; New York) |

*Note*: Underlined innovations were cooperative; that is, they had two or more principals.

bought on the market, the withdrawal of either would have meant the end of the project (Hills, 1970, pp.63–6). Defined in this way, the CIs are underlined in Table 1. Note that these CIs tended to be technologically relatively complex. Compare, for example, the atmospheric steam engine, machine spinning of cotton and smelting with coke with three NCIs from the same period such as the flying shuttle, the quadrant and stereotyping.

Allen (1983) and Nuvolari (2004) noted that innovations within a given country were not spread evenly across its territory but rather tended to cluster around a few centres. This finding suggests that the unit of observation should be an urban region within a state. Accordingly, the units of observation were 201 cities, each of which had at least 7,000 inhabitants in 1700 (the population of Birmingham in that year). Since the goal of the study was to explain variations *within* comparable societies, all of the European cities were required to be at least as close to London as the most distant innovating city—Como in northern Italy. This assumption has the advantage of keeping the number of zero observations within a reasonable limit. Also included were three American cities—New York, Philadelphia, and Boston.

An examination of Table 1 reveals that innovation during the Industrial Revolution was highly concentrated geographically. As Fig. 1 shows, one corridor ran from London up to Birmingham and Manchester. In France, there was a band stretching from Le Havre through Paris to Lyon. Finally, in the USA, most of the innovations were developed in a stretch down the east coast, from Connecticut to the Potomac River. These three strips accounted for 74% of all the innovations in the sample and 82% of the CIs.

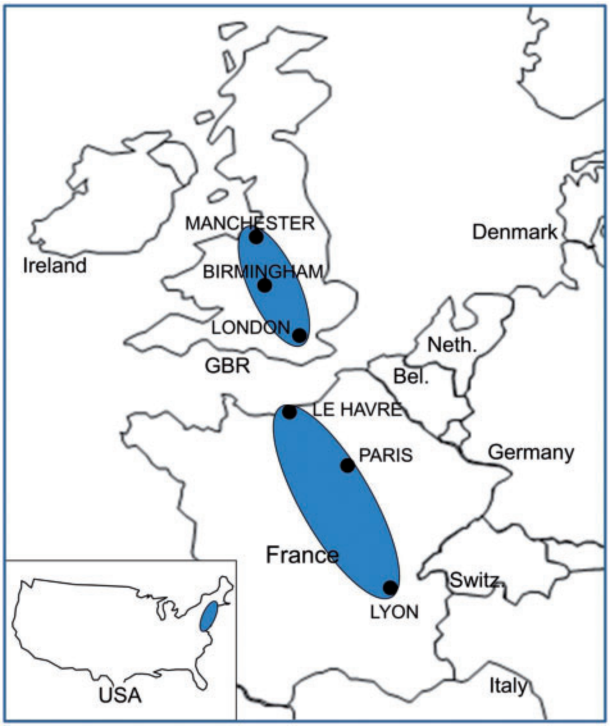


**Fig. 1.** Areas of high innovation density, 1700–1849

It is interesting to note that the English and French bands of innovation in Fig. 1 include London and Paris, the main cultural centres of the corresponding societies. These are precisely the areas within which the English and French standard national languages first took form (Harris, 1990, p.211; Crystal, 2003, p.254). The next section will explore whether the distance from these cultural centres is related to the propensity to innovate.

## 3. The language-standardization approach

Why might three-quarters of the important innovations of the Industrial Revolution, and four-fifths of those that were cooperative have been clustered around the main cultural centres in three states? This section suggests that prior to the beginning of the modern period in the West, there were barriers to innovation caused by the difficulty of communicating with those who were neither kin nor neighbours.

Consider the distance of each innovating city in the sample of Table 1 from the cultural centre of its society. For Britain, France, the Netherlands, Denmark and Austria the present capital city was chosen. For the USA, the cultural centre selected was New York; for Italy, Florence. As for Germany, the city chosen was Leipzig, a major publishing centre and after 1632 the location of the largest book fair. For multicultural Switzerland and Belgium, the centres chosen were Paris, Leipzig or Amsterdam depending on whether the city's principal language was French, German or Dutch, respectively. In Fig. 2, the resulting distances are plotted against the year of the innovation.

