NECESSITY'S CHILDREN?
THE INVENTIONS OF THE INDUSTRIAL REVOLUTION

31 July 2013

Leonard Dudley*
Université de Montréal

Abstract

What does it take for a society to be able to innovate? According to recent historical studies by Mokyr (2009), Allen (2009) and Acemoglu & Robinson (2012), the society's institutions must be able to meet its needs, as expressed by factor prices. However, this approach fails to explain why between 1700 and 1850, the well-organized markets of the commercially-oriented Netherlands failed to generate innovation while the less-competitive markets of absolutist France yielded numerous key technologies. This paper presents a complementary approach that emphasizes social networks, distinguishing between cooperative and non-cooperative innovations. The empirical results, based on data covering 117 important innovations and 201 regions in ten countries, suggest that ideology and factor prices played a role for the simpler non-cooperative subset. However, for the more complex cooperative innovations, the keys were literacy, language standardization and the openness of the social structure.

JEL Code: O3, N6

Keywords: Industrial Revolution, innovation, language, cooperation, social networks

Paper to be presented at the Meetings of the Economic History Association, Washington, D.C., September 20-22, 2013.

---

* Economics Department, Université de Montréal, Montréal QC Canada H3C 3J7, dudleylm@gmail.com, telephone 514-731-9039

Was necessity the mother of invention during the Industrial Revolution? Recent studies of this period conclude that innovation was favored when a society's institutions allowed it to meet its needs as expressed by factor prices. However, two observations from the early eighteenth century illustrate problems with this hypothesis. One case is a false positive. In 1706, experienced Dutch metal-workers employed by Abraham Darby in Bristol were unable to cast a thin-walled pot of iron, whereas the inexperienced Darby and a young apprentice subsequently succeeded and went on to develop a process for smelting iron with coke (Percy, 1864, 887). Yet the institutions and factor prices of southern England were no more favorable to innovation than those in Dutch cities (Allen, 2009, 123) (Vries and van der Woude 1997, 161-163). The other case is a false negative. Between 1726 and 1728, two French artisans, Bouchon and Falcon, developed the first process for controlling production numerically – a loom that used perforated tape or punched cards to select the appropriate warp threads for weaving a pattern in silk (Daumas, 1979, 609). Yet neither France's institutions nor its factor prices were particularly favorable to innovation (Allen, 2009, 123, 125). These two examples are not isolated cases: while the Netherlands contributed no important innovation between 1700 and 1850, France was second only to Britain in the number of new technologies produced during this long period. These prediction errors therefore suggest that something may be missing from current accounts of the Industrial Revolution.

What does it take for a society to be able to innovate? The conventional wisdom emphasizes the supply side. Following the lead of North and Weingast (1989), Acemoglu and Robinson (2012) have recently pointed to the institutions that protect property rights and contracts as the key considerations to explain why Britain outpaced Spain in the eighteenth century. A corollary put forth by Mokyr (2009) after comparing the British and continental Enlightenments is that in addition, the innovating society must have a set of beliefs – an ideology – that favors the practical application of new knowledge.

An alternative approach proposed by Allen (2009) suggests that institutions and ideology are not enough. The principal stimulus to innovation, he argued, is on the demand side. New technologies are developed through the response of entrepreneurs to the opportunities signaled by changes in factor prices. In the case of eighteenth-century

Britain, the rising costs of labor and conventional sources of energy led skilled artisans and their backers to develop new processes that replaced labor with machinery and charcoal, wind and water with coal.[1]

As the examples from the Netherlands and France indicate, however, neither of these social-needs-oriented approaches can explain why over the course of the eighteenth and early nineteenth centuries a small number of regions in the North-Atlantic community were able to innovate while others with similar institutions and factor prices were not. This paper makes three contributions to the study of innovation during the Industrial Revolution. First, it examines an aspect of innovation that has hitherto been neglected, namely, the extent of cooperation, as determined by the size of social networks. Second, it focuses on urban regions rather than nations, arguing that the functioning of social networks varied sharply among regions, even within the same society. Third, the preparation of a sample of some 117 innovations scattered across 201 regions in ten present-day countries permits testing of competing hypotheses.

The results offer some support for the role of ideology and factor prices in the innovation process but fail to confirm the hypothesis that British institutions made a difference. The empirical findings also suggest strongly that an additional element should be added to explanations of the Industrial Revolution, namely, the expansion of social networks.

This paper brings together two currents of recent research on innovation. Surprisingly, both of these avenues were suggested over sixty years ago by Thomas Ashton (1948/1962, 13-15) in a few short paragraphs of his classic study, *The Industrial Revolution*. First, he proposed, innovation during this period occurred through the combination of apparently independent ideas; for example, the mule, which combined the jenny and the water frame. Second, he added, discovery was a social process, requiring the competition and cooperation of many people.

[1] Broadberry and Gupta (2009) extended this argument, suggesting that differences in initial factor prices can explain not only the direction, but also the *rate* of factor-saving technical change.

The first of these ideas – that innovation occurs through the integration of seemingly unrelated areas of knowledge – was developed independently by Arthur Koestler (1964, 121) in his study of the creative process, *The Act of Creation*. He argued that humor, art and technological invention all involve "the sudden interlocking of two previously unrelated skills." For example, Gutenberg's printing press was a synthesis of the goldsmith's punch and the wine press. This idea has since been formalized by linguists Gilles Fauconnier and Mark Turner who proposed the concept of a "double-scope network" that takes as inputs two different organizing frames. It then combines them to form a blend that has properties of each of the original frames but also an "emergent structure of its own" (Fauconnier and Turner, 2002, 131). Art, science and religion, they argued, were all made possible by the evolution of the human brain to permit language some 50,000 or more years ago (Ibid., 186-187).

The second current of research studies the effect of communication on strategic behavior in social situations where the outcome for each individual depends on the actions of others. In a survey article, Smith (2010) observed that there are numerous ways in which communication may facilitate cooperation. When information has a cost that is negatively correlated with an individual's competence, Spence (1973) showed that players could credibly signal their capacities to one another by investing in formal education. Even if information is costless, "cheap talk" may allow individuals with convergent interests to coordinate their strategies (Farrell and Rabin, 1986). In addition, language permits information concerning the past behavior of individuals to circulate in large groups, thereby facilitating the punishment of those who deviate from social norms (Smith 2010, 236-237). For these reasons, Boyd and Richerson (2011, 3281-3282) argued, human language allows cooperation and innovation on a scale without equal among other animals.

