PAPERS on Economics & Evolution

1011

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by

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The *Papers on Economics and Evolution* are edited by the Evolutionary Economics Group, MPI Jena. For editorial correspondence, please contact: evopapers@econ.mpg.de

ISSN 1430-4716

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GENERAL PURPOSE TECHNOLOGIES AND THE INDUSTRIAL REVOLUTION

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19 April 2010

Abstract

Did breakthroughs in core processes during the Industrial Revolution tend to generate further innovations in downstream technologies? Here a theoretical model examines the effect of a political shock on a non-innovating society in which there is high potential willingness to cooperate. The result is regional specialization in the innovation process by degree of cooperation. Tests with a zero-inflated Poisson specification indicate that 116 important innovations between 1700 and 1849 may be grouped into three categories: (1) General Purpose Technologies (GPTs) tended to be generated in large states with standardized languages following transition to pluralistic political systems; (2) GPTs in turn generated spillovers for their regions in technologies where cooperation was necessary to integrate distinct fields of expertise; (3) however, GPTs discouraged downstream innovation in their regions where such direct cooperation was not required.

JEL Code: O3, N6

Keywords: General Purpose Technologies, Industrial Revolution, innovation, cooperation, spillovers

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The concept of General Purpose Technology (GPT) proposed by Bresnahan and Trajtenberg (1995) has generated considerable interest among those who formulate industrial policy. Such innovations promise to generate waves of induced innovation in a variety of industries that either use or further develop their techniques (Lipsey, Carlaw and Bekar, 2005, 97). The subsidizing of GPTs therefore offers a potentially promising way to generate jobs and accelerate economic growth. As examples, observers frequently refer to such famous inventions of the Industrial Revolution as the steam engine, smelting with coke and mechanized cotton spinning. But did these and later similar innovations actually produce externalities for the regions that generated them? To date, what little evidence exists comes from a much later period and provides scant support for the promise of spillovers.

One notable characteristic of the famous inventions mentioned above is that they were all the result of collaboration between individuals with quite different sets of skills.[1] This paper examines the possibility that the principal spillovers from these and other GPTs took the form not of inducing downstream innovation in related technologies but rather of increasing the willingness of potential entrepreneurs to cooperate with one another. Specifically, the objectives of this study are: (1) to explain the timing and location of nine General Purpose Technologies developed between 1700 and 1850; (2) to test for the presence of spillovers from these GPTs to over 100 other innovations that have been identified by historians of technology; (3) to assess the importance of learning to cooperate relative to the list of preconditions for growth proposed by other researchers.

The study brings together two threads of literature. One strand has sought to explain why the Industrial Revolution began in Britain before spreading a half-century later to continental Europe and North America. Until recently, explanations of the Industrial Revolution in Great Britain have focused on the institutions that England and Scotland had developed by the beginning of the eighteenth century. Among these were effective legal codes, educational systems that promoted literacy, efficient transport networks, commercialized agriculture, sound public finances and openness to trade.[2] Mokyr (2002,

[1] The atmospheric steam engine was developed by a hardware merchant, Thomas Newcomen, and a plumber, John Calley (Rolt and Allen, 1977, 34, 35), while casting with coke-smelted iron was the invention of a malt-mill manufacturer, Abraham Darby, and a young ironworker, John Thomas (Rolt, 1962, 8); spinning with rollers was a collaborative effort of a designer of machinery, Lewis Paul, and a carpenter, John Wyatt (Prosser, 2004).

[2] Rostow (1960) argued that such developments were preconditions for economic growth. North and Weingast (1989) offered an explanation for their effects, arguing that Britain's institutions allowed its government to commit itself to respecting property rights. Mokyr (1999, 29) suggested that rather than talk of necessary conditions for industrialization, one should use the term, "causal factors", that is, influences that increase the

2010) has emphasized the knowledge revolution that occurred as the scientific method was developed and applied. Recently, this discussion has been enriched by the addition of a powerful restatement of Adam Smith's explanation of the British Industrial Revolution based on factor prices. As set out by Allen (2007; 2009, pp. 138-144), the argument states that the high cost of British labor combined with the low costs of the country's capital and energy provided an incentive to develop technologies that substituted coal and capital for labor.

Even so amended, however, this general 'preconditions' approach has difficulty explaining the timing and the location of the innovations that were developed in the West during the years after 1700. With regard to institutions and scientific knowledge, the Dutch Republic was at least as well endowed as Britain in 1700, yet failed to industrialize before the late nineteenth century (deVries and van der Woude, 1997, 712). As concerns factor prices, Allen argues that the three famous labor-saving inventions mentioned above were triggered by a new configuration of factor prices early in the eighteenth century and that these inventions subsequently induced several trajectories of further innovation (Allen, 2009, 135 ff). But why were all of these techniques first developed in the midlands in the vicinity of a small town named Birmingham rather than in other areas of Western Europe with expensive labor and access to coal either locally or by sea[3]? And why did these inventions appear in the first few decades of the eighteenth century rather than fifty or a hundred years earlier (or later)? Throughout the preceding centuries, people had been struggling unsuccessfully to find ways to harness steam power, to cast with iron smelted by the use of coal and to automate the steps in the production of textiles.[4] Finally, how can the subsequent development of many other devices and processes less directly related to factor prices – for example, accurate timepieces, the hot-air balloon and the telegraph – be explained?

A second strand has examined the sources of innovation. Bresnahan and Trajtenberg (1995) used the term 'General Purpose Technology' (GPT) to describe an innovation that triggers a whole series of further technological developments. One of their examples was the

probability of economic change. Acemoglu et al. (2005) offered evidence that Western European economic growth before 1850 was favored not only by institutional reform but also by access to the profits of Atlantic trade.

[3] With regard to cotton spinning, this paper indentifies as the key innovation Paul and Wyatt's device for spinning with rollers, patented in 1738, rather than Hargreaves' spinning jenny of 1764 that was selected by Allen (2007).

[4] Sand casting of iron skillets was done in the foundries of Sussex from the late Middle Ages (Rolt, 1962, 3, 8). Dud Dudley attempted to smelt iron with coal prior to the Civil War (Rolt, 1962, 5). Water-powered silk spinning factories existed in Europe as early as 1272 (Munro, 1996, 479). Denis Papin had invented the steam powered piston before 1695, while Thomas Savery was granted a patent for a device that used steam to extract water from a mine (Rolt & Allen, , 24-25).

steam engine (p. 84). In a book edited by Helpman (1998), a number of other researchers discussed the implications of this concept. Recently, Lipsey, Carlaw and Bekar (2005, 540-541) used the notion of GPT to explain the discontinuous nature of technical change since prehistoric times. They argued that the presence of spillovers from such innovations may justify the use not only 'blanket' policies such as research subsidies and patent protection but also 'focused' industrial policy to support specific sectors. For example, the presence of spillovers could provide a justification for protectionist measures such as Britain's Calico Act of 1721 sought to prohibit imports of Indian cotton goods by levying heavy fines on those who wore or sold all-cotton textiles or used them in their households.

To date, empirical support for the existence of spillover effects from such policies has been weak. Moser (2005) showed that one specific blanket policy, namely, patent protection, did not affect the overall rate of innovation. Rather, data from two nineteenth-century world fair indicated that patents served primarily to channel innovative activity into sectors where the gains from novelty were otherwise difficult to appropriate. Might focused industrial policies have greater impact? Moser and Nicholas (2004) found that a strong candidate for consideration as a GPT, electricity, actually had fewer citations for its patents from the 1920s than did other innovations. A recent study of US innovations in electrical technology also suggested that industry-specific stimulus may also be ineffective. Using patent data from 1890 and 1910, Lo and Sutthiphisal (2008) found little evidence of interindustry spillovers from core technologies to crossover technologies.