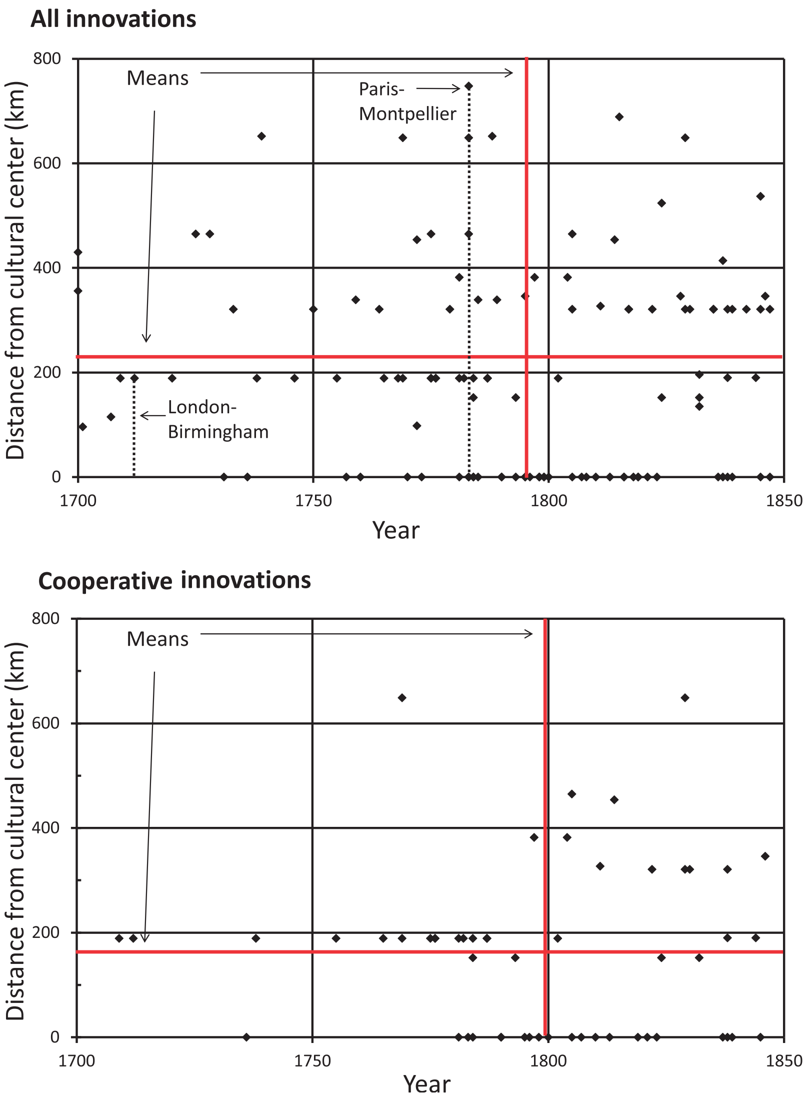


**Fig. 2.** Year of innovation and distance from cultural centre

The upper graph of Fig. 2 shows the plot for the complete sample of 117 innovations. For example, in the lower left is displayed the distance of 190 km from London to the region of Birmingham, where Newcomen and Calley invented the atmospheric steam engine in 1712. In the middle of the graph is the distance of 750 km from Paris to Montpellier where Lenormand invented the parachute in 1783. The vertical and horizontal heavy dark lines indicate that the mean distance of the innovations from their society's cultural centre was 212 km and the mean year was 1794.

The lower graph displays the corresponding data for the 54 CIs. There are several features to notice here. First, the mean distance from the cultural centre for the CIs was only

169 km. Second, the mean year for the cooperative subsample was a relatively-late 1799.[8] These differences in means for distance and years compared to the sample as a whole are significant at the 1% and 10% levels respectively. Third, it is striking that *all* of the CIs came from Britain, France or the USA. In other words, before 1850 there is little evidence of successful cooperation to innovate on the Continent outside of France.

The graphs in Fig. 2 suggest three questions. First, why were the 54 CIs developed closer to the cultural centres than the 63 non-cooperative ones were? The graphs are consistent with the notion that between 1700 and 1850, there was some factor related to distance that inhibited cooperation. Second, why were the CIs developed later than the NICs? This evidence suggests that developing the capacity to cooperate took time. Finally, why were Britain, France and the USA the only countries to develop CIs during the century and a half from 1700 to 1850?

Over time, there is a tendency of speech patterns within separated communities to drift apart. Offsetting this centrifugal trend, Milroy (1994, 20) identified two phases in the standardization of a language. First, there may emerge a spontaneous consensus of primarily *phonetic* norms at the regional level. In England, this first phase of standardization occurred from about 1400 to 1600, yielding several regional speech variants.[9] Then for the following century and a half, from 1600 to 1800, language norms were imposed from above through the publication of *written* standards in the form of dictionaries and grammar texts printed in the capital. As a result, the variety used by a prestige group within London society gradually became the norm for written communication. Standardization of the spoken language followed, although important regional differences in pronunciation persisted until the late 19th century (Stein, 1994, pp.4–6).

Supporting Milroy's analysis is a recent study of the mutual intelligibility of dialects in northern Europe. As a result of Milroy's first stage of consensus at the regional level, 17 distinct Scandinavian dialects may be identified. A study of young Danes from Copenhagen indicated that the average intelligibility of individual words today ranges from about 50% for dialects from neighbouring regions to about a third for distant regions within the same language family. Regarding the second stage, comprehension of standardized Norwegian and Swedish words averages over 60%, while for Standard Danish, the corresponding figure is 99% (Gooskens *et al.*, 2008).

The negative impact of distance on comprehension mirrors the negative effect of distance on the frequency of CI in Fig. 2. In addition, the result that standardization improves comprehension echoes the finding in Fig. 2 that all of the CIs were in the three countries that were the first to standardize their languages. Therefore, it would be seem worthwhile to test the impact of language standardization on the propensity to innovate.

8 Supporting this result that cooperation occurred relatively late is the evidence from the historical references cited in the previous section. There were few, if any, examples of successful collaborative innovation prior to the 18th century. (Note that the famous example of Gutenberg and Fust ended in joint defection.)

9 In the year 1600, the standardization of the speech of the (urban) middle classes had not yet begun (Stein, 1994, p.9). There were considerable differences between the emerging vernacular norm of the London area and the urban varieties spoken in other English regions (Milroy, 1994, pp.25–6).