How might these ideas be applied to the Industrial Revolution? Consider first the theory. Many of the decisions we take in our daily lives satisfy three conditions: they are made repeatedly; each decision is relatively unimportant; finally, the satisfaction derived from a given choice depends on the frequency with which the same option has been chosen in the recent past (Herrnstein, 1991). If so, instead of making the computations assumed by rational-choice theory, people may update their probability of cooperating by a process of contingency learning; that is, learning in which associations are strengthened by the degree to which stimuli provide new information about responses (Peterson, 1999, 209).

Under these assumptions, Brenner (1999) showed that with costly communication, society will tend toward an equilibrium in which there is no cooperation among strangers. Even if the cost of signaling competence falls, for example, because of a rise in literacy, the society may tend to remain in this non-cooperative equilibrium. However, we will argue, if language standardization gradually allows people to coordinate their actions, a society may suddenly reach a tipping point at which cooperation becomes the norm.

In the empirical section of the paper, this "social-network" model is tested against the competing "supply" and "demand" hypotheses. The data set consists of 117 innovations and 201 urban regions over three fifty-year periods from 1700 to 1849. The results indicate that factor prices played a significant role in the case of simpler innovations with a single inventor. However, for the more complex cooperative innovations, regions most likely to innovate were those in which high literacy was accompanied by a standardized vernacular and where the local social structure was open to outsiders. Moreover, spillovers from one generation of inventors to the next were not only technological but also behavioral, encouraging cooperation when the complexity of the challenge exceeded the capacities of a single individual.

II. A Social-Networks Approach

How does innovation occur? As mentioned in the introduction, linguists Gilles Fauconnier and Mark Turner (2002) have suggested that generating novelty requires the integration of concepts from different areas of knowledge that have not yet been brought together successfully. This section will argue that doing so increasingly requires a society in which people trust one another.

Let us begin by suggesting that as technologies have become more complex over the last half millennium, it has become increasingly difficult for a single individual to master the information required to develop something new. Hence, further innovation has required a widening of social networks in order to span the necessary range of competences. But how could people who did not initially know each other develop enough trust to be able to work together? Consider the proportion of strangers in a society who at any moment will cooperate in a two-player one-shot coordination game; for example, respecting each other's intellectual-property rights while developing an innovation. In Figure 1, this average propensity to cooperate is measured along the horizontal axis. At a point such as A on the extreme right, the whole society cooperates, while at a point like B on the left, everyone defects.[2]

INSERT FIGURE 1 ABOUT HERE

The vertical axis measures the expected net gain to the first player in a representative game if she decides to cooperate in innovating. Above the horizontal line, where this gain is positive, it is in her interest to cooperate. However, in the lower part, since her expected gain is negative, she will choose to defect. Consider now three stages in the development of social networks in a society.

Assume that initially the literacy rate is low. Because two uneducated individuals from different regions are able to communicate little new information to offer each other, the synergy between them is sufficiently weak to cause the expected gain for each, indicated by the point A, to be negative. If at this point the second player always

[2] For the algebra behind the graph, see Dudley and Witt (2004).

cooperates, it is in the first player's interest to defect, thereby avoiding the cost of cooperating (assumed to be positive). But by the same reasoning, it is also in the second player's interest to defect. Eventually, the society reaches a steady state at B, where no one cooperates. This, of course, is the familiar Prisoner's Dilemma game (Smith 2010, 231).

Now consider a society in which everyone is literate, but where the spoken language differs from region to region. Two educated people from different regions now have much wider areas of knowledge to offer each other. Assume that joint cooperation would lead to an expected gain at C that is positive for each player. However, because of problems of communication, the two may experience difficulty in coordinating their efforts. Both B and C are now steady-state equilibria. But since each player expects to lose if she increases her probability of cooperating while the other does not, the society remains in the neighborhood of B. The game has in effect changed from Prisoner's Dilemma to Assurance (Smith 2010, 233).

In the third stage, let the spoken language gradually become standardized. Now coordination on a cooperative outcome becomes easier. As the percentage of people who speak the standardized vernacular increases, the society approaches a tipping point at q^*, beyond which cooperation can be expected to yield a gain rather than a loss. Nevertheless, the move still further toward C, where everyone is willing to cooperate with strangers is unlikely to occur immediately, even if all have begun to speak the standard vernacular. As explained in the introduction, Brenner (1999) has shown that if people adjust their expected gains from cooperation on the basis of what they have observed in the past, there will be a process of learning to cooperate. As the society approaches the tipping point, q^*, successful examples of cooperation to innovate can therefore have an important impact in inducing further cooperation.

As for where exactly the tipping point, q^*, is situated for a given region, we would expect it to depend greatly on the openness and flexibility of the region's social order. On the one hand, a rigid municipal corporate and guild structure closed to foreign influences would act as a barrier to cooperation, thereby pushing the threshold to the right in Figure

1 and delaying cooperation to innovate. On the other hand, a social structure that no single group is able to monopolize that is open to developments abroad would permit the new associations required for Fauconnier and Turner's (2002) "double-scope blending". In this case, the tipping point would be pulled to the left and rapid innovation would occur relatively early.

This brief examination of strategic behavior under different communication regimes suggests the following hypotheses concerning rates of innovation in a society:

- a necessary but not sufficient condition for cooperation to innovate is a high *literacy* rate;
- *language standardization* in a population large enough to allow integration of widely different experiences also favors innovation;
- together, an *open and flexible local social structure* and *international openness* permit the new associations required for cooperation in innovation;

III. Model Specification and Data

In the preceding section, we studied an approach to innovation based on the expansion of social networks. This approach added an extra dimension to the supply- and demand-side approaches outlined in the introduction, namely, the extent of cooperation among strangers. Our task in this section will be to specify a procedure for comparing the explanatory power of these three sets of hypotheses empirically.

Table 1 presents 117 important innovations that were mentioned by a panel of historians of technology. Thirteen of these developments are from the period 1700-1749, 53 further technologies from the half century 1750-1799, and a final 51 innovations from 1800 to 1849. To qualify for this table, an innovation had to be mentioned by two or more experts from four different countries. The authors in question were Donald Cardwell (1991) of Britain, Maurice Daumas (1979) of France, Joel Mokyr (1990) born in the Netherlands and living in the United States, and Akos Paulinyi (1989), born in Hungary and residing in Germany. Although the overlap between the four was considerable, the *Encyclopedia Britannica* served as arbitrator in the cases of a reference by a single author.

INSERT TABLE 1 ABOUT HERE.