This paper differs from previous studies in disaggregating innovations by the degree of cooperation in the innovative process and by examining the possibility of long-term spillovers that affect the willingness to cooperate.[5] Section I below describes a set of 116 innovations over the period from 1700 to 1849 that have been identified by historians of technology. It then separates these innovations into three categories; namely, *GPTs*, all of which were developed by two or more people, *other cooperative innovations* having more than one inventor, and *non-cooperative* innovations, that is, those with a single inventor. The concentration of these innovations in three countries gives rise to several questions that have not yet been answered in the literature.

[5] Dudley (2008) uses an earlier version of the data set of this paper to identify the sources of innovation, but does not identify GPTs or test for the presence of spillovers created by them.

Section II proposes a simple model of strategic interaction between members of an innovating society in which the propensity of each to cooperate may change over time as a result of learning from experience. The model begins in a non-cooperating society in which large numbers of people are nevertheless signaling their potential willingness to cooperate. It is shown that a shock which temporarily induces cooperation can lead to regional specialization, some areas specializing in cooperative activities and others in non-cooperative but nevertheless innovative activities.

Section III uses the micro-data of the first section in a zero-inflated Poisson specification to compare this 'learning-to-cooperate' model with the more conventional 'preconditions' explanation of innovation during the Industrial Revolution. The results suggest that the development of a 'macro-invention' or 'General Purpose Technology' was a relatively rare event, likely to occur under quite special circumstances. Large economies in which information circulated freely were favored. The Protestant religion also seems to have been a positive influence, perhaps because of its emphasis on literacy and on inviolable rules governing social behavior.

The results also suggest that, at least during the Industrial Revolution, GPTs were in a class by themselves, generating externalities for derivative technologies but themselves depending little on spillovers from previous innovations. The prior development of a GPT in a given region nevertheless had important effects on the course of subsequent innovation in that region. There were strong spillovers favoring the development of other relatively complex *cooperative innovations*. However, other things being equal, such a region was less likely to develop generally simpler *non-cooperative* innovations.

The empirical results might also have implications for yet another explanation of the Industrial Revolution. De Vries (2008) suggested that the availability of new consumption goods may have increased people's willingness to work, thereby increasing the effective industrial labor force. However, it would be worthwhile to explore causality in the opposite direction, namely, that the new spirit of cooperation within national boundaries may have enlarged the reference group with respect to which people set their consumption preferences.

Finally, a possible policy implication of these results is that attempts to promote GPTs in one region may alter the future comparative advantage of both this and other regions. Collective research activities may be favored in the region in question, but other more individualistic innovative efforts may be displaced elsewhere.

I. GPTS AND INNOVATION, 1700-1850

'About 1760 a wave of gadgets swept over England,' wrote a schoolboy cited in T. S. Aston's concise study of the transformation of British Industry between mid-eighteenth and mid-nineteenth centuries (Ashton, 1948/1962, 58). Most observers of the Industrial Revolution would agree, however, that not all of these gadgets were created equal. This section is therefore divided into three parts. First, it presents 116 of these inventions that have been identified as important by historians of technology. In the second part a subset of these important innovations, described as 'macro-inventions' or 'General Purpose Technologies,' is selected for particular attention. Nine such technologies are described briefly. Finally, many of the 107 other important inventions share an important characteristic with the GPTs, namely, that they were produced through the cooperation of two or more unrelated individuals. The third part therefore compares the timing and location of new developments according to the degree of cooperation in the innovation process.

(a) Innovation

What does one mean by innovation and by Industrial Revolution? The definition of what constitutes innovation, as Thomas Kuhn (1962, 162-163) explained, is bound to be subjective. Fortunately, generations of historians of technology have polished and refined this definition. There is general agreement that an industrial innovation must incorporate something significantly new, that it must consist of a production process (such as coke smelting) or a product (such as the locomotive), and that it must be effectively applied. To avoid bias in favor of discoveries made in particular countries, this study has chosen recent accounts of the industrial revolution by recognized experts of four different nationalities.[6] These were Cardwell (1972/1991) of England, Daumas (1979) of France, Mokyr (1990) born in the Netherlands and living in the United States, and Paulinyi (1989), born in Hungary and residing in Germany. To be considered an innovation here, a technological development had

[6] In studying the characteristics of American "great inventors", Khan and Sokoloff (2004) used a method similar to that of this paper. They studied the U.S. patents awarded to those sufficiently important to be described as inventors in the *Dictionary of American Biography*, Scribner's, 1928-1936. Their approach has been criticized by MacLeod and Nuvolari (2006) for its possible biases, for example, an excessive emphasis on instruments, on the military and on steam power, combined with a neglect of chemicals, consumer goods and non-steam power. However, a glance at Appendix B will show that such biases seem to have been reduced here, owing to the use of more recent, technology-oriented sources.

to be mentioned by at least two of these authors. Although the overlap between the four was considerable, the *Encyclopedia Britannica* served as arbitrator in the cases of a reference by a single author.[7] It should be emphasized too that all of these developments are what Rosenberg (1994: 14-15) categorizes as major innovations rather than examples of the countless minor modifications made to existing techniques.

If we are to define the Industrial Revolution as a sustained acceleration in the rate of innovation, the choice of time period is important. As Cameron (1993: 165-166) has explained, the dates initially chosen by Arnold Toynbee for his Lectures on the Industrial Revolution, from 1760 to 1820, were simply the years of the reign of George III. There seems general agreement that there were important technological developments in the decades that preceded this period, for example, the use of coke for iron smelting and the atmospheric engine. In addition, the process of discovery by skilled craftsmen continued essentially unchanged beyond the reign of George III until the mid-nineteenth century, when formal scientific research first began to determine the pace and direction of technological change. Accordingly, let us focus on the century and a half that began in 1700.

What, then, were the technological developments that occurred between 1700 and 1849 and were mentioned by at least two of the chosen quartet of historians of technology? Our criteria yielded the 116 innovations presented in Appendix B and summarized in the section entitled 'All innovations' of Table 1.

[Insert Table 1 about here.]

(b) General Purpose Technologies

The question addressed in this paper is whether there were dynamic linkages from some of these innovations to others. Lipsey, Carlaw and Bekar (2005; 96, 98) defined a GPT as a 'generic product, or process, or organizational form' that generates spillovers, expanding 'the space of possible inventions and innovations,' and 'creating myriad new opportunities for profitable capital investments.' The authors cited the steam engine and the factory system as examples of GPTs. Allen (2009, 136-137) used a similar term, 'macro-invention,' to describe developments that 'set in train long trajectories of advance that resulted in great increases in

[7] The *Encyclopedia Britannica* was one of the two primary sources for 30 of the 116 innovations.

productivity.' He offered three examples, namely, the steam engine, the cotton mill and the coke-fired blast furnace, each of which appeared in the first half of the eighteenth century.[8]

Over the following century, between 1750 and 1799, there were three other technologies developed that for many observers satisfy the definition of GPT or macro-invention. In England in the 1790s there was the development of machine tools, that is, machines able to produce the metallic parts for other machines by the controlled removal of metal (Daumas, 1979, 106-107; Rosenberg, 1994, 15). At about the same time, in France, one of the first applications of science to industry yielded a chemical factory that produce soda ash from salt (Daumas, 1979, 564-567; Chow and Chow, 1992, 108-109). Meanwhile in the United States, the concept of continuous-flow production was first successfully applied to build an automatic flour mill (Mokyr, 1990, 137;Ferguson, 1980, 13-28).

The first half of the nineteenth century saw the development of three further technologies that subsequently transformed the economy of the West. In France, numerically controlled production was developed for the weaving of silk (Essinger, 2004). Two decades later, American inventors developed the technology to produce interchangeable parts for the manufacture of pistols (Muir, 2000, 129). Finally, the electric telegraph, developed in England in 1837, was the first successful application of electricity to do work – in this case, moving pointing needles in a device that could transmit information almost instantly over long distances (Mokyr, 1990, 123).

(c) Cooperation

One interesting feature of each of these nine GPTs is that they were developed through the collaboration of two or more individuals. Cooperation in innovation is potentially a two-edged sword. An inventor may find it useful to bring a second person with access to a different set of information into the development process. However, with this contribution will come the burden of coordination to assure that the efforts of both principals are complementary and to make sure that the costs and benefits are divided fairly between them.