## 4. Model specification

This section begins by proposing a simple theoretical model capable of capturing the effect of language on innovation. The result is a Poisson specification that may be adapted to accept other approaches to innovation as special cases. Missing observations of the explanatory variables are then estimated by the stochastic-regression method.

Assume that there are two cities, with populations $n_1$ and $n_2$ respectively. Initially their dialects are sufficiently different to prevent communication between their residents. Now let a standardized language be introduced into their populations. The number of *new* pairings, $x$, made up of one resident from each city made possible by this development is given by:

$$x = n_1 n_2.$$

If the fraction $\pi_1$ of these potential partnerships leads to a successful innovation in city 1, the total number of innovations there, $y_1$, is:

$$y_1 = \pi_1 n_1 n_2.$$

Of course, not all of these innovations need take place in city 1. More realistically, we assume that there may be congestion, as represented by the parameters $\alpha$ and $\beta$, when individuals from city 2 try to find partners in the city 1. Moreover, because of transaction costs, the probability of a successful pairing will be a decreasing function of the distance, $d$, between the two cities. The expected number of innovations in city 1 will then be:

$$y_1 = \pi_1 n_1^{\alpha} n_2^{\beta} e^{-\gamma d}, \ \alpha, \ \beta \leq 1.$$

Take logs:

$$\ln \ y_1 = \ln\left(\pi n_1^{\alpha} n_2^{\beta} e^{-\gamma d}\right).$$

or

$$y_1 = \exp\left[C_1 + \alpha \ln(n_1) + \beta \ln(n_2) - \gamma d\right], \text{ where } C_1 = \ln(\pi_1) \tag{1}$$

Equation (1) expresses the expected number of innovations produced after the introduction of a standardized language in a form that may be inserted into a Poisson distribution. In effect, we have a gravity model of innovation, with the logarithms of the population of two cities and the distance between them as explanatory variables. The next step is to integrate this networking approach into a specification that incorporates the supply and demand approaches used in previous studies. Define the dependent variable as the number of innovations of a given type that occurred in the region of a given city during each half-century between 1700 and 1849. Since such innovations may be considered rare events, we should use an estimation method appropriate for count data. The variance of this variable in our sample (0.182) is considerably greater than the mean (0.065). To allow for this over-dispersion (a greater frequency of zero observations than the Poisson distribution assumes), a negative-binomial specification is appropriate.

$$\mathbf{y} = \exp(\mathbf{X\beta} + \boldsymbol{\varepsilon} + \mathbf{u}), \tag{2}$$

where $y_{ijt}$ is the expected number of innovations in city $i$ of type $j$ (cooperative or non-cooperative) in period $t$, $\boldsymbol{x}_{ijt}$ is a vector of explanatory variables, $\boldsymbol{\beta}$ is a vector of parameters,

$\varepsilon_{ijt}$ is a random variable and exp $(u_{ijt})$ follows a gamma distribution with parameters $\theta$ and $1/\theta$.

Consider next the explanatory variables. Unobserved supply-side influences may be assumed to be picked up by fixed-effects variables. Accordingly, five dummy variables correspond to the principal nations included in the sample, while *1750* and *1800* represent the half-centuries after 1750 and 1800 respectively.

A second group of variables picks up the influence of demand conditions. Data for eight urban regions and three periods permitted estimation of the following equation:

$$\begin{aligned} Energy\ price/Wage\ rate \ = \ & \underset{(0.054)}{1.037} - \underset{(0.096)}{0.353} * Coal - \underset{(0.056)}{0.472} * Britain + \underset{(0.075)}{0.498} * France \\ & - \underset{(0.067)}{0.172} * 1800, -R^2 = 0.917,\ \text{Root MSE} = 0.1683 \end{aligned} \tag{3}$$

The figures in brackets are robust standard errors. Regions close to coal deposits could be expected to have lower energy prices. There were important labour productivity differences between England and France, and in the early 19th century, real wages for building labourers across northern Europe were generally higher than they had been a century earlier (Allen, 2001, p.416). From the estimated coefficients and root MSE, values for the 579 missing observations of relative energy prices were then imputed by the stochastic-regression method.

Galor *et al.* (2009) suggested that a greater stock of human capital would stimulate innovation. The literacy rate is an approximate measure of the abundance of this factor. Estimates of signature rates of marrying couples at the regional level are available for 281 of the 603 observations in the data set. With these data, it was possible to estimate the following regression:

$$\begin{aligned} Literacy = \ & \underset{(1.400)}{41.14} + \underset{(2.985)}{11.96} * 1800 - \underset{(3.414)}{7.50} * Catholic + \underset{(2.050)}{20.61} * Dissent \\ & + \underset{(0.00073)}{0.0086} * DistRome - \underset{(0.00262)}{0.0370} * DistMainz + \underset{(0.899)}{18.57} * Male - \underset{(1.233)}{4.41} * Rural, \\ & R^2 = 0.842,\ \text{Root MSE} = 10.20, \end{aligned} \tag{4}$$

where Dissent indicates a religion other than Catholic, Lutheran or Anglican, DistRome is the distance from Rome in kilometres, DistMainz is the distance from Mainz, and Male and Rural indicate that the measure applies to males or rural residents respectively. As Cipolla (1969, pp.72–3) observed, other things being equal Catholics tended to have lower literacy rates and Dissenting religions higher rates, although German Catholics were highly literate. Dittmar (2011, p.1139) used the distance from Mainz to explain 16th-century European urban population growth, explaining that this measure was positively correlated with literacy. The 322 missing observations were again imputed by the stochastic-regression method.

