This is an Accepted Manuscript for Evolutionary Human Sciences. This version may be subject to change during the production process.
DOI: 10.1017/ehs.2023.6

Quantifying the Scientific Revolution

Benoît de Courson 1

Valentin Thouzeau 2

Nicolas Baumard 3

1 Max Planck Institute for the Study of Crime, Security and Law, Günterstalstraße 73, 79100 Freiburg, Germany

2 Ecole Normale Superieure, Departement d'Etudes Cognitives, Departement d'Etudes Cognitives, Paris, France

3 Ecole Normale Superieure, Departement d'Etudes Cognitives, Departement d'Etudes Cognitives, Paris, France

nbaumard@gmail.com, b.decourson@csl.mpg.de

Wordcount: 7460 words

Keywords: Cultural Evolution, History of Science, Digital Humanities, Economic Development

The Scientific Revolution represents a turning point in the history of humanity. In the space of a few decades, it transformed the nature of knowledge and the capacities of humankind (Cohen 2012; Mokyr 2016; Wootton 2015). "Without it," writes historian of science David Wootton, "there would have been no Industrial Revolution and none of the modern technologies on which we depend; human life would be drastically poorer and shorter and most of us would live lives of unremitting toil." (Wootton 2015).

A large number of explanations have been put forward to explain the origins of the Scientific Revolution (for a review, see (Cohen 1994)), from the belief in a divine legislator (Grant & Grant 1996; Needham 1981; Stark 2007) to the role of medieval universities (Grant & Grant 1996; Huff 2017) and from political freedom (Mokyr 2016; Needham 1981) to the invention of the printing press (Eisenstein 1980; Wootton 2015) So far, "there is no general agreement on what the Scientific Revolution is, why it happened – or even whether there was such a thing" (Wootton 2015).

This lack of consensus comes arguably at least in part from the absence of quantitative data: it is hard to rule in or out a candidate explanation with purely qualitative data. However, the growing size of online datasets makes it henceforth possible to estimate cultural production over time in science as well as in the arts (Fraiberger *et al.* 2018; Gergaud *et al.* 2017a; Schich *et al.* 2014; Serafinelli & Tabellini 2017; Sinatra *et al.* 2016). In particular, Wikipedia has become the largest database of biographies, and offers reliable and well-edited data on people's demographic features (gender, lifespan, nationalities), occupations and cultural production (Baumard *et al.* 2018; Gergaud *et al.* 2017b).

In this paper, we gathered the Wikipedia pages of all individuals classified as scientists during the early modern period: mathematicians, astronomers, physicists, biologists, naturalists, chemists, botanists, entomologists, and zoologists (see Table S1). Then, we estimate the scientific contribution of each of these 6620 individuals through different proxies (the size of the page, the number of translations in other languages and the number of Wikipedia pages containing a link to this page). With such a large dataset, we can go beyond key figures such as Newton and Galileo, and take into account the thousands of little-known individuals who contributed to the rise of science (see Table S1) Put otherwise, it allows us to incorporate not only the discovery of the law of gravitation or the moons of Jupiter, but also the hundreds of mathematical theorems and astronomical discoveries that paved the way for the major breakthroughs of the Scientific Revolution. All these information are associated with academic references (Mesgari *et al.* 2015; Nielsen 2007; Willinsky 2010).

In the burgeoning field of scientometrics, two foundational papers (King 2004; May 1997) have shown that the scientific production of modern countries over a period of time can be estimated by the quantity and the impact of the papers published by the scientific community of a country. Just as gross domestic product (GDP) is a measure of economic wealth, the average impact of a scientific paper could be used as a measure of the scientific wealth of nations (Adams 1998; Albarrán *et al.* 2010; Holmgren & Schnitzer 2004; King 2004; May 1997).

The aim of this paper is to build on these works, and extend their approach to the pre-modern period in order to better understand the origins of the Scientific Revolution. Counting publications and citations is obviously complicated for ancient periods. However, data sources like Wikipedia also carry an inherent estimate of a scientist's importance: the larger an individual's output, or the more important it is in the eyes of moderns, the higher we expect the Wikipedia indicators (page length, number of links pointing to that page, number of languages with a version of that page) to be (See Table S1). As such, these estimates are very similar to the modern scientometric evaluations of scientific productivity that are based on citations index (i.e. Science Citation Index, PubMed, Web of Science, Scopus, GoogleScholar) (Aksnes *et al.* 2019; Alonso *et al.* 2009; Archambault *et al.* 2009; Falagas *et al.* 2008; Harzing & Alakangas 2016; Mongeon & Paul-Hus 2016). Indeed, the more important a scientist's contribution is, the more pages of later generations of scientists in Wikipedia will link to this page (for example, many pages of evolutionary biologists link to Darwin's page). Thus, we used Wikipedia's estimate of the importance of scientific contributions to create aggregate estimation of scientific production of countries over time (see Figures S1 and S2). Note that, throughout the article, we use modern borders to define geographical areas of interest. This is a standard method in economic history for estimates of population size, GDP and urbanization (see for instance (Bosker *et al.* 2013; Broadberry *et al.* 2015; McEvedy *et al.* 1978).

Estimates based on Wikipedia are the product of thousands of editors, using tens of thousands of academic references. Thus, they provide the most neutral estimate of the current consensus in the history of science about the importance of a specific scientific contribution. For instance, the page for Galileo has been edited by 2931 different editors (excluding bots) since its creation in 2001. Even the pages of minor figures such as Jean de Hautefeuille (1646-1724, French physicist), Thomas Johnson (1595 – 1644, English botanist) or Joachim Jungius (1597-1657, German mathematician) have been edited by more than 30 different contributors.

Another advantage of Wikipedia is that the database has not been built with a particular hypothesis in mind. For instance, for each individual, Wikipedia provides one or several "occupations" (writer, painter, theologian, etc.). This label allows us to distinguish between individuals who truly contributed to science (e.g. Newton) and those who merely commented on or recorded the advances of science (e.g. Roger Bacon, Thomas Huxley) without biasing the sample. Importantly, these choices were not influenced by the goal of this study.

Obviously, just as modern estimates (Aksnes *et al.* 2019; Alonso *et al.* 2009), an estimate based on Wikipedia has its advantages and its drawbacks (see below). For instance, in Wikipedia, some very notable people such as Goethe are included in lists of scientists because of their scientific contributions (although these are marginal in regard to their non-scientific contributions). It could thus be the case that the results were biased by these non-scientific celebrities. In an additional analysis, we only included individuals whose primary occupation as listed on their Wikidata item page was as a scientist (in one of the categories specified above). This did not substantially change the pattern (see Fig. S7).

Another bias of Wikipedia is that the scientific contributions of the English are probably overestimated due to the size of the English-speaking community both in American history of science and among Wikipedia contributors (Callahan & Herring 2011; Gergaud *et al.*

2017a). Given the current size and influence of American and other English-language communities of historians of science compared to French-, German- or Italian-speaking communities, it could be the case that scientific contributions made by English people have been overestimated, because they are more easily accessible to English-speaking historians than the scientific contributions made in other languages. To counteract this potential bias, we used the three Wikipedias (English, German and French) whose Wikipedia communities had established lists of writers, scientists, and artists by century and nationality (in line with (Gergaud *et al.* 2017a)). Combining Wikipedia entries from several different languages allows us to limit anglocentric bias. We also carried out a control analysis without the English Wikipedia. Including or excluding the English Wikipedia does not change the results (see Fig. S10).