To test theories of innovation, this study links these innovation data with information on where they occurred. 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 centers. This finding suggests that the unit of observation should be a region within a state. The dependent variable, then, is defined 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. Such innovations may be considered rare events; we should therefore use an estimation method appropriate for count data. Since the variance of this variable in our sample (0.182) was considerably greater than the mean (0.065), a Poisson distribution was not appropriate. To allow for such over-dispersion, the negative-binomial specification adds an additional variable, **u**, to the Poisson specification:

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

where y_{ijt} is the number of innovations in city i of type j in period t, $\boldsymbol{x}_{ijt}$ is a vector of explanatory variables, $\boldsymbol{\beta}$ is a vector of parameters, ε_{ijt} is a random variable and exp (u_{ijt}) follows a gamma distribution with parameters α and 1/α.

Consider next the explanatory variables. Three fixed-effects variables captured the supply-side approach. North (1990, 3) emphasized institutions ("humanly devised constraints that shape human interaction") while Mokyr (2009, 34) highlighted new ways of thinking ("the expansion of useful knowledge") in explaining the remarkable wave of innovation in Great Britain in the latter half of the eighteenth century and the first half of the nineteenth. Accordingly, the variable *Britain* represented Great Britain, while *1750* and *1800* corresponded to the half-centuries after 1750 and 1800 respectively.

A second group of variables picked up the influence of demand conditions. Allen (2009, 80-105, 172-173) argued that the presence of abundant coal provided a strong incentive to substitute this material for wood as a source of heat and for water, wind and muscle as a source of mechanical energy (Allen 2009, 80-105, 172-173). Thus the dummy variable *Factor prices*, indicating the presence or absence of coal within a radius of 30 miles (50 km) of the region's main town, could be expected to have a positive effect on the innovation rate.[3]

In addition, the incentive to develop new products and processes may have depended on the size of the market. Accordingly, the variable *Market Size*, as measured by the country's population, was included. For most cities in the sample, this variable was assumed to be captured by the population within the boundaries of the corresponding present-day state at the beginning of each period. The United States was an exception. At the beginning of the first two sub-periods, the thirteen 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 eighteenth century, over half of British exports and a third of its imports were with the Americas, including a small portion with

[3] An alternative would have been to use the ratio of the cost of coal to the wage rate, as suggested by Allen (2009, 140). However, wage data are not available for most of the urban regions in the sample.

British North America (Deane and Cole 1962, 62). Accordingly, Great Britain and the United States were assumed to form a single market.

The "social-networks" approach of the preceding section posited that there were several dimensions of social networks that could influence the probability of innovation in a given region. One was the rate of *Literacy*.[4] Another was the number of years since a country's language had became standardized, *Language standardization*. A third was the degree of flexibility and openness of the region's society, *Local openness*. Another indicator of the extent of social networks was the exposure of the region to ideas from abroad. This consideration was assumed to be captured by the dummy variable, *International openness*, indicating whether or not the region's principal city was an ocean port.

Finally, as a regional scale variable for each of the alternative hypotheses, the number of innovations in a region was allowed to change with the population of its main city or town, *City population*.

Data Sources

Number of Innovations. The cities and towns corresponding to each of the innovations in Table 1 are listed in Dudley (2012, tables 2-1, 3-1 and 4-1).

Coal. The proximity of coal deposits for each city was obtained from Barraclough (1984: 201, 210-211).

Literacy. England: Cressy (1980, 177); Scotland: Stone (1969, 121); France: Graff (1991, 193); Germany: Graff (1991, 187); Italy: Graff (1991, 191); Netherlands: Graff (1991, 223); United States: Graff (1991, 249).[5] The rates for Austria were estimated from the German rate less the German-Austrian difference in 1850 from Cipolla (1969, 115). Estimates for Belgium were calculated in the same manner from the 1850 rates for Germany and England respectively.

---

[4] As Allen (2009, 137) pointed out, because of its effects on productivity and wage rates, literacy might also have been placed among the either the supply or the demand variables. This issue is discussed in footnote 11 below.

[5] Note that separate literacy estimates were available for each of 10 regions in France.

Language standardization. In order for an entrepreneur to succeed in publishing a unilingual dictionary, he had to be confident that there were many citizens in the country who not only were literate, but also sought to master a single standard of spelling and uniform definitions. Even a national government had to take account of the number of potential speakers before subsidizing the publication of a dictionary. This concept was therefore assumed to be captured by the number of years since the publication of the nation's first privately-published monolingual dictionary as of the year 1700, based on the data in Table 2.[6] For example, the entry corresponding to Britain, for which the first dictionary dates from 1658, is 1700-1658 = 42. Similarly, for France, the number was 1700-1680 = 20, since the first French dictionary appeared in 1680.[7]

INSERT TABLE 2 ABOUT HERE.

For five countries, the dates of the first dictionary were assigned arbitrarily. The year chosen for Switzerland was the mean of those of France and Germany, while for Belgium, the year was the mean of the dates for France and the Netherlands. For Austria, the choice was the mean of Germany and the first Austrian dictionary, i.e. 1868. As for Scotland, by 1707, the year of Union with England, educated Scots were accustomed to using English rather than the Scottish dialect for formal communication (Corbett and Stuart-Smith 2003, 11). In the case of the United States, by the end of the eighteenth century, its pronunciation and vocabulary were beginning to diverge from that of Britain, as indicated by the publication of its first dictionary in 1798. Accordingly, its date was set the mean of 1798 and the date for England (1658), i.e. 1728.[8]

Local openness. Jones (2008, 39-40, 105) noted that in eighteenth-century Birmingham, in the absence of guilds and municipal corporation, the city's workers were highly productive and its entrepreneurs quick to adjust to shifts in demand. Accordingly, the

[6] Sources. Britain: Jackson (2002, 36); France: Bray (1986, 235-242); Germany: Würzel (1985); Italy: Lepschy and Lepschy (1988, 24); United States: Green (1996, 290).

[7] In 1793, the Abbé Grégoire calculated, of France's 28 million people, almost half were unable to converse in the French language (Gildea 2002, 164). Accordingly, the date of language standardization for the French population south of a line from St. Malo to Geneva was set at 1815 rather than 1680.

[8] The Accademia della Crusca's dictionary of Italian, published in 1612, was not intended to reflect the existence of a standardized language, but rather to provide a prescriptive norm to which writers were advised to conform (Lepschy and Lepschy 1988, 23).

variable *Local openness* was set at one for those British towns that were not boroughs, that is, for towns that were not corporations set up under royal charter; namely, Birmingham, Bradford and Manchester. The one French city that had an open and flexible local culture comparable to that of Birmingham in the eighteenth century was Lyon.[9] For all other towns, including those outside Britain, this variable was set at zero. Data on British municipal charters were obtained from Weinbaum (1943, xxx ff.).