What was the importance of cooperation during the Industrial Revolution? Many of the other 107 innovations listed in Appendix B resembled the GPTs just described in that they too were developed through the collaboration of unrelated individuals. An important example

[8] Allen (2009, 135).

is the collaboration between Friedrich Koenig and Andreas Bauer that produced the steam-powered printing press. With the help of available records, it was possible to identify 50 other non-GPTs that resulted from the sharing of original ideas and technological expertise between two (or more) unrelated individuals.[9] In other words, including GPTs, these records show that slightly over half the total innovations identified involved what Trivers (1985: 48) has defined as *reciprocal altruism*.[10] These "cooperative" inventions are underlined in Appendix B.

The remaining innovations listed in Appendix B were the result of the efforts of a single principal. For example, Oersted's 1819 discovery of the principle of the galvanometer occurred during an evening lecture he was giving on electricity and magnetism at the University of Copenhagen.

Three features stand out in Table 1, namely, the timing of the new developments, the geographic limits to sustained innovation, and the differences across countries in the degree of cooperation. The process of innovation that drove the Industrial Revolution occurred sequentially by region, beginning suddenly in Great Britain in the first half of the eighteenth century and accelerating in the second half of the century. Then, after a delay of over a half-century, the phenomenon spread to France and the United States. In per-capita terms, as the bottom lines in Table 1 indicate, in all three innovating countries, the peak period was the last half of the eighteenth century. Once systematic innovation started in these countries, however, the process continued on its own momentum. In none of the principal innovating countries did the rate of innovation fall back to negligible levels after the initial acceleration.

A second striking feature of the innovation process summarized in Table 1 is its geographic limits. The phenomenon was restricted essentially to three states, namely, the United Kingdom, France and the United States. The territories of present-day Germany and Italy, each with a population in the year 1700 that was considerably larger than that of the United Kingdom, contributed very little to the total number of innovations. The Netherlands, Europe's richest state in per-capita terms in 1700, did not produce a single important innovation over the following century and a half. As for the remaining 90 percent of the world's population, apart from Switzerland and Demark, they too contributed nothing to this technological revolution. Among the three principal innovating countries, the distribution was by no means uniform. Although France contributed about 20 per cent of the total number of

[9] The contribution of an assistant who simply executed instructions is not counted as cooperation.

[10] A detailed search for biographical data on the inventors of each of the 116 new technologies was carried out by means of an internet search engine. The addresses of the numerous sites consulted are available from the author upon request.

new technologies, its rate of innovation per capita was roughly one-fifth that of Great Britain and the United States.

There is a final feature of Table 1 that is worth noting. All of the innovations outside the three principal countries were solo efforts, and in France, barely a third of the innovations involved cooperation. In the two Anglo-Saxon countries, however, over half of the new techniques were the result of cooperative efforts. Despite this high revealed willingness to cooperate, Britain and after 1750, the United States, produced far more *non-cooperative* innovations per capita than any other Western states. In other words, those countries whose citizens were most inclined to cooperate were also the most capable of producing non-cooperative innovations!

In summary, this initial examination of the data on innovation between 1700 and 1850 suggests several points that should be explained. First, why did Britain and subsequently France and the United States suddenly develop the capacity to created *General Purpose Technologies*? Second, was there a link between these GPTs and the subsequent increase in the observed production of *other cooperative innovations* in these countries but not elsewhere in the West? Finally, why was there also a sharp increase in the number of *non-cooperative* technologies invented in these three countries?

II. COOPERATING TO INNOVATE

The preceding section indicated that societies which were able to foster cooperation in innovation tended to be societies that innovated more. But this specialization by degree of cooperation may also occur across regions within a single country. In a detailed study of US manufacturing, Thomson (2009, 15-65) has shown that in the early nineteenth century, networks of producers who shared ideas and equipment emerged in New England and the mid-Atlantic region. These regions also led in shares of machinery patents. How does such regional specialization develop? This section proposes a theoretical model that is able to explain changes in the rate of innovation by a rise in willingness of individuals to cooperate with strangers.

As Witt (2003, 92) has observed, since innovation involves doing something that has not been done earlier, it is difficult to model with an optimizing algorithm. Weitzman (1998) suggested that the innovation process consists of combining existing pieces of knowledge in new ways. However, to the extent that the required inputs of information are each incorporated within single individuals, there is a fundamental difficulty. Freely circulating information is a public good characterized by non-exclusion and by non-rivalry. By sharing one's knowledge with others, one allows them to free ride at one's own expense.

Consider a repeated two-person coordination game with random pairing of potential inventors. If each of the two players has two strategies, there are four possible outcomes. Should both players defect, each receives a low compensation, the Punishment payoff, $\overline{P}$. If Player 1 defects while his partner cooperates, Player 1 receives the Temptation payoff, $\overline{T}$, which may be assumed to be higher than $\overline{P}$. Meanwhile Player 2 obtains the Sucker payoff, which for simplicity we may assume to be zero. A symmetrical pattern applies if Player 2 defects while her partner cooperates. There is a fourth possibility. If *both players cooperate*, each obtains the reward payoff, *R* (assumed uniform). Since we are discussing innovation, this payment will be determined by the reliability of suppliers, by the willingness to pay of eventual purchasers of the invention and by the efficacy of the legal system in punishing those who might violate contracts or infringe on the rights of patent holders.

Should the willingness to cooperate of other players be low, *R* takes on its base value, $\overline{R}$, where $\overline{T} > \overline{R} > \overline{P} > 0$, the Prisoner's Dilemma ranking. Since the dominant strategy for each player in this case is to defect, each will receive the Punishment payment, . In the two graphs of Figure 1, the vertical axis measures the expected net gain, Π, to Player 1 if he decides to cooperate in the innovation game. In the area above the horizontal axis, where this gain is positive, it is in his interest to cooperate. Below the horizontal axis, since his expected gain is negative, he will choose to defect. Now define $q(t)$ as the probability that the Player 2 will cooperate. This variable is measured along the horizontal axis of the diagrams. Since the second player is chosen at random from the population of the region, $q(t)$ is also the mean willingness to cooperate in the region. In the absence of cooperation elsewhere in the society, will be sufficiently low that the steady-state equilibrium, B, lies above the innovation threshold, E, in the upper graph of Figure 1. In the steady state, there will be no innovation.

[Insert Figure 1 about here.]

However, should other parties prove willing to cooperate, Reward may be greater than its base level and indeed may even exceed Temptation: $R > \overline{T} > \overline{P} > 0$. In this case, the game is known as Assurance. There is no longer an incentive to defect from the joint-cooperation equilibrium (Heckathorn 1996). It follows that to the extent to which innovation requires the collaboration of strangers, it cannot occur without some assurance of reciprocal altruism. Field (2003: 232-235) has argued that humans, like their closest primate relatives, have a genetic predisposition to cooperate with unrelated individuals they think will cooperate with them. Experimental evidence presented by Frank (1988: 139-143, 157) shows that on the basis of visual and aural clues, we are remarkably successful at predicting who will cooperate with us in a one-shot prisoner's dilemma game. Appendix A demonstrates that under behavioral assumptions distinct from rational-choice theory, social and political transformations may trigger a learning process that raises the rate of cooperation in a society.

For cooperative innovation to be a steady-state equilibrium, two conditions must be satisfied. First, players must be informed about the potential willingness to cooperate of strangers. Let λ represent the quality of the information about third parties, both within and outside the region, where $0 \leq \lambda \leq 1$. Second, this information must indicate that strangers are indeed willing to cooperate

Let the Reward payoff take the form $\overline{R} + \lambda a q(t)$, where a is a positive scalar. On the one hand, if the quality of information is poor (λ=0), Player 1 assumes the worst about strangers. We have the Prisoner's Dilemma game described above. Even if both players are potentially willing to cooperate, because of the unreliability of third parties, each player estimates Reward to be lower than Temptation and defects, as shown by the point A. The steady-state equilibrium in this state of the world is at point B in the upper graph of Figure 1, where all are defecting and receiving the Punishment payoff.