Although national contribution to world science is clearly an important indicator, it is crucial to compare scientific outputs relative to population (King 2004; May 1997). Today, for instance, the U.S., China, Japan and the U.K. are prominent contributors to world science. Yet, the size of their population hides the fact that some countries such as the Scandinavian countries, Israel, and Switzerland are in fact more productive than the great scientific nations (King 2004; May 1997). In the same way, it is usual to consider that, in the modern period, Italy (with Galileo and Torricelli), England (with Newton and Boyle) and France (with Pascal and Descartes) were more or less equally productive scientifically (see Figure S2). But this assessment overlooks the fact that in 1650, France had 16 million people, Italy 12 million, and England only 3 million. In other words, for England to contribute as much to the Scientific Revolution, it had to be much more productive than France or Italy. Current qualitative estimates of total national productivity fail to capture the differential of productivity between Italy, England and France.

In this paper, we explore the role of economic development, an important factor in cultural evolution (Baumard 2017; Inglehart 2018; Welzel 2014) that has been relatively neglected in the history of the Scientific Revolution (Cohen 1994). One of the reasons for the relative neglect is that it has long been thought that economic development was stagnant before the Industrial Revolution (Clark 2008) However, recent works in economic history have demonstrated that North-Western Europeans, and English people in particular, enjoyed an unprecedented level of living standard from the 17th century onward (Fouquet & Broadberry 2015). English people were richer, healthier, taller, better nourished and better equipped than individuals in any previous society (Allen *et al.* 2011; Cummins 2014; Fouquet & Broadberry 2015; Morris 2013).

Economic development might be crucial for the cultural evolution of science. First, quantitative works on modern countries have demonstrated that GDP per capita is strongly correlated with scientific productivity (Allik *et al.* 2013; Grossetti *et al.* 2014; King 2004; Meo *et al.* 2013; Vinkler 2008). Second, recent advances in behavioral and social sciences has shown that affluence has predictable effects on human psychology, risk-taking, exploration and creativity (for a recent review, see (Haushofer & Fehr 2014; Pepper & Nettle 2017), and can alter the dynamics of cultural evolution (André & Baumard 2020; Baumard *et al.* 2015; Inglehart 2018). Basically, when humans have met their basic needs for survival, they can turn to more long-term oriented goals such as learning and exploration (Maslow 1943). In line with this idea, research inspired by life-history theory has shown that in a harsh environment, when the levels of available resources are low and unpredictable, individuals tend to be more short term-oriented, less exploratory and more conservative because exploration is both risky and costly. By contrast, in a resource-rich environment, individuals are future-oriented, more exploratory and more open-minded because they have more resources to cope with the inherent costs of exploration and learning (Haushofer & Fehr 2014; Jacquet *et al.* 2019; Pepper & Nettle 2017). Since science relies heavily on exploration, this predicts that a higher level of resources should be associated with a higher level of scientific creativity (Baumard 2018). This prediction contrasts with a common assumption in cultural evolution according to which population size is crucial in explaining creativity (Collard *et al.* 2013; Henrich 2004; Kremer 1993; Shennan 2001).

Interestingly, this behavioral framework makes further predictions (Baumard 2018). First, scientific creativity should be associated with artistic creativity, because both science and the arts rely on exploration. Second, inclusive (Robinson & Acemoglu 2012), more democratic institutions are also likely to be associated with scientific creativity because trust is a long-term investment and democratic institutions require a high level of trust. In fact, a growing body of works both in political science (Abramson & Boix 2014; Boix & Stokes 2003) and in the behavioral sciences (Hörl *et al.* 2016; Petersen & Aarøe 2015; Safra *et al.* 2017) suggests that better life conditions are associated with higher level of interpersonal trust and higher support for inclusive institutions.

Results

The Evolution of Scientific Production

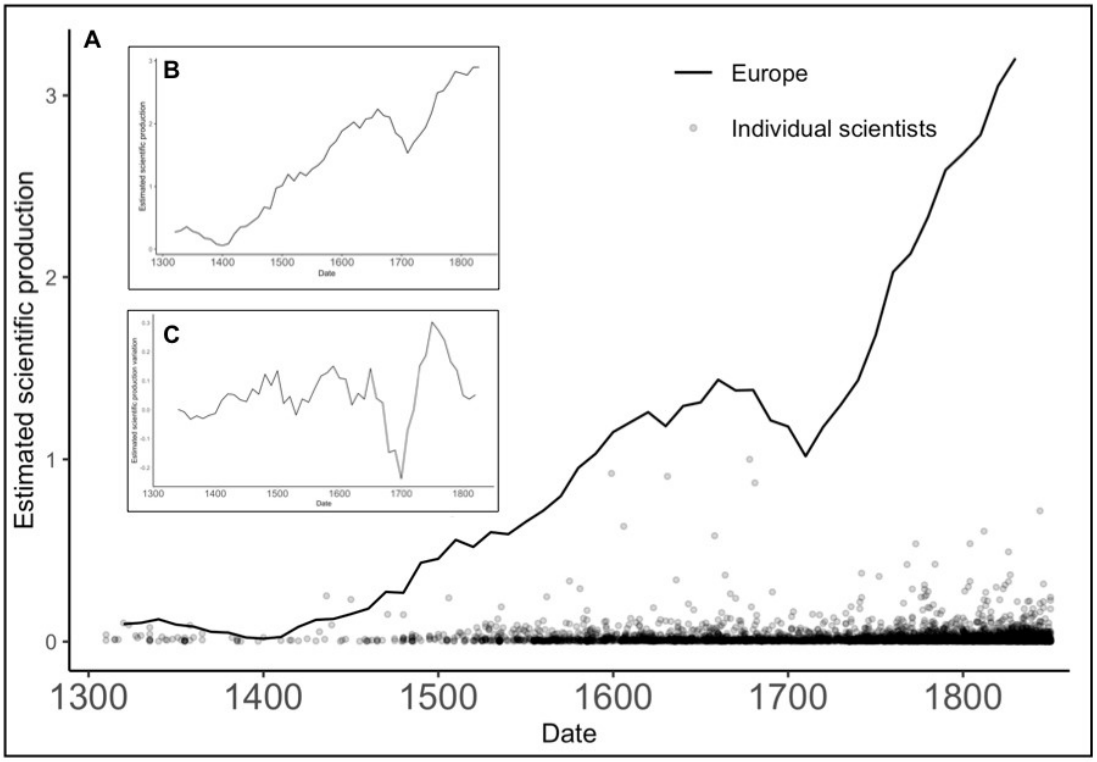

Figure 1 here

Our estimates show an increase of scientific production in Europe during the period 1300 - 1850, except for a period of crisis from 1690 to 1730 (see Fig. 1A). Interestingly, the increase in scientific production does not seem to be higher during the 17th century than during the period before and after the Scientific Revolution. Our estimates also show an increase in scientific production per capita, suggesting that the European population becomes more productive over time (see Fig B). In both cases, the growth rate in production and production per capita is regular over the period, except for a period of crisis at the end of the 17th century (see Fig. 1C for growth rate in per capita production). Overall, this suggests that the scientific revolution corresponds less to an acceleration of science than to an accumulation of discoveries until a point during the 17th century when scholars began to realize that they had reached a level of knowledge unprecedented in human history (Wootton 2015).