Allen (2009, pp.109–11) also suggested that openness to international trade made an important contribution to Britain's economic success. This consideration was assumed to be captured by a dummy variable indicating whether or not the region's principal city was an ocean port in 1700. By the end of the period being studied, inland cities such as

Manchester and Birmingham had been linked to the sea by canals. However, since these changes were in part endogenous, depending on the region's previous innovating success, river cities are excluded as ports.

The next step is to integrate the language-network model of eq. (1) into the specification of eq. (2). Three additional variables were inserted. The first was the log of the population of the urban region's main centre, City population. This variable, as a measure of the scale of the unit of observation, would of course also play a role in the supply and demand models described above. Next was the log of the population of the rest of the society, Country population. For most cities in the sample, this variable was assumed to be captured by the population within the present-day country (less the city's population) at the beginning of each period.[10] The USA was an exception. At the beginning of the first two sub-periods, the 13 colonies were a part of the British Empire. Even after the American War of Independence, the two countries remained important trading partners. At the end of the 18th century, over half of British exports and a third of its imports were with the Americas, including a small portion with British North America (Deane and Cole, 1962, p.62). The British Isles also remained the most important source of immigration to the new nation (Bankston, 2010). Accordingly, Great Britain, and the USA were assumed to form a single society.[11]

For the third networking variable—the distance of the city in question from the rest of the country—two different measures were used. One factor that would reduce the willingness to cooperate of two individuals is simply physical separation, Distance, defined as the number of kilometres of the city in question from the country's main cultural centre. However, willingness to cooperate may also depend on the degree of standardization of linguistic signals. Accordingly, a second measure of distance is the degree of language standardization, as measured by dictionary year, the year of publication of the country's first monolingual dictionary (normalized with Britain in 1658 equal to zero), as shown in Table 2. The successful publication of such a work demonstrates that one variant of the language has become sufficiently accepted to cover the high cost of preparing the manuscript, setting it to type and printing it.[12]

10 The West-Germanic language area poses a problem. Should one use the state boundaries of the 18th century or those of the present day? If one is interested in some minimum probability of mutual comprehension within a cultural area from which potential collaborators may emerge, then present-day political boundaries are arguably appropriate since they correspond closely to those of major language groups. In 1700, within the German Empire, there was a continuum of dialects as one passed from one political unit to another (Crystal, 1997, p.25).

11 Implicitly, by measuring distances in the USA from New York rather than London, while placing both cities within the same cultural region, we are assuming that the cultural distance of New York from London is negligible. There is some justification for this position. In 1759, during the Seven Years' War, New York was the only American colony to help finance the British Army in its combat with the French (Anderson, 2001, pp.321–2). During the American Revolution, New York was one of the last colonies to declare its independence.

12 Milroy (1994) argued that there was an identifiable *process* in the standardization of the European languages. First came the setting of standards for spelling and meaning; next came the diffusion of these standards for the written language; finally came the diffusion of norms for variability in the spoken language. The publication of the first monolingual dictionary marks the boundary between the first and second steps and thus provides a suitable marker for comparing language areas.

**Table 2.** Year of first monolingual dictionary

| Country | Year | Author(s) | Publication |
|---|---|---|---|
| Austria | 1868 | Otto Back *et. al.* | *Österreichisches Wörterbuch* |
| England | 1658 | Edward Phillips | *The New World of English Words* |
| Belgium (French) | 1680 | | Same as France (north) |
| Belgium (Flem.) | 1864 | | Same as Netherlands |
| Denmark | 1833 | Christian Molbech | *Dansk Ordbog* |
| France (north) | 1680 | Pierre Richelet | *Dictionnaire français* |
| France (south) | 1815 | | Standardization delayed[a] |
| Germany | 1786 | Johann Christoph Adelung | *Grammatich-kritisches Wörterbuch der hochdeutschen Mundart* |
| Ireland | 1800 | | Year of Union with England |
| Italy | 1897 | Emilio Broglio & Giovanni Battista Giorgini | *Nòvo vocabolario della lingua italiana secondo l'uso di Firenze* |
| The Netherlands | 1864 | Marcus and Nathan Solomon Calisch | *Nieuw Woordenboek der Nederlandsche Taal* |
| Scotland | 1707 | | Year of Union with England |
| Switzerland (Fr.) | 1680 | | Same as France (north) |
| Switzerland (German) | 1786 | | Same as Germany |
| United States | 1728 | Nathan Bailey | A Universal Etymological English Dictionary |

*Notes:* [a]South of a line from St. Malo to Geneva, standardization occurred through the integrating effects of the Revolutionary and Napoleonic Wars (Graff, 1991, 193).
Other early dictionaries fail to reflect the existence of a standardized written vernacular. Robert Cawdrey's *Table Alphabeticall* (1604) was a list of hard words to spell. Josua Maaler's, *Die Teütsch Spraach* (1561) was devoted to Swiss and Upper German vocabulary. The Accademia della Crusca's dictionary of Italian (1612) was intended to provide a prescriptive norm to which writers were advised to conform. Kornelius Kiliaan's (1599) *Etymologicum* used Latin to explain Dutch words, as did Jean Nicot's (1606) *Trésor de la langue françoise* for the French language.