On the other hand, should the quality of information about other players be high (λ=1), the situation is more complex. There are two sub-cases to examine, each with its own mass point. Consider first a region in which a shock has raised the level of cooperation above the threshold, q^*. Given the previous rise in information quality, the right half of the path to the steady state will meet the right vertical axis at a point such as C, above the origin in the lower graph of Figure 1. It is in Player 1's interest to cooperate, since Reward is greater than Temptation. The steady-state equilibrium is at C.

However, if the shock fails to lift the observed degree of cooperation in the region above q^*, it makes no sense for Player 1 to cooperate. The steady-state equilibrium is once again on the left-hand axis, where all in the region defect. Nevertheless, if cooperation has increased *outside* this region, for the reasons just explained, the path to the steady state may cut the left vertical axis at a point below B. Let the second mass point be at D.

Suppose that initially a society is in equilibrium at B in the lower graph of Figure 1. Then let there be a rise in the quality of information followed by a political shock.[11] In some regions, where people belong to groups with high levels of education, the cooperation rate will rise above q^*. Projects requiring cooperation that were unfeasible previously now become possible. Among the first projects to be undertaken, at a point such as F, will be *General Purpose Technologies*. Since such projects have multiple uses, they will have high expected returns. Then, as people learn to cooperate increasingly, q rises and the position of these regions moves to a point such as G. At this higher cooperation rate, *other cooperative* projects become feasible.

In regions where literacy is lower, the political shock may not be sufficient to cause the average cooperation rate to rise above q^*. As a result, the level of cooperation gradually declines, reaching steady-state equilibrium of zero cooperation. However, the rise in

[11] For example, in England there was a gradual rise in literacy over the sixteenth and seventeenth centuries (Graff, 1991, p. 151, ff). Then, as Steve Pincus (2009) has argued, from 1688-1696, in what has become known as the Glorious Revolution, the great majority of the English population reached a consensus, deliberately choosing a 'participatory state' under William III rather than a centralized absolutist monarchy under James II.

cooperation *outside* of this region may raise the Punition payoff from to *. As a result, the whole left part of the curve shifts downward. Should the shift cause the left intercept to drop below the threshold level, *E,* to a point such as D, where unaided innovation becomes profitable, the region in question will begin to specialize in *non-cooperative* innovation.

In short, the pattern predicted by the theoretical model corresponds to the stylized facts of Section I. The model suggests three verifiable hypotheses. First, the combination of greater literacy and political revolution creates conditions in certain regions for a rise in cooperation that makes the development of GPTs profitable. Second, as the level of cooperation continues to rise further over time in these regions, they begin producing other cooperative innovations. Finally, in other regions, where the initial level of literacy is lower, the political shock will lead to specialization in non-competitive innovations.

It remains to determine whether these hypotheses may be verified empirically.

III. AN EMPIRICAL TEST

The preceding section developed a 'learning-to-cooperate' model of innovation that contrasted with the 'preconditions' approach to the Industrial Revolution described in the introduction. The latter emphasizes institutions and factor prices, whereas the former posits a cultural transformation. This section reports the results of tests of these alternative approaches that were carried out on cross-section time-series data. The 116 innovations described in Section I were matched with 201 urban regions of Western Europe and North America for the three fifty-year sub-periods between 1700 and 1849.

(a) The Zero-inflated Poisson Specification and the Data

The spatial clustering of innovations observed in the empirical studies of Allen (1983) and Nuvolari (2004) suggests that the unit of observation should be a region within a state. The count data will measure the number of innovations of type *i* that occurred in the region of city *j* in period *t*, y_{ijt}. If we may assume that the probability of an innovation in the region of a given city was independent of the number of innovations near other cities in the same period, a Poisson distribution is appropriate:

, (1)

where is a vector of explanatory variables, is a vector of parameters and is a random variable. However, since over 90 percent of the observations were zero, the variance of the dependent variable in the sample was much greater than its mean, in contradiction to a characteristic of the Poisson distribution. To correct for this over-dispersion, it was decided to use the zero-inflated version of the latter specification. Under this method, a logit specification determines whether a given observation is generated by equation (1) or by a process that generates only zeros.

The components of will depend on the hypothesis being tested. The 'preconditions' approach focuses on factors the British economy, such as the commercialization of agriculture, clearly defined property rights, well-developed financial institutions, sound public finances, good internal and external transport, openness to trade and appropriate natural resources. One might think of using such variables as wage rates, densities of roads, the capacity of ports, tariff policy or the fraction of public debt financed through financial markets as measures of such preconditions. However, the difficulty with such variables is their possible endogeneity, since each could be as much the result as the cause of an innovating society. Since the individual coefficients of such factors were not of great interest, it was considered preferable to use variables that were predetermined. It was assumed that Great Britain had certain distinct geographic and social conditions whose effects were picked up by dummy variables. Accordingly, *DumGBr* represented Great Britain, while *Dum1750* and *Dum1800* corresponded to the second and third half centuries respectively.

Two predetermined effects at the level of the individual urban region may be specified directly. Since overland transport was extremely expensive prior to the construction of the railroads, we will allow transport costs to be measured by a dummy variable, *Port*, indicating whether or not the city was an ocean port.[12] As for natural resources, the presence of coal deposits was a crucial factor both for supplying inputs to industry and in demanding innovations to improve its own productivity. Thus the dummy variable *Coal* indicating the presence or absence of this resource within a radius of 30 miles could be expected to have a positive sign.

The alternative approach, the 'learning-to-cooperate' model of the preceding section, posited that there were two conditions favorable to innovation. One condition was the presence of a signal indicating the conditional willingness to cooperate of customers, suppliers and authorities responsible for the enforcement of contracts in a radius of perhaps 300 km from the innovators' region. The ability of millions of people to communicate in the written form of a standardized language may be considered one component of such a signal. In eighteenth-century Britain or France, this condition would have been satisfied, while in Germany, the Netherlands, Belgium or Denmark, it would not.[13] For most cities in the sample, this factor was captured by the population within the boundaries of the present-day state at the beginning of each period, *Country population*. One exception was the United

[12] The *Port* variable also permits a test of the hypothesis of Acemoglu, Johnson and Robinson (2005) that access to the Atlantic reinforced the position of merchant groups and constrained the power of absolutist monarchs, since the results varied little when Baltic and Mediterranean ports were excluded.

[13] The first privately-published dictionaries in French and English were Pierre Richelet's *Dictionnaire français* and John Kersey the Younger's *A New English Dictionary*, printed in 1680 and 1702 respectively. In no other European vernacular was a dictionary published privately before 1850.

States. Even in the late eighteenth century, the American spoken language was still very similar to that of south-eastern England.[14] Accordingly, the populations of Great Britain and the United States were assumed to form a single linguistic zone. The other exception was Germany, where the boundaries of individual states within the German Confederation of 1815 were used.

Another component of the signal that an individual was conditionally willing to cooperate may have been religion, for example, the shared Baptist faith of Newcomen and Calley. Blum and Dudley (2001) offered evidence to support Max Weber's (1930) thesis that in the early-modern period, Protestants (and the Jews who sought refuge in Protestant states) were more likely to cooperate with one another than were Catholics. Accordingly, the dummy variable *Protestant*, indicating that the majority of a city's population was Protestant, was included in the specification.

As for the second condition suggested by the theoretical model of Section II, even though people were able to observe that most of their fellow citizens shared their language or religion, they may still have been unwilling to leave the non-cooperative equilibrium. Accordingly, a shock was required in order to raise the average rate of cooperation in the society above a certain threshold. Beyond that critical point, learning on the basis of successful past interactions with strangers communicating in one's language would cause the overall rate of cooperation in the society to rise to its maximum level. The occurrence over the previous half-century of a revolution that introduced pluralistic government institutions, as measured by the dummy variable *Revolution*, was assumed to constitute such a shock.[15] The lagged value of the number of General Purpose Technologies in the region, *Lagged GPTs*, captured the importance of spillovers from GPTs to subsequent innovations. Finally, as a scale variable for each of the alternative hypotheses, the number of innovations in a region was allowed to change with the main city's population, *City population*. This variable was also used in the inflation equation.