We now partition the scientific production into countries. Just like for modern science (King 2004; May 1997), this analysis reveals striking differences between countries, with four countries (Italy, Germany, the United Kingdom and France) accounting for over 80 per cent of the European production (see Fig. 2). Although these countries dominate the scientific production in all disciplines, there are slight differences between countries. For instance, compared to other countries, France has a larger share in mathematics than in physics and biology (see Fig panels B, C and D). Since France still has a larger share in mathematics today (King 2004; May 1997), this reveals the existence of very long national scientific traditions.

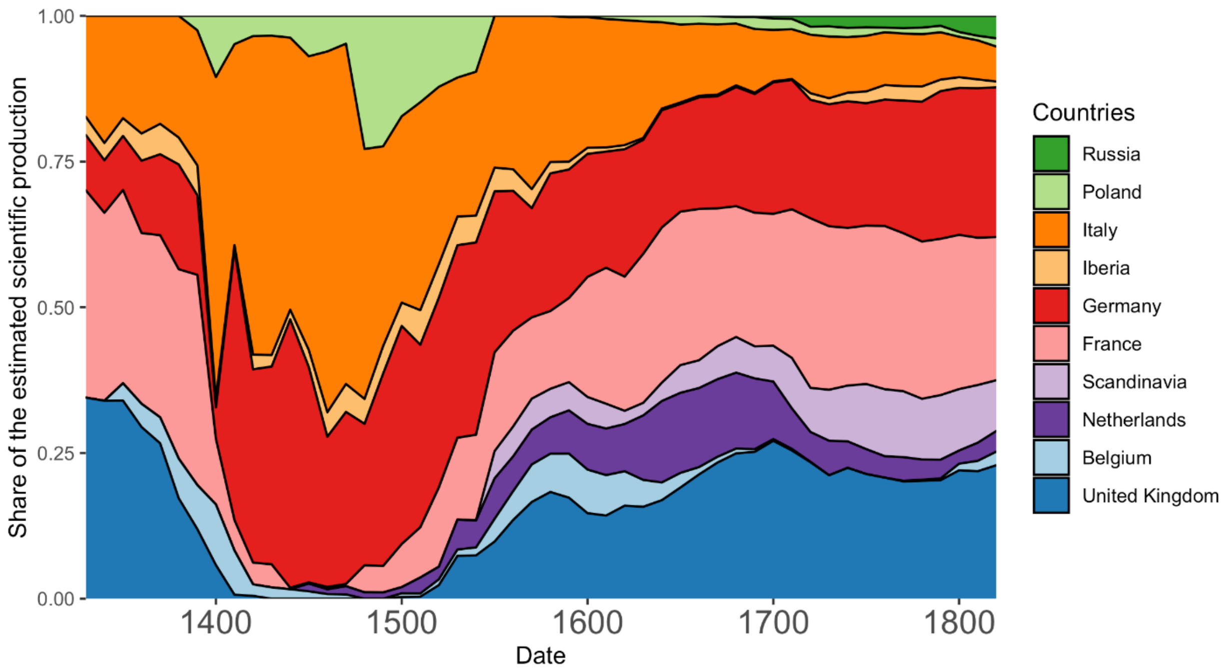

Figure 2 here

Per Capita National Scientific Production

We calculated estimates of per capita National Scientific Production in different countries (see Fig. 3) with the Netherlands leading in the 17th century, followed by England in the 18th century. During the Scientific Revolution, these countries were much more productive than Germany, France or Italy on a per capita basis. It is worth nothing that the high

https://doi.org/10.1017/ehs.2023.6 Published online by Cambridge University Press

productivity of the Netherlands is visible both across indices (bytes, languages, quotations) and across Wikipedia languages (see Fig. S3). During their Golden Age, the Dutch were more productive than the rest of Europe regardless of the choice of indicator. This is also the case for England in the 18th century, with the exception of two of the German indicators.

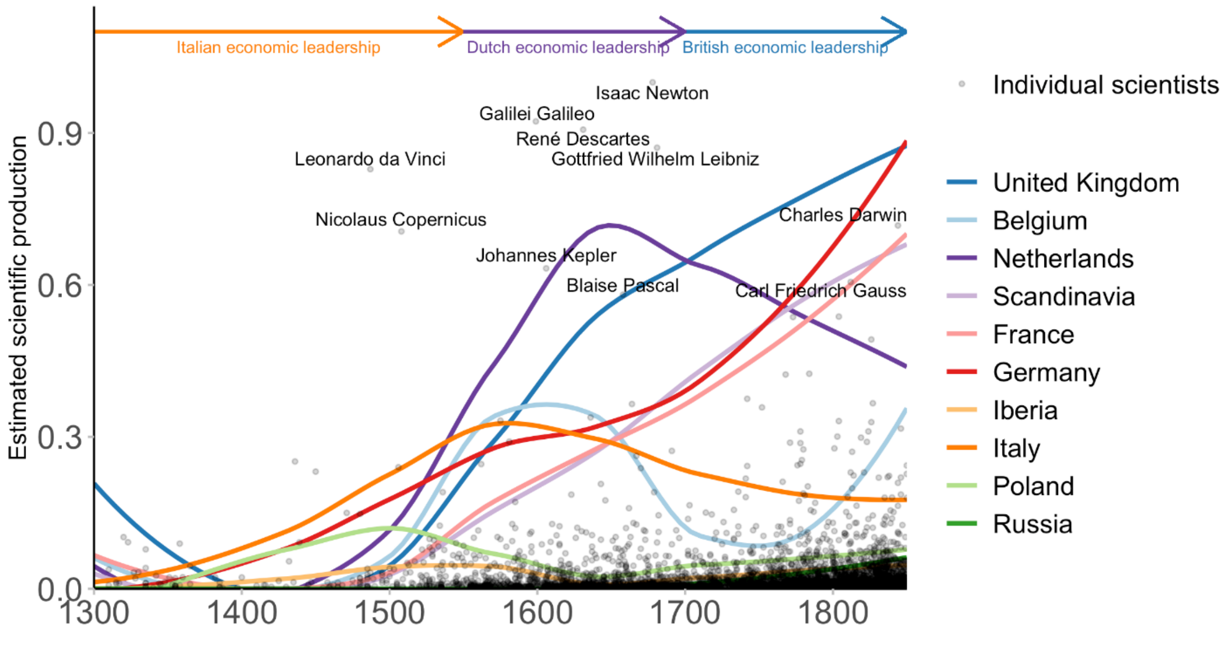

Figure 3 here

These results are in keeping with more qualitative modern assessments by historians of science (Rossi 2001; Wootton 2015). The relative decline of Italy is also visible from the early 17th century on, starting during Galileo's lifetime. The late rise of Germany's scientific productivity is also visible, and foreshadows the success of German science in physics, technology and chemistry at the end of the 19th century. Finally, although Scandinavia remained a small player during the early modern period due to its small population size, it was among the most productive countries from 1700 onward. The same trends are also visible in the spatial distribution of scientists. As Fig. 4 shows, scientific production was extremely concentrated in the most dynamic cities (Rome, London, Paris, Amsterdam, Florence and Venice) and shifted toward the North-West during the 17th and 18th c.

The picture painted by these results differs considerably from the one derived from national totals (see Fig. S2). National estimates are distorted by the population size of countries. If we were to use them in 2021, they would highlight the production of China rather than Switzerland or Singapore. Another important take-home message from these results is that scientific productivity is highly variable from one period to the other. For instance, the Netherlands are much less productive in the 16th and 18th century than during their Golden Age (17th). Similar observations could be made about all the main players of the Scientific Revolution. This suggests that there are no permanent "national traits", no countries that are intrinsically more scientific than others, but rather transient factors of scientific productivity.