## 5. Results

Does taking account of language standardization improve the explanatory power of the supply and demand approaches used in previous studies of innovation? We shall consider separately each of two sub-groups of the total sample; namely, the 54 CIs and the 63 NCIs.

Table 3 presents the results for the CIs. In column (1) is a reduced-form specification that captures the demand and supply approaches. One finding is that the country fixed effects for Germany, Belgium and the Netherlands are arithmetically much smaller than those for the other North European countries. These differences are quite in keeping with those who argue that geography and institutions had an important effect on economic performance. In addition, the gaps may reflect the lasting impact of the wars that devastated Belgium, the Netherlands and Germany between the 19th and 19th centuries. As for the demand side, we see that the relative energy price and the literacy rate are also significantly different from zero with the expected signs.

Column (2) adds two networking variables, Country population and Distance from the principal cultural centre. We find that the coefficients of these variables are both highly significant with the expected signs. This result is compatible with the hypothesis that there

**Table 3.** Negative binomial regressions for cooperative innovations

| Group variable | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| *Fixed effects* | | | | |
| Britain | −0.018 | −0.517 | **−4.575**** | **−4.854**** |
| | *(0.391)* | *(0.222)* | *(0.829)* | *(0.805)* |
| France | 0.391 | −0.889 | **−5.735**** | **−6.735**** |
| | *(1.493)* | *0.832)* | *(1.178)* | *(0.868)* |
| Germany | **−17.239**** | **−16.308**** | **−17.128**** | **−19.347**** |
| | *(1.205)* | *(1.146)* | *(1.133)* | *(1.120)* |
| Belgium | −17.126** | −13.892** | −15.868** | −17.975** |
| | *(1.183)* | *(1.824)* | *(1.631)* | *(1.464)* |
| Netherlands | −17.842** | −14.178** | −11.594** | −13.383** |
| | *(1.154)* | *(1.631)* | *(2.042)* | *(2.164)* |
| 1750 | 0.960 | 0.429 | 0.320 | 0.275 |
| | *(0.492)* | *(0.629)* | *(0.784)* | *(0.872)* |
| 1800 | −0.410* | −1.497* | −1.536 | −1.652 |
| | *(0.188)* | *(0.751)* | *(1.029)* | *(1.238)* |
| *Demand* | | | | |
| Relative energy price | −3.285** | −3.087** | **−2.148**** | −2.038** |
| | *(1.279)* | *(0.643)* | *(0.230)* | *(0.155)* |
| Literacy | 2.777* | 1.627* | 0.165 | 0.363 |
| | *(1.166)* | *(0.813)* | *(1.570)* | *(1.852)* |
| Ocean port | −0.179 | −0.391 | −0.893** | −0.944** |
| | *(0.714)* | *(0.466)* | *(0.356)* | *(0.306)* |
| *Language networks* | | | | |
| City population | 1.148* | 0.923* | 1.215** | 1.321** |
| | *(0.455)* | *(0.267)* | *(0.313)* | *(0.225)* |
| Country population | | **1.619**** | **1.736**** | **1.788**** |
| | | *(0.529)* | *(0.585)* | *(0.658)* |
| Distance | | **−0.212**** | | 0.085 |
| | | *(0.082)* | | *(0.111)* |
| Dictionary year | | | **-3.297**** | **-3.493**** |
| | | | *(0.517)* | *(0.495)* |
| Constant | 2.948** | 3.765** | 8.465** | 8.615** |
| | *(1.125)* | *(1.124)* | *(1.787)* | *(1.716)* |
| $\theta$ | 2.015** | 1.704** | 1.204 | 1.153* |
| | *(0.352)* | *(0.387)* | *(0.636)* | *(0.659)* |
| Log pseudolikelihood | −80.389 | −77.678 | −72.538 | −72.431 |

*Notes:* Time-series cross-section of 201 cities for 1700–49, 1750–99 and 1800–49.
Dependent variable: number of CIs in the region of city $i$ in period $t$.
Number of observations: 603.
Standard errors adjusted for five clusters in country are shown in parentheses.
*Coefficient significantly different from zero at 0.05 level, two-tailed test.
**Coefficient significantly different from zero at 0.01 level, two-tailed test.
Coefficients in bold face are significantly different from corresponding estimates in Table 4 at 0.05 level, two-tailed test.

were significant network effects and that these effects diminished with distance. The other results remain essentially unchanged.

Column (3) presents an alternative explanation of network effects, based on the degree of language standardization rather than physical distance. Inclusion of Dictionary year significantly improves the fit of the model. However, the coefficients of the relative energy price and the literacy rate fall, the latter becoming no longer significant. Column (4) shows that these results are insensitive to the inclusion of distance.

The drop in statistical significance of the human-capital variable between columns (2) and (3) has potential implications for our understanding of the process of innovation, helping to explain the uneven pattern of industrialization across Europe between 1700 and 1850. Despite well-educated populations, many regions—even in Britain and France—failed to experience rapid innovation before the middle decades of the 19th century. A possible interpretation is that in England, France and the USA, the creation of large networks of people speaking standard languages set off a series of social changes in regions close to the main cultural centre, encouraging the development of energy resources, raising the real wage rate, and stimulating innovation. Elsewhere, these changes were delayed. It is worth noting that the first phase of Prussian industrialization described by Becker *et al.* (2011) occurred only in the 1830s—roughly a half century after the publication of the first monolingual Standard German dictionary (in 1786).