Country population. The source was Maddison (2007).

City population. Population estimates for 201 European cities, each of which had at least 7,000 inhabitants in 1700, were from Bairoch et al. (1988). Of this set, there were 46 cities at or near which one or more innovations occurred. To these, were added the 155 other European cities that were at least as close to London as the most distant innovating city (Como, in northern Italy). Also included were three American cities – New York, Philadelphia and Boston. The city list appears in the Appendix.

Table 3 presents the means of the dependent and explanatory variable, for cities with a positive number of innovations and for those with no innovations. We see that compared to non-innovating regions, the centers of innovating regions tended to be larger, more British, closer to coal, had better access to large domestic and foreign markets, had more open social structures and had standardized vernaculars earlier. The question now is whether these apparent influences will survive more rigorous statistical testing.

INSERT TABLE 3 ABOUT HERE.

[9] Since the fifteenth century, Lyon had been the most important publishing center in France. Along with the port of La Rochelle, it was one of the centers of French Protestantism until the repressions of the 1570s. In 1595, the power of local elites was constrained by the Edict of Chauny of Henri IV (Lyon, 2012). Henceforth, the city was to be governed by four aldermen and a provost elected every two years by assemblies of guild masters, subject to royal approval (Lyon, 2012). In the seventeenth and eighteenth centuries, abuses of power were further constrained by a credible threat of revolt on the part of the city's textile workers. During the Revolution of 1789, the city formed a moderate Girondin government until it was crushed by the forces of the Convention. Accordingly, in the case of Lyon, *Local openness* was set at one.

Finally to avoid potential endogeneity, population and literacy were determined at the beginning of each of the three half-century periods.

IV. Results

Which set of hypotheses presented in the preceding sections best explained the innovations of the industrial revolution: supply, demand or social networks? We begin with the whole sample of 117 innovations and then examine two sub-samples, namely, the 54 Cooperative Innovations and the 63 Non-Cooperative Innovations.

All innovations

Detailed results from the negative-binomial specification applied to the entire sample are presented in Columns (1), (2) and (3) of Table 4. We see from these estimates that each version offers a plausible account of the observed data. In column (1) is a representation of the supply-side position defended by Mokyr (2009). The dummy variable for Great Britain was highly significant, suggesting that British institutions were more favorable to innovation than those of other countries. However, the half-century of the Enlightenment – the 50 years after 1750 – does not appear to have been particularly favorable to innovation, other things being equal.[10]

INSERT TABLE 4 ABOUT HERE.

Column (2) presents a test of the demand-side arguments put forth by Allen (2009). His suggestion that the low cost of coal relative to wage rates was a major incentive to innovation in Britain finds support in the significant coefficient of *Factor prices*. The size of the domestic market was also statistically highly significant. The pseudo R^2 coefficient shows that the explanatory power of this model is similar to that of the supply-side model in column (1).

In column (3), we see the corresponding test of the social-networks approach. All four variables associated with this approach were highly significant. Higher literacy, language standardization, an open and flexible local social structure, and international openness all had highly significant effects on a region's capacity to innovate. The pseudo

[10] Note that the estimates of the over-dispersion parameter, α, are all significantly greater than zero, indicating rejection of the hypothesis that the data follow a Poisson distribution.

R^2 coefficient indicates that this specification had considerably more explanatory power than the supply- and demand-side approaches of the first two columns.

In column (1) of Table 5, we see the results of a nested specification that incorporates all variables of the three approaches within a single equation. One consequence of this reformulation of the model is that the supply-side variable, *Britain*, was no longer statistically significant. Turning to the demand-side variables, we see that that the estimated effect of *Factor prices* on the demand side was substantially reduced, although the effect remained statistically significant. Finally, in this nested specification, both *Local openness* and *International openness* remained highly significant. *Literacy* and *Language standardization* were no longer statistically significant. In short, elements of each of the three hypotheses seem to have been important.

INSERT TABLE 5 ABOUT HERE.

Cooperative and Non-Cooperative Innovations

Underlying the specifications presented in column (1) is the hypothesis that all innovations were generated by the same process. However, as we saw in Table 1, there seem to have been two quite distinct types of innovation. The other two columns of Table 5 present the results from separate estimates for each of these classes of innovations. In column (2) are the results for the 54 Cooperative Innovations. The coefficients of *Literacy*, *Language standardization*, *Local openness* and *Foreign openness* were all significantly positive. The pseudo R^2 of 0.451 indicates that the model explained the data quite well.

Column (3) of Table 5 presents the same specification for the 63 Non-Cooperative Innovations. For these technologies, *Factor prices* and the *1750* dummy were significant. Among the social-network variables, however, only *Local openness* and *International openness* were significant. The pseudo R^2 coefficient of 0.276 indicates that the explanatory power of the model was considerably lower than for the cooperative innovations of column (2).

Were the observed differences between Cooperative and Non-Cooperative Innovations significant? Comparing the size of the coefficients of column (2) with those of column (3), we find that all four of the social-networking variables – namely, *Literacy*, *Language Standardization*, *Local Openness* and *International Openness* – had a significantly greater effect on innovations in which there was cooperation than in the case of a single inventor.[11] These findings suggest that the integration of hitherto uncombined ideas, a feature required for many of the complex Cooperative Innovations, was facilitated by low barriers to information flows. As for *Factor Prices*, they seem to have had a greater impact on simpler Non-Cooperative Innovations than on more complex Competitive Innovations, although the difference between the two categories was not statistically significant.

These results help explain why for 150 years after 1700, technological innovation was limited almost entirely to a few regions in Britain, northern France and the north-eastern United States. On the one hand, the Germanic countries, Scandinavia and the Low Countries had high literacy rates, but their non-standardized vernaculars prevented people originating in different regions from collaborating easily. On the other hand, in southern Europe not only did each region have its own dialect, but also literacy rates were low. Even in Britain and France, there were few regions where the absence of local monopolies allowed innovators to challenge existing producers.

---

[11] The significantly greater effect of *Literacy* on Cooperative than on Non-Cooperative Innovations suggests that its impact is through its effect on willingness to cooperate rather than through any direct productivity effect. Accordingly, the inclusion of *Literacy* among the social-networking variables instead of in the supply or demand categories would appear justified.