We hypothesized that the results might be biased either by the top scientists (Newton, Huygens, etc.) or by the bottom scientists (the unknown 90%). Since the English Wikipedia is bigger than the French and German Wikipedia, this might lead to more English top scientists (because they are more visible, and have more translations) or more English bottom scientists (because there are more editors, which translate into a higher number of pages). To find out whether this was the case, we performed the same analysis for the top 10% of scientists and for the bottom 90%. We found that the pattern remained very similar in both cases (see Figs. S4 and S5), in line with similar studies on contemporary countries (King 2004).

Another potential bias is due to the fact that England and the Netherlands are smaller than Italy, France and Germany. It could thus be the case that their high productivity was due to the fact that similarly highly productive areas in France (such as Ile-de-France) or Italy (such as Tuscany) were drowned within bigger areas. To account for this possibility, we combined England, Scotland, Wales, Ireland, the Netherlands and Belgium into a larger unit as “northwestern Europe”, with a combined population of 12.5 million people in 1700 (compared to 22 million for France, 13 million for Germany, and 13 million for Italy). The pattern, although less spectacular, is substantially similar: Northwestern Europe comes out as the scientific leader from 1500 to 1800 (see Fig. S6).

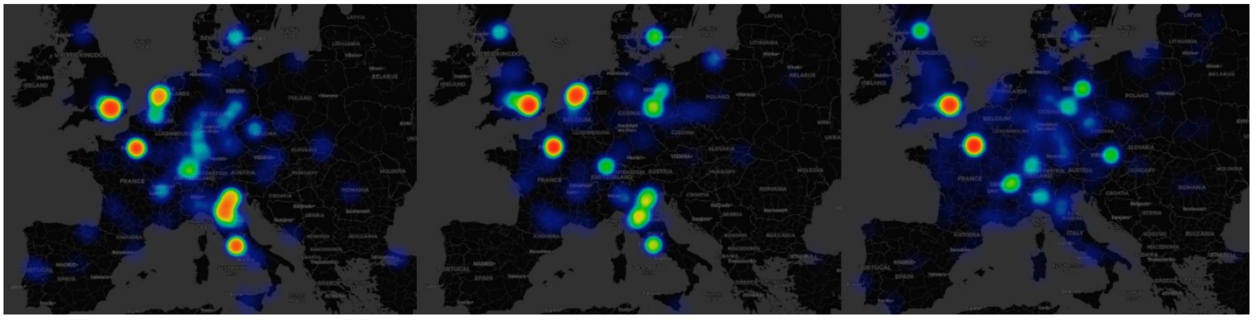

Figure 4 here

Another potential bias is that, in Wikipedia, some very notable people such as Goethe are included in lists of scientists because of their scientific contributions (although these are marginal in regard to their non-scientific contributions). It could thus be the case that the results were biased by these non-scientific celebrities. In an additional analysis, we only included individuals whose primary occupation as listed on their Wikidata item page was as a scientist (in one of the categories specified above). This did not substantially change the pattern (see Fig. S7).

Scientific productivity and economic development

Our results suggest that economic development and living standards are key to explaining scientific productivity, in line with similar studies on contemporary countries (Allik *et al.* 2013; Grossetti *et al.* 2014; King 2004; Meo *et al.* 2013; Vinkler 2008). To further investigate this relationship, we tested the association between scientific production and two proxies for living standards: GDP per capita and urbanization rate. To investigate the link between environmental variables and scientific production, we built autoregressive linear mixed models using the `R` package `spaMM` (Rousset 2017), whose results are displayed in Table 1. The dependent variable is the scientific production per capita, measured for each country each 50 year (to avoid any overlap between the datapoints). The scientific production values being overdispersed, we applied a logarithmic transformation. Each model has two fixed effect. First, the one mentioned in the columns, whose coefficient and associated p-value figured in Table 1 (population, GDP per capita, urbanization, number of universities per capita). Second, we added the date as a covariate to (1) control for a potential historiographic bias, overstating the scientific production in the latest studied period because of the abundance of sources, and (2) to avoid a spurious correlation between affluence and scientific production, due to the fact that both affluence and scientific production tend to increase with time. We added the country as an autoregressive random effect, to account for the fact two data points coming from the same country are not independent, in particular when they represent two consecutive time steps.

The results show a strong association between per capita scientific production, per capita GDP and urbanization. Remarkably, the period of Italian, Dutch and English domination matches their period of maximum affluence during the studied period (i.e. the period during which their GDP per capita was over $1,500 and their economic activity was growing, see Fig. 3). Our dataset also allows for exploring alternative hypotheses, although better data would be required to test these hypotheses properly. We first considered the role of printing. Printing has often been cited as a cause of the Scientific Revolution, as it allows for better communication between scientists (Eisenstein 1980; Febvre & Martin 1997; Wootton 2015). Although the increase in scientific productivity coincides roughly with the invention and diffusion of printing in Europe, it is notable that the invention of the printing press does not lead to the acceleration of scientific production. This result is in line with what can be observed outside Europe. For instance, the diffusion of printed books did not drastically change China's scientific productivity during the Tang dynasty (Xu 2017), or that of the Ottoman Empire in the 17th century (Coşgel *et al.* 2012). By contrast, it is worth noting that Ancient Greece achieved a level of productivity often deemed similar to that of early modern Europe despite the absence of printing (Leroi 2014; Russo 2013).

We also examined the impact of universities. Medieval universities are often seen as an institutional innovation, acting as a driver of scientific improvement (Grant & Grant 1996; Huff 2017). This hypothesis is particularly favored when comparing European institutions of higher education and scholarship with their equivalents in Muslim, Indian and Chinese societies (Grant & Grant 1996; Huff 2017). Moreover, it is true that the timing of the take-off of European science matches the creation of the major European universities (Bologna, Paris, Oxford). To test this hypothesis, we extended our study to the medieval period (500 – 1500). We found no significant association between scientific productivity and number of universities, suggesting that universities did not in fact play an important role in the Scientific Revolution (see Table 1).

One important hypothesis in cultural evolution is that the probability of innovations being discovered and maintained through social learning is greater in large populations than in small ones (Collard *et al.* 2013; Henrich 2004; Kremer 1993; Shennan 2001; Vaesen *et al.* 2016). Our results, however, suggest that, at least in science, population size does not play an important role in explaining per capita scientific productivity. Small societies such as England, Holland and Scotland, despite their limited population, were much more innovative than larger societies such as France, Italy or Russia (see Table 1). This suggests that creativity is more important in determining the pace of cultural evolution than has been previously thought (André & Baumard 2019; Fogarty *et al.* 2017).