Table 4 presents the same specifications for NCIs. Looking at the most general results in column (4), we find certain similarities to the results for CIs. The country fixed effects for Germany, Belgium and the Netherlands are again significantly arithmetically greater than those for Britain and France. In addition, neither the relative energy price nor the literacy rate has a significant effect on the frequency of this group of innovations.

The significant positive coefficient for 1750 is consistent with the argument of Mokyr and Voth (2009) that the Enlightenment promoted a dissemination of knowledge across Europe and North America, allowing scientific discoveries to be applied by individuals with practical problems to solve. However, in results not shown, when terms capturing interaction between Britain and 1750 or 1800 were added to these specifications, they were not significant either for CIs or NCIs. In other words, there was no evidence of a peculiarly British 'Industrial Enlightenment' that was more favourable to innovation than its continental counterpart, *ceteris paribus*.

A closer examination of Table 4 nevertheless reveals important differences with respect to the preceding table. For one thing, the relative energy price is no longer significant. Nor is the measure of network size, country population. Indeed, the coefficients of the latter variable and the other key networking measure, dictionary year, are both significantly smaller in absolute value than in Table 3. This result suggests that inventors working on their own were not as dependent on the input of colleagues from other regions as cooperators were. However, since dictionary year was still significant, independent inventors did seem to require clear standardized communication with those from their own region. Undoubtedly even inventors working alone depended on precisely-expressed contracts with suppliers, employees and clients.

In short, the priority of Britain and France in the formation of large standardized language networks was highly significant in explaining their innovation performance, especially for innovations involving cooperation between two or more principals. Low relative

**Table 4.** Negative binomial regressions for non-cooperative innovations

| Group variable | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| *Fixed effects* | | | | |
| Britain | 0.606 | 0.679 | −0.634 | −0.790 |
| | *(1.314)* | *(1.203)* | *(1.271)* | *(1.297)* |
| France | 0.268 | 0.434 | −0.926 | −1.096 |
| | *(0.983)* | *(1.116)* | *(1.081)* | *(1.355)* |
| Germany | −1.972** | −1.879** | −2.073** | −2.204** |
| | *(0.051)* | *(0.163)* | *(0.214)* | *(0.158)* |
| Belgium | −16.030** | −18.050** | −17.604** | −16.655** |
| | *(1.101)* | *(1.124)* | *(1.202)* | *(1.326)* |
| The Netherlands | −16.511** | −18.591** | −17.190** | −16.189** |
| | *(1.182)* | *(1.120)* | *(1.264)* | *(1.254)* |
| 1750 | 0.646** | 0.680** | 0.674** | 0.684** |
| | *(0.214)* | *(0.176)* | *(0.191)* | *(0.198)* |
| 1800 | −0.358 | −0.301 | −0.101 | −0.117 |
| | *(0.781)* | *(0.685)* | *(0.887)* | *(0.890)* |
| *Demand* | | | | |
| Relative energy price | −1.376 | −1.429 | −1.103 | −1.054 |
| | *(1.885)* | *(1.941)* | *(1.823)* | *(1.849)* |
| Literacy | 2.153 | 2.201 | 0.740 | 0.844 |
| | *(1.993)* | *(1.871)* | *(2.308)* | *(2.089)* |
| Ocean port | −0.596 | −0.592 | −0.516 | −0.512 |
| | *(0.586)* | *(0.588)* | *(0.524)* | *(0.519)* |
| *Language networks* | | | | |
| City population | 1.017** | 1.049** | 0.970** | 1.051** |
| | *(0.093)* | *(0.212)* | *(0.060)* | *(0.204)* |
| Country population | | −0.117 | −0.011 | −0.054 |
| | | *(0.213)* | *(0.153)* | *(0.203)* |
| Distance | | 0.026 | | 0.084 |
| | | *(0.131)* | | *(0.159)* |
| Dictionary year | | | −0.929** | −1.009* |
| | | | *(0.350)* | *(0.484)* |
| Constant | 1.878 | 1.818 | 3.386 | 3.368 |
| | *(2.522)* | *(2.512)* | *(2.847)* | *(2.814)* |
| $\theta$ | 2.131* | 2.141* | 1.795* | 1.760* |
| | *(0.973)* | *(0.978)* | *(0.792)* | *(0.750)* |
| Log pseudolikelihood | −129.858 | −129.794 | −128.147 | −127.926 |

*Notes:* Time-series cross-section of 201 cities for 1700–49, 1750–99 and 1800–49.
Dependent variable: number of NCIs in region of city $i$ in period $t$.
Number of observations: 603.
Standard errors adjusted for five clusters in country are shown in parentheses.
*Coefficient significantly different from zero at 0.05 level, two-tailed test.
**Coefficient significantly different from zero at 0.01 level, two-tailed test.

energy prices also help explain such CIs. The spread of knowledge between regions and internationally during the last half of the 18th century favoured innovation by independent inventors. Finally, the statistically-significant fixed effects across countries are compatible with important geographic and institutional differences on the supply side.