To calculate the value of the dependent variable in equation (1), two different types of data were necessary. One set that has already been mentioned consisted of 116 major innovations, each referred to by at least two of four historians of technology whose work was

[14] Bragg (2003: 166). It should be noted that Webster's dictionary of American English was not published until 1828 (McCrum et al. 1986: 240).

[15] To avoid simultaneous determination, the revolution, population and literacy variables are defined as of the *beginning* of each sub-period.

consulted.[16] A second set of data consisted of population estimates for 201 European cities, each of which had at least 7,000 inhabitants in 1700, from Bairoch et al. (1988). Of this set, there were 46 cities at or near which one or more innovations occurred. To these, we added the 155 other European cities that were at least as close to London as the most distant innovating city (Como, in northern Italy). In addition, we included three American cities – New York, Philadelphia and Boston. The city list appears in Appendix C. Since the Bairoch urban-population data are available only at fifty-year intervals for the period under consideration, we divided the data into three half-century groups, namely, 1700-1749, 1750-1799 and 1800-1849.

Sources of literacy rates in 1700, 1750 and 1800 were: England, Cressy (1980: 177); France, Graff (1991: 193); Germany, Graff (1991: 187); Italy, Graff (1991: 191); Netherlands, Graff (1991: 223); United States, Graff (1991: 249). The rates for Austria were estimated from the German rate less the German-Austrian difference in 1850 from Cipolla (1969: 115). Estimates for Belgium and Scotland were calculated in the same manner from the 1850 rates for Germany and England respectively. The source for each European city's religion was Darby and Fullard (1978: 126-127); deposits of coal were from Barraclough (1984: 201, 210-211).

(b) Results for All Innovations

To estimate the zero-inflated Poisson model, the data were divided into three cross-sections, one for each of the periods 1700-1749, 1750-1799 and 1800-1849. Table 2 presents the estimates for all 116 innovations. Note first that the inflation variable, *City population*, was significant in determining whether an arbitrary value of zero was appropriate for some observations all four specifications. The first column displays results for the specification representing the "preconditions" approach. Among the Poisson coefficients, both the dummy variable for Great Britain and the dummy corresponding to the half-century beginning in 1750 were significant with positive signs. The proximity of coal deposits was another significant factor favoring innovation. As might be expected, the larger the city, the greater the number of innovations. These results suggest that institutions and factor prices together have considerable explanatory power. Innovation required favorable institutions and high enough

[16] See Section I above.

costs of labor to make a search for new techniques potentially profitable. It would appear that once these conditions had been satisfied, in Britain around 1750, takeoff could occur.

[Insert Table 2 about here.]

Column (2) displays the alternative "learning-to-cooperate" specification. The two components of a signal indicating willingness to cooperate, namely, belonging to a large language network, as measured by *Country population*, and to a *Protestant* religious community, were both significant. However, the political shock variable, *Revolution*, was not significant. Instead, the jolt that shocked a society into producing a large number of innovations would appear to be the number of GPTs in the preceding period. In terms of the log of the pseudo-likelihood function, this learning specification offered a considerably better fit than the preconditions approach.

One possible explanation for the success of the learning-to-cooperate approach in column (2) is that its cultural and political variables were picking up the fixed effects of the Great Britain dummy and the geographic variables of column (1). To examine this possibility, column (3) pitted these alternative explanations of the Industrial Revolution against one another by including all variables from these approaches within a nested specification. One striking aspect of this last set of results is that the time and country dummy variables lost their significance. However, the cultural variables, *Protestant*, *Country population* and *Lagged GPTs* remained significant. The coefficient of *Coal* remained essentially unchanged, but was no longer significant.

One possibility that should be explored is that *Protestant* was simply a proxy for *Literacy*. When *Literacy* replaced *Protestant* in column (4), the log of the pseudo-likelihood coefficient dropped significantly. It may therefore be suggested that *Protestant* was signaling something more than simply the ability to read and write. Possibly literate Protestants were more willing to trust one another in contractual relations than were literate Catholics.

These results offer support for David Landes's (1998, p. 516) argument that it is necessary to introduce cultural variables, in the sense of 'inner values and attitudes' when attempting to explain international differences in productivity growth. International differences in rates of innovation depend not only on economic institutions and factor prices but also on such considerations as religion, nationalism and the degree of homogeneity of values. Might such differences also be important at the regional level? We turn next to this question.

(c) GPTs, Other Cooperative and Non-cooperative Innovations

Underlying the specifications presented in Table 2 is the hypothesis that all innovations were generated by the same process. However, an examination of the list of innovations in Appendix B reveals that all nine developments that were classified as General Purpose Technologies – because they provide key inputs for a number of different downstream sectors – were cooperative. Examples were the atmospheric steam engine, factory spinning of cotton, smelting with coke, continuous production, machine tools and industrial chemicals, all of which had more than one inventor. A further group of innovations brought together distinct areas of expertise through the collaboration of two or more inventors but were extensions of existing techniques. Examples were the condensing chamber for the steam engine, the water frame and the mechanical printing press. As for the effects of the remaining innovations with a single inventor, defined as non-cooperative, with few exceptions they were simpler modifications of existing techniques. Examples are the flying shuttle, the spinning jenny and crucible steel. It is therefore worthwhile to disaggregate the data, separating the nine GPTs from the 51 other cooperative innovations and the 56 innovations classified as non-cooperative.[17]

The results for GPTs are presented in column (1) of Table 3.[18] Despite the inclusion of fixed effects, both of the signals of conditional willingness to cooperate, *Country population* and *Protestant*, were significant. The shock variable, *Revolution*, was also highly significant. However, the lagged number of GPTs was not significant. These results are consistent with the theoretical model presented in Section II. In a country of sufficient size, with appropriate factor prices and with a potential willingness to cooperate, rapid political transformation to establish representative government had a major effect on the capacity to innovate. In Britain, the United States and France, revolution to create a political nation would appear to have

[17] See section I above.

[18] Note that because of multicollinearity, the German dummy variable was been dropped from the estimates in this table.

constituted a shock that pushed a cultural nation (a literate population speaking a standardized language) beyond a threshold at which new experience induced people to cooperate more readily.

[Insert Table 3 about here.]

The results for *other cooperative* innovations, presented in column (2) of Table 3, offer an important extension to this argument. Despite the inclusion of the fixed effects, both of the signals of conditional willingness to cooperate, *Country population* and *Protestant*, were significant. The shock variable, *Revolution*, was not significant, suggesting that within the first fifty years, the social effects of political transformation were limited to areas of technology where important bottlenecks were blocking further progress. However, lagged GPTs had a large and significant effect. In other words, the opening of these bottlenecks did indeed generate additional cooperative innovation in the following half century. This was the only regression in which the inflation variable, *City population*, was not significant in the logit equation.

Yet a question remains: is the positive effect of *Country population* merely a reflection of market size? The results for the generally less complex *non-cooperative* innovations displayed in column (3) of Table 3 suggest an answer to this question. The coefficient of *Country population* is significantly smaller than for the two categories of cooperative innovations. These estimates suggest that the country-population variable in columns (1) and (2) was not simply capturing market size, for if so, it should also have been equally important for all categories of innovations. Possibly cooperative innovation, perhaps because of the complexity of its product, required access to freely circulating information whose importance was not limited to a single urban region. For example, there is evidence that Thomas Newcomen knew of previous research by Thomas Savery and through him of work by Denis Papin (Rolt and Allen 1977: 39).

Neither *Revolution* nor *Lagged GPTs* was significantly positive in column (3). Indeed, the latter variable was marginally significant with a *negative* sign. In other words, a region that had previously developed a GPT was less likely to come up with a non-cooperative technology. This result suggests that as a result of previous experience, there was regional specialization by type of technology. Regions that developed a local culture favorable to cooperation tended to specialize in the development of complex techniques such as machine spinning of cotton with rollers. Meanwhile regions with more individualistic regional cultures specialized in techniques that required a less important modification of existing technologies; for example, the spinning jenny or the spinning mule.