	Pop.	GDP pc	Urbanization. rate	Universities pc	Parliament	Protestant
scientists	-.02	.31 **	.16	.05	.42 ***	.47 ***
composers	-.03	.22	-.11	-.09	.12	.33 *
painters	-.04	.46 ***	.68 ***	.33 *	.13	0

https://doi.org/10.1017/ehs.2023.6 Published online by Cambridge University Press

	Pop.	GDP pc	Urbani-zation. rate	Universi-ties pc	Parlia-ment	Protesta nt
philoso-phers	.06	.17	.29 .	.24	.14	.08
writers	.05	.19	.23	.12	.23	.19
sculptors	.16	.45 **	.42 *	.24	-.04	-.14
all	-.03	.44 ***	.48 ***	.23 .	.31 *	.17

Table 1: Associations between environmental variables and cultural productions. Each cell represents a different model, with the row indicating the dependent variable and the column the independent one. We report the regression coefficient, and the p-value of a t-test: $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

A common creativity factor

Recent work in behavioral sciences has shown that innovation and creativity are strongly associated with affluence, whereas harsh and unpredictable environments lead to informational conformism, the tendency to defer to others' judgments (Baumard 2018; Inglehart & Welzel 2005; Jacquet *et al.* 2018; Nettle 2018). This behavioral approach to creativity suggests that individuals in affluent environments should be more innovative in science, but also in all kinds of activities, because the trade-offs between exploration and social learning are similar (Baumard 2018). We therefore look at other kind of creative activities, such as literature, philosophy, painting, sculpture and music, and build a general per capita "Cultural Domestic Product". In this index, scientists account for a small minority of the sample (19.9%), compared to painters (32.9%), writers (29.8%) and musicians (14.4%) (see Table S1). The pattern for cultural production is strikingly similar to the pattern of scientific production, with the Netherlands and then Britain leading (see Fig. 5). This suggests a common general cause - a "culture of growth" (Mokyr 2016) - behind this high level of scientific, literary, and artistic production.

https://doi.org/10.1017/ehs.2023.6 Published online by Cambridge University Press

We also look at the correlation between artistic production and living standards using an analogous method. The results reveal a strong association between per capita cultural production and per capita GDP, urbanization (see Table 1). Finally, to test the prediction that all forms of cultural productions are associated to a common underlying creativity factor, we used the same autoregressive linear mixed models to measure how much the cultural productions predict one another, while controlling for time and country (see Table [tab:5]).

To test the association with inclusive institutions, we used the the number of calendar years per century in which for the various areas a parliament (or estates-general, cortes, corts, diet, sejm, riksdag, Generallandtag, or Reichstag) assembled for official sessions during shorter or longer periods in a year (Van Zanden *et al.* 2012). In line with the life-history framework, our results show a strong association between per capita scientific production and the activity of parliaments.

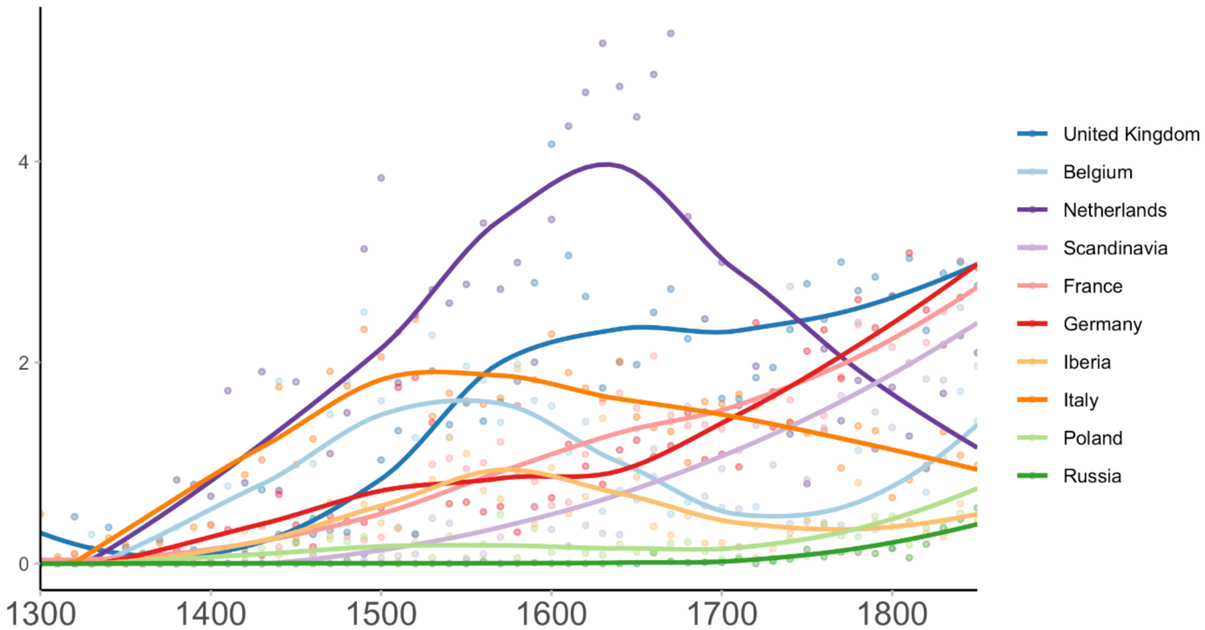

Figure 5 here

	scientists	composers	painters	philosophers	sculptors	writers
scientists		0.12	0.39 ***	0.59 ***	0.28 *	0.57 ***

https://doi.org/10.1017/ehs.2023.6 Published online by Cambridge University Press

	scientists	composers	painters	philosophers	sculptors	writers
composers	0.1		-0.07	0.01	-0.01	0.1
painters	0.46 ***	-0.07		0.71 ***	0.68 ***	0.56 ***
philosophers	0.25 **	-0.11	0.36 ***		0.22 *	0.48 ***
sculptors	0.11	-0.02	0.35 ***	0.25 *		0.22 **
writers	0.58 ***	0.11	0.51 ***	0.83 ***	0.4 **	

Table 2: Associations between the different cultural productions

Modelling the role of economic development in the cultural evolution of science

We further investigate the importance of economic development by systematically studying the role of economic development and cultural transmission in a series of models. At first sight, cultural transmission should be key in explaining the variation in scientific productivity. Science is a cumulative process (Mesoudi 2011; Mesoudi & Thornton 2018). As Bernard of Chartres (and Newton after him) famously said, scientists "stand on the shoulders of giants". Yet, the history of science shows that the cultural transmission of science from one period to the other, or from one region to the other is not automatic. The Europeans inherited the Greek and the Arab science, but with few exceptions, they did not really start being scientifically productive before the 16th century. In the same way, while Spain and Portugal were culturally close to France and Italy, they played a very limited role during the Scientific Revolution. These observations suggests that while the 'Republic of Letters' was an important proximate cause, it might not be the ultimate factor in explaining the rise of science in Early modern Europe.

Modelling the process of cultural transmission is particularly complex. For example, a region that produces a lot of scientific knowledge at a given time may lead a neighboring region to produce a little more. This second region may in turn influence the scientific production of the first region by feedback. Also, economic development is likely to influence both the level of production, and the level of learning because higher economic development is associated with more investment in human capital and communication technology.

It therefore seems difficult to reconstruct the evolution of scientific production with simple statistical models. However, there are statistical inference methods, developed primarily in population biology, which allow us to study non-linear phenomena at the population level, including random processes and interactions between spatially distributed populations over time (see for instance (Stocks *et al.* 2020). This method is particularly well suited to the study of the evolution of scientific productivity, since the productivity of a region of the world is likely to depend both on its own past productivity (e.g. through the knowledge stored in books) as well as on the output of neighboring regions (e.g. through the diffusion of books from one country to its neighbours.