**Table 5.** Robustness check for cooperative innovations

| Group variable | Mean | AvgSTD | %Sig | %+ | %- | AvgT | Obs |
|---|---|---|---|---|---|---|---|
| *Fixed effects* | | | | | | | |
| Britain | −1.08 | 0.46 | 75 | 39 | 61 | 6.06 | 64 |
| France | −2.74 | 0.97 | 58 | 13 | 88 | 5.07 | 64 |
| Germany | **−17.61** | **1.18** | **100** | **0** | **100** | **15.00** | **64** |
| Belgium | **−16.95** | **1.64** | **100** | **0** | **100** | **11.26** | **64** |
| Netherlands | **−15.46** | **1.64** | **100** | **0** | **100** | **10.47** | **64** |
| 1750 | **1.03** | **0.66** | **36** | **100** | **0** | **1.71** | **64** |
| 1800 | 0.14 | 0.87 | 19 | 50 | 50 | 1.30 | 64 |
| *Demand* | | | | | | | |
| Relative energy price | **−2.28** | **1.29** | **50** | **0** | **100** | **2.65** | **32** |
| Literacy | 3.03 | 1.83 | 47 | 97 | 3 | 2.34 | 32 |
| Ocean port | −0.01 | 0.73 | 13 | 47 | 53 | 0.84 | 32 |
| *Language networks* | | | | | | | |
| City population | **1.16** | **0.36** | **100** | **100** | **0** | **3.31** | **32** |
| Country population | **1.61** | **0.76** | **69** | **100** | **0** | **2.20** | **32** |
| Dictionary year | **−3.38** | **0.47** | **100** | **0** | **100** | **8.23** | **32** |

## 6. Methodological issues

One of the issues that the specification of eq. (2) raises is the possible endogeneity of relative factor prices and the literacy rate. To test for the presence of feedback to these two variables from the dependent variable (the number of innovations), the observed values of these two variables were replaced by instrumental variables estimated with eq. (3) and eq. (4) respectively. The resulting estimates (not shown here) were almost identical to those in Table 3. This result should not surprise us, since for the countries that accounted for 95% of the innovations (Britain, France and the USA), the relative abundance or rarity of coal and the initial sharp rise in literacy were determined *prior* to the first important innovations. A similar argument applies to the possible endogeneity of dictionary year. In only two of 117 cases did this date precede the first innovation in the corresponding country.

As mentioned in Section 2, most of the observations for two key independent variables—the relative energy price and literacy—were estimated by the stochastic regression method. How likely is it that this estimation procedure significantly biased our conclusions? A first point to note is that since the estimates in eq. (3) and eq. (4) explained the available observations well, the measurement errors were probably not large. Second, by construction these errors were uncorrelated with the possibly poorly-measured observations. As a result, the estimated coefficients in Table 3 are unbiased and consistent. Nevertheless, since the variances are not efficient, we will tend to underestimate the level of significance of the resulting coefficients.

Third, we can take this underestimation of the variances of the relative-price and literacy coefficients into account when we consider the robustness of the estimates. In Tables 5 and 6, the explanatory variables of eq. (3) are divided into two sets. The seven country and period fixed effects appear in all of the 64 specifications of each table. Each of the six remaining primary variables appears in 32 specifications – one for every possible combination of the five other primary variables. The column headed '%Sig' in each table indicates the percentage of the resulting coefficient estimates that were significant at the 5% level under

**Table 6.** Robustness check for non-cooperative innovations

| Group variable | Mean | AvgSTD | %Sig | %+ | %− | AvgT | Obs |
|---|---|---|---|---|---|---|---|
| *Fixed effects* | | | | | | | |
| Britain | 0.47 | 0.71 | 31 | 50 | 50 | 3.59 | 64 |
| France | −0.88 | 0.88 | 38 | 19 | 81 | 2.44 | 64 |
| Germany | **−2.01** | **0.22** | **100** | **0** | **100** | **13.64** | **64** |
| Belgium | **−16.44** | **1.13** | **100** | **0** | **100** | **14.56** | **64** |
| Netherlands | **−16.26** | **1.16** | **100** | **0** | **100** | **14.12** | **64** |
| 1750 | **0.96** | **0.24** | **100** | **100** | **0** | **4.09** | **64** |
| 1800 | 0.44 | 0.56 | 27 | 80 | 20 | 1.11 | 64 |
| *Demand* | | | | | | | |
| Relative energy price | −0.44 | 1.98 | 0 | 50 | 50 | 0.42 | 32 |
| Literacy | **1.56** | **1.87** | **25** | **100** | **0** | **1.10** | **32** |
| Ocean port | −0.14 | 0.41 | 6 | 50 | 50 | 1.00 | 32 |
| *Language networks* | | | | | | | |
| City population | **0.95** | **0.12** | **100** | **100** | **0** | **8.58** | **32** |
| Country population | 0.07 | 0.16 | 22 | 72 | 28 | 0.91 | 32 |
| Dictionary year | **−1.21** | **0.25** | **100** | **0** | **100** | **11.73** | **32** |

a two-tailed test. To make allowance for the measurement errors in the estimated explanatory variables, as mentioned above, let us consider a variable as robust if all of the corresponding coefficients had the expected sign, even if not all were statistically significant. The robust variables so defined are printed in bold face in Tables 5 and 6.