If neither of these politically-influenced variables was significantly positive in column (3), why did the number of non-cooperative innovations suddenly accelerate after 1700? The simplest answer is that relative to fifty years before this date, the cultural implications of the two variables, *Protestant* and *Country population*, had changed remarkably. The Glorious Revolution had brought members of dissident congregations together to defend their freedom to worship. And, as mentioned above, by the first decade of the eighteenth century, the French and English written and spoken languages had become sufficiently standardized for the first privately published dictionaries in these languages to have appeared.

The significant coefficients of *Protestant* and *Country population* in column (3) nevertheless suggest that even solitary inventors would appear to have depended to an important degree on the reliability of third parties such as suppliers, clients and the members of the legal system. This result helps explain why 90 percent of the 60 non-cooperative innovations were developed in Britain, France and the United States after their revolutions. Finally, despite being non-significant in the nested specifications of Table 2, coal deposits were significant for all three categories of innovations in Table 3.

This disaggregation by type of innovation suggests the importance of distinguishing not only between nations but also between regions within states when examining the sources of innovation. Patterns such as the role of factor prices and the positive and negative spillovers from GPTs may be lost in aggregate data but appear clearly when they are broken down by region and type of innovation.

CONCLUSION

This study has examined the evidence of spillovers from General Purpose Technologies (GPTs) – that is, techniques that are applicable in a wide range of sectors – during the first century and a half of industrialization in the West. The goal was to determine whether the concept of GPT can help explain the timing and location of innovation between 1700 and 1850. The study used a sample of 116 important innovations that have been identified by historians of technology. Nine of these innovations satisfy the definition of GPTs: (1) casting with coke-smelted iron, (2) the atmospheric steam engine, (3) the manufacture of cotton thread in factories, (4) continuous production (5) the application of science to the industrial production of chemicals, (6) machine tools (7) numerically-controlled production (8) interchangeable parts and (9) electrical machinery. Over half of all the innovations during this period, including the GPTs just mentioned, involve cooperation between two individuals with different capacities. It was therefore possible to distinguish between three types of innovation, namely, GPTs, other cooperative innovations and non-cooperative innovations.

The development of GPTs seems to have depended on the combination of two or more sets of knowledge embodied in separate individuals. Large national economies with well-educated populations where information circulated easily would appear to have been favored – not only Britain, but also France and the United States. In each country, the half century following the transition from absolutism to representative institutions witnessed considerable GPT innovation, possibly because of a reduction in the social barriers to cooperation. The Protestant religion, in part because of its emphasis on education, also seems to have been an important factor in the development of the cooperation that gave rise to these GPTs.

Almost half of the remaining important innovations identified by economic historians also required cooperation. For these other cooperative innovations, there were very strong positive spillovers from the previous development of GPTs. Regions such as Birmingham and London and to a lesser extent, Paris and Philadelphia, that had earlier been able to develop GPTs had considerable success in generating other cooperative innovations. One possible explanation is the development of a local culture that favoured the sharing of information. The Protestant religion again seems to have been an important factor in the development of such cooperation.

As for the remaining category of innovations, classified as non-cooperative, the previous development of GPTs in the same region seems to have been of little benefit. Indeed, GPTs may even have had a negative effect on such innovation, perhaps by predisposing potential innovators with a high willingness to cooperate toward complex technologies that required the contribution of partners. Protestantism and language-network size were also significant positive factors. Even lone inventors were dependent on the rest of their society for the respect of contracts and property rights. In all types of innovations during the century and a half studied, access to low-cost energy in the form of coal seems to have made a significant contribution. Relative factor prices were thus important, but they were not the whole story.

Finally, there is scant support in these results for using focused industrial policies such as Britain's Calico Act of 1721 to generate innovation in a region. As mentioned, the key factors favouring the development of GPTs would seem to have been cultural, for example, religion or level of education and the size of the language network. Even if focused policies did manage to stimulate GPTs, there was no guarantee that the regions in which they appeared would be net beneficiaries of the spillovers that resulted. Although the Calico Acts were intended to protect the Midlands wool weavers, the principal long-run beneficiaries were undoubtedly Lancashire cotton mill owners.

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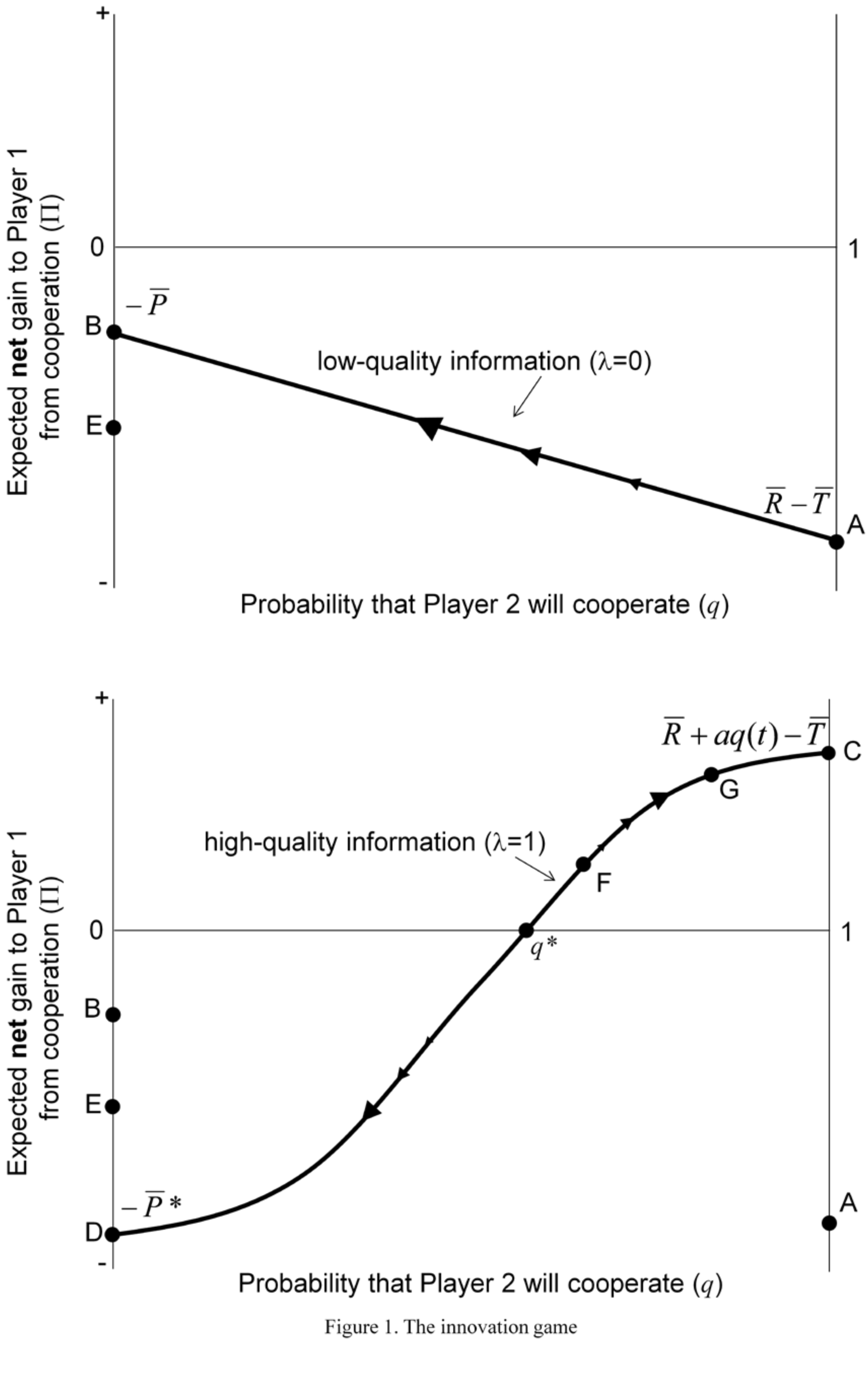