In terms of statistical properties, the data points we study are neither temporally independent (a country's scientific production at some time might depend on his own earlier production), nor spatially independent (the Netherlands' scientific production might have influenced Belgium's, for instance). This means that to account for our data, a model should allow for (i) autocorrelation, (ii) vertical diffusion (from one period to the next, within the same country) and (iii) horizontal diffusion (influence of two neighbouring countries on each other). Besides, the fat-tailed nature of the data makes gaussian statistics unsuitable.

Several non-exclusive hypotheses can be proposed to explain its dynamics: a productivity based on random phenomenon (1), a productivity based on the recent production of science in the region (2), a productivity influenced by economic development (3), a productivity influenced by the past production of science in the region (4), a productivity influenced by the recent production of science in neighboring regions (5), a productivity influenced by the past production of science in neighboring regions (6), an influence of other regions mediated by economic development (7). We constructed 11 models with different combinations of hypotheses 1 to 7, to represent the dynamics of cultural productivity over time (see Fig. S11), in order to determine the most credible hypotheses to explain the data using Markov chain methods ((King *et al.* 2016). The method and the results are described more thoroughly in the Supplementary Materials. A very large number of models can be proposed, and we have chosen to evaluate only a subset of the plausible combinations of processes responsible for scientific production, focusing on the potential role of the GDP on scientific production.

To evaluate best models the history of science, we use two indicators: model comparison using AIC and BIC (Table 2), and, when applicable (i.e., for nested models), hypothesis testing by a likelihood ratio test (Table S4). All methods yield the same picture. In Table 2, we also report the scaled estimated effect of the covariates for all the models.

In these models, economic development is the only variable which helps to explain the scientific production data. Our results reject the idea that horizontal diffusion is an important parameter in explaining scientific productivity during the early modern period: if added alone, its impact is estimated to be much lower than GDP per capita (.025 vs .07), and when added alongside GDP per capita, its effect disappears (Table 2). In both cases, the addition of horizontal diffusion to the model increases AIC and BIC (Table 2), and fails to reject the simpler model in log-likelihood tests (D vs B: $p = .50$, E vs C: $p = .86$). Similarly, the cumulative production over the entire past (the variable Cum) does not helps to account for scientific production (Italy after the 17th c. is a case in point). Knowing only the productivity in the immediately preceding time interval and the GDP per capita seems to be the best way to predict scientific production, in our sample.

From these results, one should not conclude that the transmission of information was not important during the scientific revolution and that the exchange of ideas was useless, but rather that doing science probably requires a certain level of economic development. This would explain why, despite their proximity to Germany and the influence of the German culture, Poland and Hungary did not develop vibrant scientific communities until the 19th century and their economic take-off (Bukowski *et al.* 2019). In the same way, this would explain why, after a flourishing period of scientific production (e.g. Galileo, Toricelli and Malpighi) the Italian scientific production declined after the mid-17th c. in parallel to the stagnation of the Italian economy (Malanima 2011). Thus while the 'Republic of letters' was possibly important during the early modern period, our results suggest that economic development is a key cause of scientific productivity.

	GDPpc	Diff	GDPpc *Diff	Cum	GDPpc *Cum	Cum_diff	AIC	BIC
A							304.8	321.4
B							148.9	168.3
C	0.07						136.9	159.1
D				0.09			150	172.1
E	0.074				0.004		138.9	163.8
F		0.025					148.7	170.9
G	0.065	0.009					138.6	163.5

	GDPpc	Diff	GDPpc *Diff	Cum	GDPpc *Cum	Cum_d iff	AIC	BIC
H			0.042				148.4	170.6
I	0.068		0.013				138.5	163.4
J						0.029	145.9	165.3
K	0.086	-0.087	-0.067	-0.237	-0.1	0.184	138.8	172

Table 3: Scaled coefficients for covariates of the Pomp models, and information criterions for these models. "Diff" stands for horizontal diffusion (the sum of productions of neighbouring countries divided by the squares distance between capital cities). "Cum" stands for the cumulative estimated scientific production of a country before that time – i.e. vertical diffusion. "Cum_diff" stands for the cumulative horizontal diffusion. The models A and B are excluded, as they use no covariate. The coefficients of model K are difficult to interpret, some covariates like horizontal diffusion having a negative effect. This is due to high covariance between covariates, especially when interactions are included.

Ancient and medieval science

Finally, our study focused on early modern Europe. However, scientific production has been important in other societies as well, in particular in Ancient Greece and in the Arab and Persian worlds. Recent works in economic history suggests that these periods in these places were also characterized by increasing living standards (Morris 2013; Ober 2015; Özmucur & Pamuk 2002). We thus wanted to test whether the association between affluence and scientific production holds for non-European societies, and whether increased prosperity could explain the rise of science during the ancient and medieval periods.

During the medieval period (500 - 1500 CE), the most productive area was the Muslim world (see Fig. 6). The Muslim area not only transmitted the Greek advances but also improved them in many ways and foreshadowed the development of the Western science (Chaney 2018; Cohen 2012; Huff 2017; Rashed 2002; Starr 2013). Important examples of improvements are al-Khwarizmi's contribution to algebra and geometry, Ibn al-Haythan's theory of vision or Ibn Sahl's discovery of the law of refraction. Possibly the clearest evidence in favor of the advancement of science in the Muslim world is astronomy, in which there was a clear sense of progress, from the early criticisms of the Ptolemaic system by Ibn al-Haytham in the 11th. c to the creation of new mathematical models by al-Bitruji (d. 1204), al-'Urdi (d. 1266), al-Tusi (d. 1274), Qutb al-Din al-Shirazi (d. 1311) and Ibn al-Shatir (d. 1375) which were mathematically equivalent to the ones proposed by Copernicus a century and half later. This very high level of productivity is consistent with the higher level of urbanization, GDP per capita and energy capture of the Muslim world during the period 700-1400 (Bosker *et al.* 2013; Morris 2013; Pamuk & Shatzmiller 2014).