VI. Conclusion

What can the Industrial Revolution teach us about innovation? The main lesson from this study is that institutional change and factor-price shocks were unlikely by themselves to jumpstart the process of innovation in regions where it had yet to begin. Rather, generating innovation seemed be a matter of building networks of trust that allowed strangers to collaborate easily. A possible explanation for the low explanatory power of theories emphasizing supply and demand conditions is that once these networks had formed, improved institutions and sensitivity to factor markets tended to follow.

Social-network influences were especially important for the *Cooperative Innovations* that made up almost half of the sample. These tended to be technologically the more complex innovations; for example, the atmospheric steam engine, machine spinning of cotton, smelting with coke, continuous production, machine tools, industrial chemicals, the Jacquard loom, interchangeable parts, and the electric telegraph. In addition, the breakthroughs that generated important downstream spinoffs tended to belong to this group.

As for the remaining category, the *Non-Cooperative Innovations*, they appear to have been not only less complex but also more a matter of chance. Examples such as the parachute, the visual telegraph, the breast wheel, the cast-iron railroad, the arc lamp, and the ring-spinning machine suggest that these innovations were more likely to be improvements to existing technologies rather than breakthroughs. Factor prices and openness also played a role in the location of this second group of innovations, particularly during the second half of the eighteenth century.

Finally, given social networks and resource availability, being British does not seem to have had any significant effect on a region's rate of innovation.

References

Acemoglu, Daron, and James A. Robinson. *Why Nations Fail: The Origins of Power, Prosperity and Poverty.* London, UK: Profile Books, 2012.

Allen, Robert C. "Collective Invention." *Journal of Economic Behavior and Organization* 4 (1983): 1-24.

—. *The British Industrial Revolution in Global Perspective.* Cambridge, UK: Cambridge University Press, 2009.

Ashton, Thomas S. *The Industrial Revolution, 1760-1830.* London: Oxford University Press, 1948/1962.

Bairoch, Paul, Jean Batou, and Pierre Chèvre. *The Population of European Cities, 800-1850.* Geneva: Librairie Droz, 1988.

Barraclough, Geoffrey. *The Times Atlas of World History.* Maplewood, NJ, USA: Hammond, 1984.

Boyd, Robert, and Peter J. Richerson. "Culture and the Evolution of Human Cooperation." *Philosophical Transactions of the Royal Society B,* 2009: 3281-3288.

Bray, Laurent. *César-Pierre Michelet (1626-1698).* Tübingen, Germany: Max Niemeyer, 1986.

Brenner, Thomas. *Modelling Learning in Economics.* Cheltenham, UK: Edward Elgar, 1999.

Broadberry, Stephen, and Bishnupriya Gupta. "Lancashire, India, and Shifting Competitive Advantage in Cotton Textiles, 1700–1850: the Neglected Role of Factor Prices." *Economic History Review* 62 (2009): 279–305.

Cardwell, D. S. L. *Turning Points in Western Technology.* Canton, MA: Science History Publications/USA, 1991.

Cipolla, Carlo M. *Literacy and Development in the West.* Harmondsworth, UK: Penguin, 1969.

Corbett, John, and Jane Stuart-Smith. "A Brief History of Scots." In *The Edinburgh Companion to Scots*, by John Corbett, Derrick McClure and Jane Stuart-Smith, 1-16. Edinburgh: Edinburgh University Press, 2003.

Cressy, David. *Literacy and the Social Order: Reading and Writing in Tudor and Stuart England.* Cambridge, UK: Cambridge University Press, 1980.

Daumas, Maurice. *A History of Technology and Invention, Volume III, The Expansion of Mechanization, 1725-1860.* New York: Crown Publishers, 1979.

Deane, Phyllis, and W. A. Cole. *British Economic Growth, 1688-1959 : Trends and Structure.* Cambridge, UK: Cambridge University Press, 1962.

Dudley, Leonard. *Mothers of Innovation: How Expanding Social Networks Gave Birth to the Industrial Revolution.* Newcastle upon Tyne, UK: Cambridge Scholars Publishing, 2012.

Dudley, Leonard, and Ulrich Witt. "Arms and the Man: World War I and the Rise of the Welfare State." *Kyklos* 57 (2004).

Farrell, Joseph, and Matthew Rabin. "Cheap Talk." *Journal of Economic Perspectives* 10, no. 3 (1996): 103-118.

Fauconnier, Gilles, and Marc Turner. *The Way We Think: Conceptual Blending and the Mind's Hidden Complexities.* New York: Basic Books, 2002.

Gildea, Robert. "Province and Nation." Chap. 6 in *Revolutionary France 1788-1880*, by Malcolm Crook. Oxford, UK: Oxford University Press, 2002.

Graff, Harvey J. *The Legacies of Literacy.* Bloomington, Indiana, USA: Indiana University Press, 1991.

Green, Jonathon. *Chasing the Sun: Dictionary Makers and the Dictionaires They Made.* New York: Henry Holt, 1996.

Herrnstein, Richard J. "Experiments on Stable Suboptimality in Individual Behavior." *American Economic Review, Papers and Proceedings* 81, no. 2 (1991): 360-364.

Jackson, Howard. *Lexicography: An Introduction.* London: Routledge, 2002.

Jones, Peter. *Industrial Enlightenment: Science, Technology and Culture inte Birmingham and the West Midlands, 1760-1820.* Manchester, UK: Manchester University Press, 2008.

Koestler, Arthur. *The Act of Creation.* London: Hutchison & Co., 1964.

Lepschy, Anna Laura, and Giulio G. Lepschy. *The Italian Language Today.* London: Routledge, 1988.

Lyon. "Décembre 1595: Publication de l'Edit de Chauny." *Archives municipales.* 2012. http://www.archives-lyon.fr/archives/sections/fr/histoire_de_lyon/archives_commentees/les_personnages/henri_iv2935/1595_edit_chauny/.