Figure 1. The innovation game

Table 1. Descriptive statistics

Period	Gr. Britain	France	USA	Germany	Italy	Others[a]	Total
General Purpose Technologies							
1700-1749	3	0	0	0	0	0	3
1750-1799	1	1	1	0	0	0	3
1800-1849	1	1	1	0	0	0	3
Sub-total	*5*	*2*	*2*	*0*	*0*	*0*	*9*
Other cooperative innovations							
1700-1749	1	0	0	0	0	0	1
1750-1799	19	3	1	0	0	0	23
1800-1849	19	3	5	0	0	0	27
Sub-total	*39*	*6*	*6*	*0*	*0*	*0*	*51*
Non-cooperative innovations							
1700-1749	6	2	0	1	0	0	9
1750-1799	14	7	1	1	0	2	25
1800-1849	13	5	2	0	1	1	22
Sub-total	*33*	*14*	*3*	*2*	*1*	*3*	*56*
All innovations							
1700-1749	10	2	0	1	0	0	13
1750-1799	34	11	3	1	0	2	51
1800-1849	33	9	8	0	1	1	52
Total	*77*	*22*	*11*	*2*	*1*	*3*	*116*
Cooperative innovations per million inhabitants at beginning of period							
1700-1749	*0.4*	*0*	*0*	*0*	*0*	*0*	*0.1*
1750-1799	*1.3*	*0.2*	*0.8*	*0*	*0*	*0*	*0.3*
1800-1849	*0.8*	*0.1*	*0.9*	*0*	*0*	*0*	*0.3*
Non-cooperative innovations per million inhabitants at beginning of period							
1700-1749	0.6	0.1	0	0.1	0	0	0.1
1750-1799	0.9	0.3	0.4	0.1	0	0.2	0.3
1800-1849	0.5	0.2	0.3	0	0.1	0.1	0.2
Total innovations per million inhabitants at beginning of period							
1700-1749	1.1	0.1	0	0.1	0	0	0.2
1750-1799	2.2	0.4	1.2	0.1	0	0.2	0.5
1800-1849	1.3	0.3	1.2	0	0.1	0.1	0.5

Sources: see section III (a) of text.

[a] Austria, Belgium, Denmark, Ireland, Netherlands, Switzerland.

Table 2. Zero-inflated Poisson regressions for all innovations, 1700-1850

Variable	(1) Precon-ditions	(2) Learning to cooperate	(3) Nested	(4) Nested with literacy
Poisson				
DumGBr	1.429*		0.240	1.570**
	(2.08)		*(0.40)*	*(3.41)*
Dum1750	1.055*	0.411	0.621	0.216
	(2.20)	*(0.80)*	*(1.28)*	*(0.43)*
Dum1800	0.641	-1.042*	-0.898	-1.245*
	(1.48)	*(1.91)*	*(1.33)*	*(1.79)*
City pop'n	3.173**	2.489**	3.468**	3.354**
	(4.35)	*(5.14)*	*(3.96)*	*(3.87)*
Coal	0.884*		0.793	0.760
	(2.09)		*(1.31)*	*(1.40)*
Port	-0.230		-0.529	-0.354
	(0.47)		*(1.00)*	*(0.75)*
Protestant		2.219**	2.310**	
		(3.61)	*(3.87)*	
Country pop'n		0.124**	0.130**	0.089**
		(6.09)	*(3.74)*	*(3.29)*
Revolution		0.263	0.769*	0.853*
		(0.53)	*(1.80)*	*(1.87)*
Lagged GPTs		0.609**	0.415**	0.505**
		(4.72)	*(3.05)*	*(3.50)*
Literacy				3.336**
				(2.82)
Constant	-2.025**	-4.301**	-5.115**	-4.703**
	(3.11)	*(4.84)*	*(5.25)*	*(4.97)*
Logit				
City pop'n	-38.4**	-48.2**	-60.8*	-52.9**
	(2.67)	*(2.67)*	*(2.05)*	*(2.47)*
Constant	2.190**	2.042**	1.870**	1.832**
	(3.96)	*(4.10)*	*(3.06)*	*(2.93)*
Log pseudo-likelihood	-198.7	-177.4	-167.5	-171.4

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; absolute value of *z*-statistics in parentheses.
Inflation regressions use constant and Country population.
* Coefficient significantly different from zero at 0.05 level, one-tailed test.
** Coefficient significantly different from zero at 0.01 level, one-tailed test.

Table 3. Zero-inflated Poisson regressions for innovations by type, 1700-1850

Dependent variable: number of innovations of type *i* in region of city *j* in period *t*.			
Variable	(1) GPTs	(2) Other cooperative	(3) Non-cooperative
Poisson			
DumGBr	-2.047	0.697	0.297
	(1.11)	*(0.74)*	*(0.45)*
Dum1750	0.795	1.340	0.535
	(0.71)	*(1.63)*	*(0.91)*
Dum1800	-3.283	-0.364	-0.223
	(1.31)	*(0.27)*	*(0.33)*
City pop'n	6.797*	3.156**	4.439**
	(1.98)	*(3.06)*	*(2.92)*
Coal	2.418*	1.188**	1.105*
	(1.89)	*(2.60)*	*(1.68)*
Port	-2.239	0.356	-0.570
	(1.63)	*(0.44)*	*(1.21)*
Protestant	5.770*	2.667**	1.653**
	(1.98)	*(3.11)*	*(2.40)*
Country pop'n	0.244**	0.227**	0.090**
	(2.37)	*(3.79)*	*(2.93)*
Revolution	2.938**	0.693	0.396
	(3.11)	*(1.04)*	*(0.78)*
Lagged GPTs	-0.459	1.015**	-1.323*
	(0.55)	*(3.59)*	*(1.72)*
Constant	-11.120**	-10.512**	-4.577**
	(3.10)	*(6.76)*	*(3.97)*
Logit			
City pop'n	-41.6*	-55.2	-39.0**
	(2.08)	*(1.45)*	*(2.54)*
Constant	2.630*	-0.491	1.649*
	(1.84)	*(0.13)*	*(1.96)*
Log pseudo-likelihood	-21.8	-63.9	-120.2
Non-zero obs.	7	22	31

Time-series cross-section of 201 cities for 1700-1749, 1750-1799 and 1800-1849.
Number of observations: 603.
Robust standard errors; absolute value of *z*-statistics in parentheses.
Inflation regressions use constant and Country population.

* Coefficient significantly different from zero at 0.05 level, one-tailed test.

** Coefficient significantly different from zero at 0.01 level, one-tailed test.

Appendix A. Learning to Cooperate

Consider a repeated coordination game with random pairing to develop an innovation. The normal-form game is presented in the following table, where the base values to the payoffs are $\overline{T} > \overline{R} > \overline{P} > \overline{S}$.

Player 2 Player 1	Cooperate	Defect
Cooperate	$R = \overline{R} + \lambda aq(t)$ $R = \overline{R} + \lambda aq(t)$	$T = \overline{T}$ $S = \overline{S}$
Defect	$S = \overline{S}$ $T = \overline{T}$	$P = \overline{P}$ $P = \overline{P}$

The expected Reward payoff from joint cooperation is assumed to take the form $R = \overline{R} + \lambda aq(t)$, where a is a positive scalar, λ measures the quality of information about third parties in the same region, with $0 \le \lambda \le 1$, and $q(t)$ is the proportion of these third parties who are expected to cooperate at time t.

(i) Melioration Learning

If either the quality of information, λ, or the propensity to cooperate, q, is very small, then we have the Prisoner's Dilemma game, discussed above. However, with technological change and learning, the possibility arises that a sufficient increase in λ and q could raise R above T, thereby converting the game from Prisoner's Dilemma to Assurance.

Let the moving-average component of the payoffs change in the following way:

$$q(t+1) = \sum_{i=0}^{m} \beta_i p_c(t-i), \qquad \beta_i > 0, \qquad \text{(A.1)}$$

where $p_c(t)$ is the percentage who cooperate at time t.