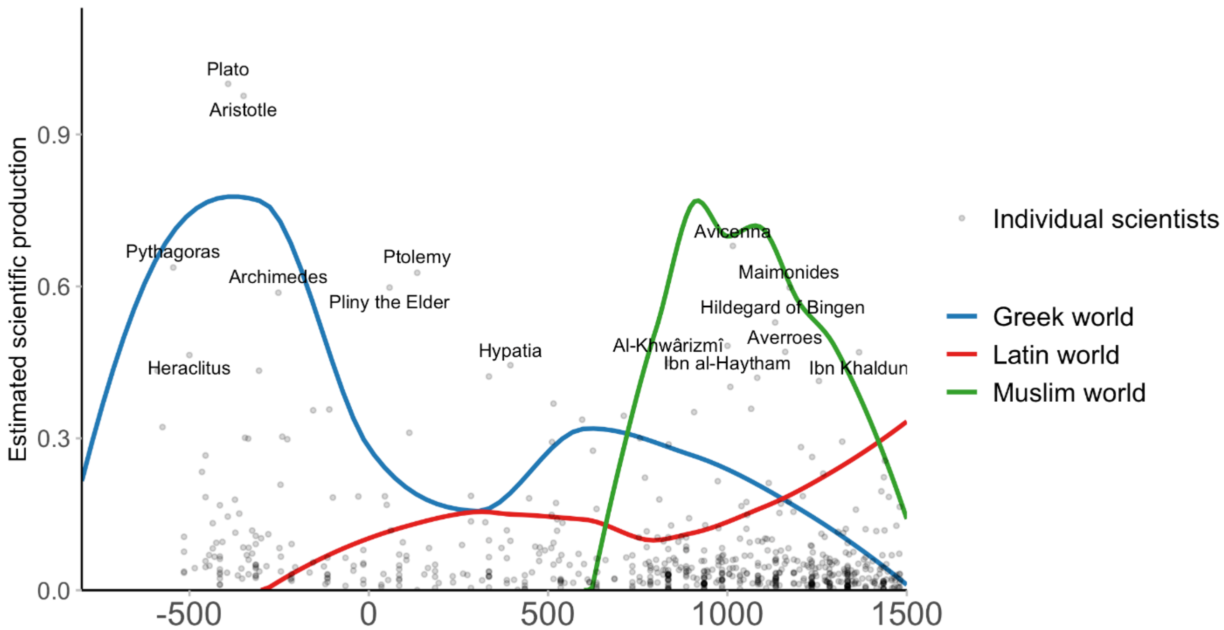

Figure 6 here

Our results also shed light on the decline of the Muslim science. In 1350, the Muslim science was about to reach the level Western scientists reached during the Scientific Revolution (in particular in astronomy with Al-Tusi). Yet, not only did progress stop but also scientific production almost disappeared totally (Chaney 2018; Cohen 2012; Huff 2017; Rashed 2002; Starr 2013). As historians of Muslim science Sabra writes: "It is precisely the high quality and sophisticated content of Islamic science that give poignancy to the problem of decline. The question is not why the efforts of Islamic scientists did not produce 'the scientific revolution' (…) but why their work declined and eventually ceased to develop after the impressive flowering of the earlier centuries. Why, for instance, did algebra fail to make significant progress after the twelfth century? Why was the work of Ibn al-Haytham and Kamal al-Din in experimental optics not continued along lines drawn by these two mathematicians?"

Our results confirm these qualitative assessments (see Figure [fig:antiquity]). Muslim countries reached a peak c. 1000 but started to decline very early on, c. 1150. Importantly, this is unlikely to be due to a measurement problem, as the most productive period is also the most ancient period.

In line with our main hypothesis, it must be noted that the decline of the Muslim science parallels the economic decline of the Muslim countries. From the 11th c. on, urbanization and GDP per capita started to decline (Bosker *et al.* 2013; Morris 2013; Pamuk & Shatzmiller 2014), in particular because of environmental problems associated with a dry and difficult environment (Allen & Heldring 2021; Montgomery 2012; Ponting 2007). In Iraq for instance, arguably the most affluent part of the Muslim world and the central hub of the scientific culture, GDP per capita decreased from 1400 in 720 to 900 in 1400 (Bosker *et al.* 2013; Morris 2013; Pamuk & Shatzmiller 2014; Van Bavel *et al.* 2018). This probably also contributed to the weakening of the Islamic institutions. After the 12th c., the average ruler duration started to decrease in the Muslim world (while it was increasing in Europe (Blaydes & Chaney 2013)).

In contrast to the Muslim societies, Medieval Europe is often regarded as a backwater area, in particular in opposition to both Classical Greece and the Renaissance period. Our results are consistent with this negative view (See Figure [fig:antiquity]). Up until the 12th century, European scientific productivity is well below the Muslim scientific productivity. These results are consistent with recent assessment of economic development during the Early and Central medieval periods (Bosker *et al.* 2013; Maddison 2007; Milanovic 2013; Morris 2013). They are also consistent with the fact that while the most affluent parts of Europe (in particular Northern Italy and Flanders) catch-up with the Middle East around 1200, it is only around 1400 that Europe as a whole achieved level of economic development similar with the Muslim world during (Bosker *et al.* 2013; Maddison 2007; Milanovic 2013; Morris 2013).

Our results show that scientific production started to rise as soon as the 11th century, reached the level of the Muslim world around 1350 and quickly overtook it. This is in line with historians' qualitative assessment (Cohen 2012; Grant & Grant 1996; Huff 2017; Lindberg 2010). For instance, historian of optics Mark Smith notes that the very fact that Alhacen's *De aspectibus* was translated in the 13th c. suggests that European scientists had reached a level in optics high enough to be able to translate, read and understand this highly technical treatise:

‘First, there were translators available who were adequate to the task of rendering the text, with all its complexity, in a reasonably faithful manner. Second, there must have been a potential readership; otherwise, why undertake the laborious process of translating the text in the first place? We can thus assume that by no later than the beginning of the thirteenth century there was already a community of scholars in Europe prepared to assimilate or at least attempt to assimilate the De aspectibus.’ (Smith 2014 p. 15)

Regarding total scientific production, and not per capita production, Europe overtook the Muslim world during the 13th century. This is because the population of Europe tripled during the central medieval period (1000 – 1300), and went from 22 to 66 million, while the population of the Muslim world stagnated around 20 millions. So although European scientists were less productive individually up until 1350, Latin Europe was the most productive area from the 13th c. on. For instance, although *De aspectibus* was produced by a Muslim scholar (Alhacen) in 11th c. Egypt, the book was much popular in Europe than in the Muslim world, with 18 complete copies in medieval Europe, against only one in the Muslim world. As Mark Smith notes: ‘It is possible, of course, that as-yet-undiscovered manuscripts of the Arabic text are squirreled away in badly cataloged collections, but it is highly unlikely that these will add significantly to the current total. As far as the *De aspectibus* is concerned, then, there was a significantly larger community of interest in medieval Europe than in the medieval Muslim world.’(Smith 2014 p. 15)

Discussion: The Cultural Evolution of Science

We present the first estimates of scientific production during the late medieval and early modern period. They reveal important variations across countries and across periods. They also show a strong association between scientific productivity and economic development, as well as with artistic productivity, inclusive institutions and ascetic religiosity, suggesting a common underlying mindset of creativity (Baumard 2019; McCloskey 2016; Mokyr 2016). Small but economically advanced societies such as England, Holland and Scotland, despite their limited population, were much more innovative than larger but less economically advanced societies, such as France, Italy or Russia (see Table 1). This result challenges a common idea in cultural evolution that population size is crucial in explaining creativity and innovation (Collard *et al.* 2013; Henrich 2004; Kremer 1993; Shennan 2001).

It is worth noting that these results strikingly fit with the observations of contemporary observers. For instance, Voltaire, began his discussion of “great men” with the three greatest—all of them English: Bacon, Locke, and Newton (Mokyr 2016 p. 68). Similarly, when Count Marsigli of Bologna visited the Royal Society in 1721, he was struck by the difference

https://doi.org/10.1017/ehs.2023.6 Published online by Cambridge University Press

between Italy and England with regard to science: "[A]ll speculation unsupported by observation or experiment is utterly rejected. In England all study and teaching is based on fact" (cited in (Wootton 2015)).

In addition, our statistical modelling analysis suggests that economic development was a primary factor in the cultural evolution of science, whereas, horizontal transmission does not seem to explain the rise of scientific production, as well as its geographic distribution. Beyond the specific case of science, this is an interesting result for the understanding of human cultural evolution. It converges with recent work in behavioral and political sciences, putting forward the explanatory power of economic development (Baumard *et al.* 2015; Inglehart 2018; Martins & Baumard 2020; Safra *et al.* 2019; Welzel 2014) and demonstrates that ecological parameters (here and economic development) can drive the evolution of some aspects of human culture.