Maddison, Angus. *Contours of the World Economy, 1-2030 AD: Essays in Macro-Economic History.* Oxford, UK: Oxford University Press, 2007.
Mokyr, Joel. *The Enlightened Economy: An Economic History of Britain 1700-1850.* New Haven, USA: Yale University Press, 2009.
—. *The Gifts of Athena : Historical Origins of the Knowledge Economy.* Princeton, NJ: Princeton University Press, 2002.
—. *The Lever of Riches: Technological Creativity and Economic Progress.* Oxford, UK: Oxford University Press, 1990.
North, Douglass C. *Structure and Change in Economic History.* New York: Norton, 1981.
North, Douglass C., and Barry R. Weingast. "Constitutions and Commitment: The Evolution of Institutions Governing Public Choice in Eighteenth Century England." *Journal of Economic History* 49 (1989): 803-832.
North, Douglass C.l. *Institutions, Institutional Change, and Economic Performance.* Cambridge, UK: Cambridge University Press, 1990.
Nuvolari, Alessandro. "Collective Invention during the British Industrial Revolution: The Case of the Cornish Pumping Engine." *Cambridge Journal of Economics* 28, no. 3 (2004): 347-363.
Paulinyi, Akos. *Industrielle Revolution: Vom Ursprung der modernen Technik.* Reinbek bei Hamburg, Germany: Rowohlt, 1989.
Percy, J. *Metallurgy: Iron and Steel.* London: John Murray, 1864.
Peterson, Christopher. "Personal Control and Well Being." In *Well Being: The Foundations of Hedonic Psychology,* by Daniel Kahneman, Ed Diener and Norbert Schwarz, 288-301. New York, USA: Russell Sage Foundation, 1999.
Smith, Eric Alden. "Communication and Collective Action: Language and the Evolution of Human Cooperation." 31 (2010): 231-245.
Spence, Michael. "Job Market Signaling." *Quarterly Journal of Economics* 87, no. 3 (1973).
Stone, Lawrence. "Literacy and Education in England 1640-1900." *Past & Present* 42 (1969): 69-139.
Vries, Jan de, and Ad van der Woude. *The First Modern Economy: Success, Failure, and Perseverence of the Dutch Economy, 1500-1815.* Cambridge, UK: Cambridge University Press, 1997.
Weinbaum, Martin. *British Borough Charters, 1307-1660.* Cambridge, UK: Cambridge University Press, 1943.
Würzel, Wolfgang. *Konrad Duden.* Leipzig: VEB Bibliiographisches Institut, 1985.

Appendix

List of cities

Germany: Aachen, Altona, Augsburg, Bamberg, Berlin, Brandenburg, Braunschweig, Bremen, Dresden, Duesseldorf, Emden, Erfurt, Esslingen, Frankfurt am Main, Frankfurt an der Oder, Freiberg, Gotha, Halberstadt, Hamburg, Hannover, Ingolstadt, Kassel, Koblenz, Koeln, Leipzig, Luebeck, Magdeburg, Mainz, Mannheim, Muenchen, Muenster, Naumburg, Nuernberg, Regensburg, Stralsund, Stuttgart, Trier, Ulm, Wuerzburg, Zittau

Austria: Innsbruck, Salzburg, Schwaz,

Belgium: Aalst, Antwerpen, Brugge, Bruxelles, Gent, Ieper, Kortrijk, Leuven, Liege, Lokeren, Mechelen, Mons, Namur, Oostende, Tournai, Verviers

France: Abbeville, Agen, Aix, Albi, Alencon, Amiens, Angers, Arles, Arras, Aurillac, Avignon, Bayeux, Bayonne, Beauvais, Besançon, Beziers, Blois, Bordeaux, Bourges, Brest, Caen, Cambrai, Carcassonne, Castres, Chalons-sur-Marne, Chambery, Chartres, Clermont-Ferrand, Colmar, Dieppe, Dijon, Douai, Dunkerque, Grenoble, La Rochelle, Langres, Laval, Le Havre, Le Mans, Le Puy, Lille, Lyon, Marseille, Mayenne, Metz, Montauban, Montpellier, Moulins, Mulhouse, Nancy, Nantes, Narbonne, Nimes, Orleans, Paris, Poitiers, Reims, Rennes, Rouen, Saumur, Soissons, St-Etienne, St-Malo, St-Omer, St-Quentin, Strasbourg, Toulon, Toulouse, Tours, Troyes, Valenciennes, Versailles, Vienne, Vitry-le-François

Great Britain: Aberdeen, Birmingham, Bradford, Bristol, Cambridge, Colchester, Coventry, Dundee, Edinburgh, Exeter, Glasgow, Great-Yarmouth, Ipswich, London, Manchester, Newcastle-upon-Tyne, Norwich, Oxford, Plymouth, Salisbury, Shrewsbury, Worcester, York

Ireland: Cork, Dublin, Kilkenny, Limerick

Italy: Alessandria, Asti, Como, Milano, Monza, Novara, Pavia, Torino, Vercelli, Vigevano

Netherlands: Alkmaar, Amersfoort, Amsterdam, Delft, Dordrecht, Enkhuizen, Gouda, Groningen, Haarlem, Harlingen, Hoorn, Leeuwarden, Leiden, Maastricht, Middelburg, Nijmegen, Rotterdam, 's Gravenhague, 's Hertogenbosch, Schiedam, Utrecht, Vlissingen, Zwolle