Under Herrnstein's (1991) melioration-learning hypothesis as specified by Brenner and Witt (2003), the probability that an agent cooperates changes according to the following equation:

$$p_c(t+1) = p_c(t) + p_c(t)\left[1 - p_c(t)\right]\phi\left[\Pi_c(c) - \Pi_d(t)\right], \tag{A.2}$$

where $\Pi_c(t)$ is the average payoff to cooperation in the recent past, $\Pi_d(t)$ is the average payoff to defection and the scalar, $\phi > 0$, is the rate at which people learn from experience.

Let the number of times the agent has cooperated in the recent past be represented by $k_c(t)$. On these occasions, assume that the other players cooperated $k_{cc}(t)$ times and defected $k_{cd}(t)$ times. The average payoff when the agent cooperated is then calculated as follows:

$$\Pi_c(t) = \frac{k_{cc}(t)}{k_c(t)}R + \frac{k_{cd}(t)}{k_c(t)}S\ , \tag{A.3}$$

where *R* and *S* are the Reward and Sucker payoffs respectively, as defined in the table above. Similarly, if on the $k_d(t)$ occasions that the agent defected in the past, the other players cooperated $k_{dc}(t)$ times and defected $k_{dd}(t)$ times, the average payoff to defection is calculated as:

$$\Pi_d(t) = \frac{k_{dc}(t)}{k_d(t)}T + \frac{k_{dd}(t)}{k_d(t)}P\,, \tag{A.4}$$

where *T* and *P* are the Temptation and Punishment payoffs respectively.

Now $k_{cc}/k_c = q = k_{dc}/k_d$ and $k_{cd}/k_c = 1 - q = k_{dd}/k_d$, where the time notation has been dropped for simplicity. Substituting from (A.3) and (A.4), we may then define the individual's expected *net* benefit from cooperation, Π, as

$$\Pi \equiv \Pi_c - \Pi_d = q(R-T) + (1-q)(S-P). \tag{A.5}$$

It remains now to show how individuals can be induced to cooperate with one another.

(ii) The Necessary Conditions for Innovation

Under what conditions will people be willing to cooperate in order to innovate? To answer this question, we must first explore the properties of the function that determines the net gain to a player if he cooperates rather than defecting, and then determine the values of this function under alternative values of the technological parameters.

Substitute the values of the payoffs from into the net-gain function, (A.5):

$$\Pi = q(\overline{R} + \lambda aq - \overline{T}) + (1-q)(\overline{S} - \overline{P}). \qquad \text{(A.6)}$$

The values of q for which $\Pi = 0$ are the roots of the equation,

$$\lambda aq^2 + q\left[(\overline{R} - \overline{T}) + (\overline{P} - \overline{S})\right] - (\overline{P} - \overline{S}) = 0 .$$

Let $\overline{Z} = (\overline{R} - \overline{T}) + (\overline{P} - \overline{S})$. Then these roots are:

$$q = \frac{-\overline{Z} \pm \sqrt{\overline{Z}^2 + 4\lambda a(\overline{P} - \overline{S})}}{2\lambda a}. \qquad \text{(A.7)}$$

If λ=0, (A.6) indicates that the expected gain, Π, is negative, as illustrated by the solid trajectory AB in Figure 1. In this Prisoner's Dilemma game, there is a unique steady-state equilibrium at B.

If λ>0, since $\overline{P} > \overline{S}$, one of the roots to (A.7) will be negative and the other positive. The latter is illustrated by the point q^* in Figure 1. If in the meantime $\overline{P}$ has risen to $\overline{P}^*$ because of increased cooperation in *other* regions, the result is the trajectory CD in Figure 1. Both C and D are steady-state equilibria for individual regions in this Assurance game.

Appendix B. 116 significant innovations[a], 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)	Automatic loom (Vaucanson, 1775) Single-action press (Didot, 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, 1790) Visual telegraph (Chappe, 1793) Vacuum sealing (Appert, 1795) Paper-making machine (Robert, 1803) Illuminating gas from wood (Lebon, 1799)	AUTOMATIC LOOM WITH PERFO-RATED CARDS (Jacquard, 1805) Wet spinning for flax (de Girard, 1815) Electromagnet (Arago, 1820) Water turbine (Burdin, 1824) Single-helix propeller (Sauvage, 1832) Three-color textile printing machine (Perrot, 1832) Water turbine with adjustable vanes (Fourneyron, 1837) Photograpy (Daguerre, 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, 1709) ATMOSPHERIC ENGINE (Newcomen, 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, 1738) Stereotyping (Ged, 1739) Lead-chamber process for sulphuric acid (Roebuck, 1746)	Crucible steel (Huntsman, 1750) Rib knitting attachment (Strutt, 1755) Achromatic refracting telescope (Dollond, 1757) Breast wheel (Smeaton, 1759) Bimetallic strip chronometer (Harrison, 1760) Spinning jenny (Hargreaves, 1764) Creamware pottery (Wedgewood, 1765) Cast-iron railroad (Reynolds, 1768) Engine using expansive steam operation (Watt 1769) Water frame (Arkwright, 1769) Efficient atmospheric steam engine (Smeaton, 1772) Dividing machine (Ramsden, 1773) Cylinder boring machine (Wilkinson, 1775) Carding machine (Arkwright, 1775) Condensing chamber for steam engine (Watt, 1776) Steam jacket for steam engine (Watt, 1776)	Machines for tackle block production (Brunel, 1800) Illuminating gas from coal (Murdock, 1802) Steam locomotive (Trevithick, 1804) Winding mechanism for loom (Radcliffe, 1805) Compound steam engine (Woolf, 1805) Arc lamp (Davy, 1807) Food canning (Durand, 1810) Rack locomotive (Blenkinson, 1811) Mechanical printing press (Koenig, 1813) Steam locomotive on flanged rails (Stephenson, 1814) Safety lamp (Davy, 1816) Circular knitting machine (M. I. Brunel, 1816) Planing machine (Roberts, 1817) Large metal lathe (Roberts, 1817) Gas meter (Clegg, 1819) Metal power loom (Roberts, 1822) Rubber fabric (Hancock, 1823)

		Spinning mule (Crompton, 1779) Reciprocating compound steam engine (Hornblower, 1781) Sun and planet gear (Watt, 1781) Indicator of steam engine power (Watt, 1782) Rolling mill (Cort, 1783) Cylinder printing press for calicoes (Bell, 1783) Jointed levers for parallel motion (Watt, 1784) Puddling (Cort, 1784) Power loom (Cartwright, 1785) Speed governor (Watt, 1787) Double-acting steam engine (Watt, 1787) Threshing machine (Meikle, 1788) Single-phase combing machine (Cartwright, 1789) LOCK-PRODUCTION MACHINES (Bramah, 1790) Single-action metal printing press (Stanhope, 1795) Hydraulic press (Bramah, 1796) High-pressure steam engine (Trevithick, 1797) Slide lathe (Maudslay, 1799)	Locomotive with fire-tube boiler (Stephenson, 1829) Hot blast furnace (Neilson, 1829) Self-acting mule (Roberts, 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,1838) Transatlantic steamer (I. K. Brunel, 1838) Assembly-line production (Bodmer, 1839) Multiple-blade propeller (Smith, 1839) Steam hammer (Nasmyth, 1842) Iron, propellor-driven steamship (I. K. Brunel, 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, 1784) Cotton gin (Whitney, 1793) Machine to cut and head nails (Perkins, 1795)	Single-engine steamboat (Fulton, 1807) Milling machine (North, 1818) Ring spinning machine (Thorp, 1828) INTERCHANGEABLE PARTS (North, 1828) Grain reaper (McCormick, 1832) Binary-code telegraph (Morse, 1845) Sewing machine (Howe, 1846) Rotary printing press (Hoe, 1847)

Sources: Daumas (1979), Cardwell (1972/1991), Mokyr (1990), Paulinyi (1989).
[a]General Purpose Technologies are capitalized; cooperative inventions are underlined.

Appendix C. 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