In Table 5, we see that for CIs, the negative country fixed effects for Germany, Belgium, and the Netherlands along with the relative energy price are all robust. As expected, literacy is more fragile, changing sign in one specification. As for the measure of language standardization, dictionary year, it is always significant with the expected negative sign. The other language variables, city population and country population, always have the expected positive sign. Note that although almost a third of the estimates for the latter variable are not significant at the 5% level, all pass at the 20% level. Since the measures of significance are conservative, we cannot easily reject the hypothesis that CI increases with network size.

Examining now the corresponding results for the NCIs in Table 6, we find a similar pattern for the country fixed effects. Moreover, once again dictionary year is quite robust, although the mean of its coefficient is considerably less in absolute value than for the CIs. It is interesting to note that the Enlightenment variable, 1750, is also very robust. This result is consistent with the hypothesis of Mokyr and Voth (2009) that innovators in all European countries benefited from the dissemination of knowledge across international borders during the latter half of the 18th century. Once one has controlled for these other variables, Literacy has a consistently positive effect.

Complementing these robustness estimates is a series of sensitivity tests presented in the Appendix, available at the OUP website. In each of nine re-estimates of the specification in column (3) of Table 3 under changed assumptions, the main conclusions hold. Together these results help explain why before 1850, countries without a standardized language (Germany and Italy) or with a small number of native speakers (Austria, Belgium, Denmark, the Netherlands, and Switzerland) were unable to develop innovations requiring the collaboration of two or more principals. The results also suggest why NCIs were also concentrated in Britain, France and the USA, since even independent inventors depended on clear communication with local suppliers, employees and clients.

## 7. Conclusion

One lesson to be drawn from this study is that although new institutions, cheaper energy and rising literacy were important causal factors, they alone cannot account for the jump in the rate of innovation observed in the West between 1700 and 1850. The evidence presented here suggests that the creation of novelty depended also on the diffusion of standardized languages which permitted the formation of broad networks of trust within which strangers could collaborate easily. In societies where such language network formation was delayed, there was little innovation before 1850 even when literacy rates were high.

A second tentative conclusion is that these new language networks were especially important for the CIs that made up almost half of the sample. Compared to the technologies with a single inventor, these CIs tended to be technologically relatively complex. Mutual trust between two or more individuals would therefore have been required to span the skills that were integrated in developing these technologies. For the generally simpler NCIs, the measure of language standardization was statistically significant but quantitatively less important.

A final regularity was the limited spread of the capacity to innovate within narrow territorial bands in Britain, France and the USA over the century and a half after 1700. The evidence suggested that the rate of diffusion of standard languages was an important factor in this geographic concentration. To have learned to speak and write in the standard national language was to be able to signal to strangers that one was reliable as a potential partner even when one's reputation was not known.

## Supplementary material

Supplementary material (the Appendix) is available online at the OUP website.

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## Data sources

City population. Population estimates for European cities were from Bairoch *et al.* (1988).[13] Estimates for New York, Philadelphia and Boston were from Longman Publishing (http://wps.ablongman.com/wps/media/objects/244/250688/Appendix/12.pdf). There were 46 cities at or near which one or more innovations occurred. To avoid potential endogeneity, population and literacy were determined at the beginning of each of the three half-century periods.

Country population. The source was Maddison (2007).

Coal. The identification of cities with coal deposits within 30 miles (50 km) was obtained from Barraclough (1984, p.201, pp.210–11).

Distances. The driving distance in kilometres to each city from Rome and Mainz was obtained from Google Maps (https://maps.google.com/).

Catholic. Equal to one for cities in which a majority of the residents are Catholic, otherwise zero. *Catholic Answers* (http://forums.catholic.com/showthread.php?t=640044, accessed 10 November, 2014).

Dissent. Darby and Fullard (1978, p.127).

Ocean port. Hammond and Hammond (1992).

Language standardization. See Table 2. Note that for five countries, the dates of the first monolingual dictionary were chosen arbitrarily. Cities in Belgium and Switzerland were assigned the dates of French, Dutch or German dictionaries, depending on their main languages. As for Scotland, by the year of Union with England, 1707, educated Scots were growing accustomed to using English rather than the Scottish dialect for formal communication (Herman, 2001, p.116). A similar argument applies to Ireland for 1800. In the case of the USA, the first settlers spoke the language of their home regions. However, by the year 1725, the more popular English dictionaries were beginning to be imported (Green, 1996, p.285).

Literacy. Signature rates at marriage are not necessarily an accurate measure of people's ability to read and write (Mitch, 1999, 244). However, unlike the *national* publication rates used by Baten and van Zanden (2008), differences in signature rates provide an indication of changes in capital at the *regional* level. By country, the sources were England: Cressy (1980, p.177); Scotland: Stone (1969, p.121); France: Houdaille (1977, p.68); Germany: Hofmeister *et al.* (1998); Italy: Reis (2005, p.202); the Netherlands: van der Woude (1980, pp.257–64); USA: Graff (1991, p.249).

Wage rates. Wage rates for eight European cities in the sample were from Allen (2001, Table 2).

Prices of coal. Coal prices for the same cities were available in Allen (2009, pp.99–100).

13 Bairoch *et al.*'s (1988) data do not contain population estimates for Portsmouth where Henry Cort invented the rolling mill and the puddling process. These observations were assigned to London.