Switzerland: Basel. Bern. Geneve. Zuerich

United States: Boston. New York. Philadelphia

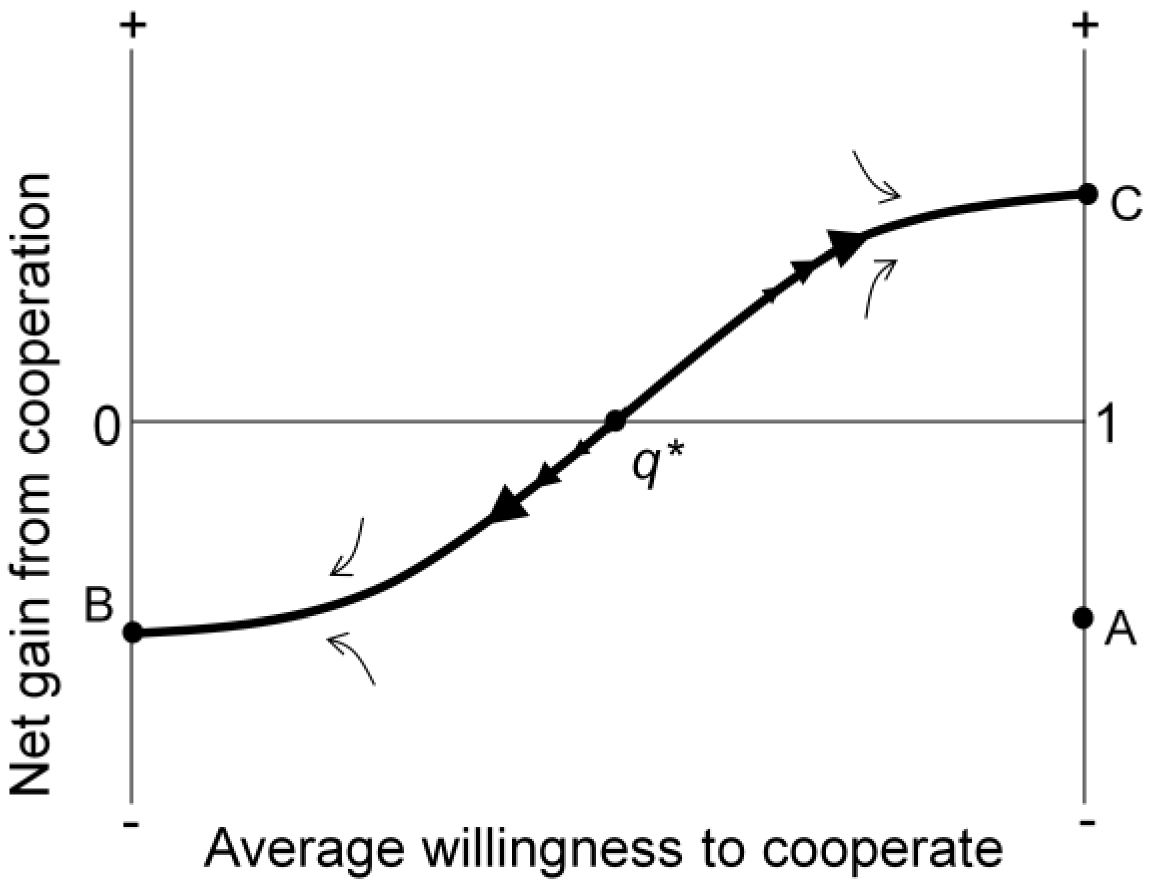

Figure 1. Repeated one-shot Assurance game with learning

Table 1. 117 important innovations, 1700-1849

Country	1700-1749	1750-1799	1800-1849
Denmark			Galvanometer (Oersted, 1819)
France	Loom coded with perforated paper (Bouchon, 1725) Loom coded with punched cards (Falcon, 728)	Steam-powered wagon (Cugnot, 1770) Automatic loom (Vaucanson, 1775) Single-action press (Didot, Proudon,1781) Two-engine steamboat (Jouffroy d'Abbans, 1783) Hot-air balloon (Montgolfier, 1783) Parachute (Lenormand, 1783) Press for the blind (Haüy, 1784) Chlorine as bleaching agent (Berthollet, 1785) Sodium carbonate from salt (Leblanc, d'Arcet, 1790) Visual telegraph (Chappe, 1793) Vacuum sealing (Appert, 1795) Paper-making machine (Robert, Didot, 1798) Illuminating gas from wood (Lebon, 1799)	Automatic loom with perforated cards (Jacquard, Breton, 1805) Wet spinning for flax (de Girard, 1815) Electromagnet (Arago, Ampère, 1820) Water turbine (Burdin, 1824) Single-helix propeller (Sauvage, 1832) Three-color textile printing machine (Perrot, 1832) Water turbine with adjustable vanes (Fourneyron, 1837) Photography (Daguerre, Niepce, 1838) Multiple-phase combing machine (Heilmann, 1845)
Germany	Porcelain (Tschirnhaus, 1707)	Lithography (Senefelder, 1796)	
Great Britain	Seed drill (Tull, 1701) Iron smelting with coke (Darby, Thomas, 1709) Atmospheric engine (Newcomen, Calley,1712) Pottery made with flint (Astbury, 1720) Quadrant (Hadley, 1731) Flying shuttle (Kay, 1733) Glass-chamber process for sulphuric acid (Ward, 1736) Spinning machine with rollers (Wyatt, Paul 1738) Stereotyping (Ged, 1739) Lead-chamber process for sulphuric acid (Roebuck, 1746)	Crucible steel (Huntsman, 1750) Rib knitting attachment (Strutt, Roper, 1755) Achromatic refracting telescope (Dollond, 1757) Breast wheel (Smeaton, 1759) Bimetallic strip chronometer (Harrison, 1760) Spinning jenny (Hargreaves, 1764) Creamware pottery (Wedgewood, Wieldon, 1765) Cast-iron railroad (Reynolds, 1768) Engine using expansive steam operation (Watt, Roebuck, 1769) Water frame (Arkwright, Kay, 1769) Efficient atmospheric steam engine (Smeaton, 1772) Dividing machine (Ramsden, 1773) Cylinder boring machine (Wilkinson, 1775)	Machines for tackle block production (Brunel, Maudslay, 1800) Illuminating gas from coal (Murdock, Watt Jr., 1802) Steam locomotive (Trevithick, Homfray, 1804) Compound steam engine (Woolf, Edwards, 1805) Winding mechanism for loom (Radcliffe, 1805) Arc lamp (Davy, 1808) Food canning (Durand, Girard, 1810) Rack locomotive (Blenkinsop, Murray, 1811) Mechanical printing press (Koenig, Bauer, 1813) Steam locomotive on flanged rails (Stephenson, Wood, 1814) Safety lamp (Davy, 1816) Circular knitting machine (M. I. Brunel, 1816) Planing machine (Roberts,

Country	1700-1749	1750-1799	1800-1849
		Carding machine (Arkwright, Kay, 1775) Condensing chamber for steam engine (Watt, Boulton, 1776) Steam jacket for steam engine (Watt, Boulton, 1776) Spinning mule (Crompton, 1779) Reciprocating compound steam engine (Hornblower, 1781) Sun and planet gear (Watt, Boulton, 1781) Indicator of steam engine power (Watt, Southern, 1782) Rolling mill (Cort, Jellicoe, 1783) Cylinder printing press for calicoes (Bell, 1783) Jointed levers for parallel motion (Watt, Boulton, 1784) Puddling (Cort, Jellicoe, 1784) Power loom (Cartwright, 1785) Speed governor (Watt, Boulton, 1787) Double-acting steam engine (Watt, Boulton, 1787) Threshing machine (Meikle, 1788) Single-phase combing machine (Cartwright, 1789) Machines for lock production (Bramah, Maudslay, 1790) Single-action metal printing press (Stanhope, Walker, 1795) Hydraulic press (Bramah, Maudslay, 1796) High-pressure steam engine (Trevithick, Murdoch, 1797) Slide lathe (Maudslay, 1799)	1817) Large metal lathe (Roberts, 1817) Gas meter (Clegg, Malam, 1819) Metal power loom (Roberts, Sharp, 1822) Rubber fabric (Hancock, Macintosh, 1823) Locomotive with fire-tube boiler (Stephenson, Booth, 1829) Hot blast furnace (Nielson, Macintosh, 1829) Self-acting mule (Roberts, Sharp, 1830) Lathe with automatic cross-feed tool (Whitworth, 1835) Planing machine with pivoting tool-rest (Whitworth, 1835) Even-current electric cell (Daniell, 1836) Electric telegraph (Cooke, Wheatstone, 1837) Riveting machine (Fairbairn, Smith, 1838) Transatlantic steamer (I. K. Brunel, Guppy, 1838) Assembly-line production (Bodmer, 1839) Multiple-blade propeller (Smith, Currie, 1839) Steam hammer (Nasmyth, 1842) Iron, propellor-driven steamship (Brunel, Guppy, 1844) Measuring machine (Whitworth, 1845) Multiple-spindle drilling machine (Roberts, 1847)
Italy			Electric battery (Volta, 1800)
Switzer-land		Massive platen printing press (Haas, 1772) Stirring process for glass (Guinand, 1796)	
United States		Continuous-flow production (Evans, Ellicott, 1784) Cotton gin (Whitney, Green, 1793) Machine to cut and head nails (Perkins, 1795)	Single-engine steamboat (Fulton, Livingston, 1807) Milling machine (North, 1818) Interchangeable parts (North, Hall, 1824) Ring spinning machine (Thorp,

Country	1700-1749	1750-1799	1800-1849
			1828) Grain reaper (McCormick, Anderson, 1832) Binary-code telegraph (Morse, Vail, 1845) Sewing machine (Howe, Fisher, 1846) Rotary printing press (Hoe, 1847)

Table 2. Year of first monolingual dictionary

Country	Year	Author(s)	Publication
Austria	1868	Otto Back *et. al.*	*Österreichisches Wörterbuch* (1951)
England	1658	Edward Phillips	*The New World of English Words*
Belgium	1772		Average of France and Netherlands
Denmark	1833	Christian Molbech	*Dansk Ordbog*
France (north)	1680	Pierre Richelet	*Dictionnaire français*
France (south)	1815		See footnote 7 of text.
Germany	1786	Johann Christoph Adelung	*Grammatich-kritisches Wörterbuch der hochdeutschen Mundart*
Ireland	1958	Ireland, Parliament, Translation Bureau	*Gramadach na Gaeilge agus Litriú na Gaeilge: An Caighdeán Oifigiúil*
Italy	1897	Emilio Broglio & Giovan Battista Giorgini	*Nòvo vocabolario della lingua italiana secondo l'uso di Firenze*
Netherlands	1864	Marcus and Nathan Solomon Calisch	*Nieuw Woordenboek der Nederlandsche Taal*
Scotland	1707		Year of Union with England
Switzerland	1733		Average of France and Germany
United States	1798	Samuel Johnson Jr.	*A School Dictionary*

Sources: See Section IV of text.

Table 3. Means of variables for cities with positive and zero innovations

	1700-1749		1750-1799		1800-1849	
	Positive	Zero	Positive	Zero	Positive	Zero
Variable	(1)	(2)	(3)	(4)	(5)	(6)
Number of innovations	1.86	0.00	3.31	0	2.43	0
Population (thousands)	110	22	104	23	114	27
Britain dummy	0.71	0.09	0.50	0.08	0.38	0.08
Factor proportions dummy	0.29	0.08	0.31	0.07	0.29	0.07
Domestic market (millions)	12.6	13.4	17.2	16.5	28.6	20.1
Foreign markets dummy	0.29	0.20	0.44	0.18	0.48	0.17
Local openness dummy	0.43	0.01	0.19	0.01	0.19	0.00
Literacy (%)	33	32	50	40	56	51
Lang. standardization[a]	21	-48	12	-51	4	-51
Number of observations	7	194	16	185	21	180

[a] in years since first monolingual dictionary as of 1700

Table 4. Negative binomial regressions for all innovations, 1700-1850

Variable	Specification: Supply	Specification: Demand	Specification: Social networks
	(1)	(2)	(3)
Supply			
Britain	2.710**		
	(0.414)		
1750	1.073		
	(0.556)		
1800	1.312*		
	(0.552)		
Demand			
Factor prices		2.593**	
		(0.456)	
Market size		0.624**	
		(0.209)	
Social networks			
Literacy			0.424**
			(0.131)
Language standard'n			1.321**
			(0.342)
Local openness			3.610**
			(0.453)
International openness			1.178**
			(0.333)
City population	7.944**	8.221**	6.342**
	(2.020)	*(1.220)*	*(1.519)*
Constant	-4.115**	-4.296**	-4.890**
	(0.477)	*(0.501)*	*(0.760)*
α	4.862**	1.616**	1.242**
	(1.479)	*(0.293)*	*(0.372)*
Pseudo R^2	0.171	0.161	0.299

Time-series cross-section of 201 cities for 1700-1749, 1750-1799 and 1800-1849.
Number of observations: 603, of which 44 non-zero.
Robust standard errors 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.

Table 5. Negative binomial regressions for innovations by type, 1700-1850

	All innovations	Cooperative innovations	Non-cooperative innovations
	(1)	(2)	(3)
Supply			
Britain	0.058	-0.022	-0.256
	(0.503)	*(0.769)*	*(0.612)*
1750	0.891	0.234	1.005*
	(0.465)	*(0.799)*	*(0.484)*
1800	0.269	-1.301	0.347
	(0.616)	*(1.034)*	*(0.650)*
Demand			
Factor prices	0.938*	0.564	1.052**
	(0.398)	*(0.595)*	*(0.415)*
Market size	0.211	0.733	-0.001
	(0.314)	*(0.569)*	*(0.031)*
Social networks			
Literacy	0.347	**1.042****	0.218
	(0.179)	*(0.251)*	*(0.185)*
Lang. standard'n	0.950	**2.470****	0.909
	(0.558)	*(0.629)*	*(0.557)*
Local openness	3.228**	**4.613****	2.829**
	(0.513)	*(0.764)*	*(0.626)*
Internat'l openness	1.326**	**1.959****	0.883*
	(0.346)	*(0.502)*	*(0.438)*
City population	6.338**	7.804**	5.741**
	(1.288)	*(1.970)*	*(1.192)*
Constant	-5.700**	-11.278**	-4.798**
	(0.828)	*(1.767)*	*(0.782)*
α	1.109**	1.763**	1.033*
	(0.349)	*(0.616)*	*(0.526)*
Pseudo R^2	0.322	0.451	0.276
Non-zero obs.	44	19	34

Time-series cross-section of 201 cities for 1700-1749, 1750-1799 and 1800-1849.
Dependent variable: number of innovations of type *i* in region of city *j* in period *t*.
Number of observations: 603.
Robust standard errors 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 type in column (2) are significantly greater than those in column (3) at the 0.01 level, one-tailed test.