Several limitations need to be noted. First, our analysis is based on aggregate production at the country level. However, these aggregate estimates do not give a true estimate of the productivity of smaller units (but see (Akaliyski *et al.* 2021)). For instance, it is possible that the productivity of Ile-de-France (the region of Paris) is underestimated because it is pooled with the rest of France, which was much less developed. Similarly, the pooling of Southern and Northern Italy might downplay the burgeoning Italian Renaissance. Second, our indices of economic development are necessarily limited, and are likely to be revised in the future (Pleijt & Zanden 2020). For instance, recent works suggest that the GDP per capita of Renaissance Italy has been overestimated. It is likely that Northern Italy as its peak was not as rich as it has been thought (Zanden *et al.* 2017) which fits with our own results showing a lower scientific productivity than during the English and Dutch golden age. Third, GDP per capita is obviously a crude measure of human development, and a limited indicator of human capabilities. For instance, it is notable that Scandinavia was more productive scientifically than could be predicted from its GDP per capita. Other factors could play a role, such as individual freedom, education and gender equality, that are higher in northwestern Europe (Santos Silva *et al.* 2017; Welzel 2014)

Among the most discussed factors in the history of science, it is important to mention religion, and in particular Protestantism. Since the work of Max Weber and Robert K. Merton, Protestantism has often been cited as a possible cause of the Scientific Revolution. Protestant beliefs (in predestination), the work ethic, asceticism, and the insistence on reading the Bible would have led Protestant countries to have a more favourable attitude to science (Cohen 2012). The problem with such a theory is that Protestantism is not an exogenous factor. Even if there is an association between Protestantism and scientific production, this association could be the product of another hidden cause. In fact, religious asceticism, and in particular Protestantism, is also likely to be associated with scientific creativity because individuals with more long-term orientations are more likely to embrace a religion that value self-control, self-determination and investment in learning (Baumard *et al.* 2018; Baumard & Chevallier 2015).

To test the association with Protestantism, we created two groups of countries based on the religious affiliation of the majority of the population after the Wars of Religion and the Treaty of Westphalia, when the borders of each religion were more and less settled. Protestant countries include England, Scotland, Germany, the Netherlands, Switzerland and Scandinavia. Catholic countries include France, Italy, Portugal, Spain and Belgium. In line with the life-history framework, our results show a strong association between per capita scientific production and Protestantism. In line with Weber and Merton's account, both Protestantism and GDP are significantly associated with scientific productivity in a bivariate model ($\beta = .46$ for Protestantism, $p < 10^{-3}$, $\beta = .30$ for GDP per capita, $p < 10^{-3}$). Again the correlational nature of these analyses do not allow us to make any causal claim.

More generally, studying the evolution of science over the very long term seems to tend to downplay the role of religion. (Cohen 2012; Grant & Grant 1996; Needham 1981; Stark 2007) As shown by our results, Islam has been both associated with a very high scientific production (800 - 1200) as well as with a more limited scientific production (1200 - 1500). The same is true for Christianity, which is associated with a low scientific production during the medieval period, and a higher productivity during the early modern period. This results goes against standard hypotheses in history of science

It is worth noting that our study does not demonstrate a causal link between economic development and scientific productivity. Changes in both prosperity and creative productivity could have been caused by another, hidden change in history. One candidate is institutional change: inclusive institutions could have caused a rise in both scientific productivity and economic development (Acemoglu & Robinson 2012; North 1990), generating a spurious correlation between scientific production and economic development. However, economic development could have generated both the rise of science and the rise of democracy. But things could have gone the other way around, from economic development to inclusive institutions and scientific creativity. In fact, a growing body of work both in political science (Abramson & Boix 2014; Boix & Stokes 2003) and in the behavioral sciences (Martins & Baumard 2020; Petersen & Aarøe 2015; Safra *et al.* 2019) suggests that better life conditions are associated with higher level of interpersonal trust and higher support for inclusive institutions. In other words, institutional development, political freedom and inclusiveness are endogenous and accompany economic development (Boix & Stokes 2003). At present, it is difficult to disentangle these hypotheses. In the remainder of the article, we discuss an important aspect of this question, namely that good theories of the Scientific Revolution must explain not only the link between economic development and scientific productivity, but also the link between scientific productivity and a new attitude towards novelty and exploration.

Explaining the new attitudes toward innovation and exploration

Several interpretations of our results are possible. One possibility is simply that, in more economically advanced societies, individuals have more time, energy and resources to invest in scientific innovation. Science is indeed an expensive activity, because it requires a high level of human and material capital, but also because, until the end of the 19th century, it rarely brought substantial economic benefits. Our results suggest that rising living standards and economic prosperity further the advancement of science: scientific productivity was higher in the most affluent countries, and there is a positive association between living standards and both scientific and artistic productivity. One possible conclusion from these results could be that the Scientific Revolution is just the consequence of an increase of material resources.

Another interpretation is that, in addition to having more resources, Northwestern Europeans also had different preferences that were more conducive to innovation. The history of science, however, suggests that there was more than simply more time and more resources behind scientific advances. In his account of the Scientific Revolution, David Wootton ((Wootton 2015)) observes that, in many cases, what prevented people from advancing their knowledge was not a lack of time or money, but the inability to question authorities:

Mondino de Liuzzi (1270–1326), for example, the author of the first medieval textbook on how to perform a dissection, had plenty of hands-on experience, but he still found at the base of the human brain the *rete mirabile* (miraculous network) of blood vessels that Galen claimed was there, despite the fact that it isn't there at all – it is only present in ungulates. (...) The first anatomist regularly to disagree with Galen on the basis of direct experience was Jacopo Berengario da Carpi, whose Anatomy was published in 1535, only a few years before Vesalius's Fabric. Only in a culture where the authority of the great classical authors such as Ptolemy and Galen had begun to be undermined could a project like Vesalius's Fabric be undertaken. (Wootton 2015 p. 335)

Wootton makes a similar point about the 19th-century revolution in medicine. He points out that the germ theory of disease could have been discovered much earlier than the 19th century for the primary obstacle to progress, he argues, was not practical (Leeuwenhoek's microscopes worked well), nor theoretical (the germ theory of putrefaction was not difficult to formulate) but psychological and cultural ((Wootton 2015 p. 286)).

More generally, as Wootton points out, before the 16th and 17th centuries, history was assumed to repeat itself, and tradition taken to provide a reliable guide to the future. The greatest achievements of civilization were believed to lie not in the present or the future but in the past, in ancient Greece and classical Rome. By contrast, a new optimistic attitude toward the future and the possibility of progress gradually emerged in the 16th century.

This new attitude was summed up by Louis Le Roy (or Regius, 1510–77) in 1575:

[T]here remayne more thinges to be sought out, then are alreadie invented, and founde. And let us not be so simple, as to attribute so much unto the Auncients, that wee beleeve that they have knowen all, and said all; without leaving anything to be said, by those that should come after them.... Let us not thinke that nature hath given them all her good gifts, that she might be barren in time to come: ... How many [secrets of nature] have bin first knowen and found out in this age? I say, new lands, new seas, new formes of men, maners, lawes, and customes; new diseases, and new remedies; new waies of the Heaven, and of the Ocean, never before found out; and new starres seen? yea, and how many remaine to be (cited in (Wootton 2015 p. 118)).

A similar attitude can be found in writings by Bacon, Descartes and Galileo (Rossi 2001; Wootton 2015). This is reflected in the titles of the scientific books of the time: *Nova de universis philosophia* (Patrizi, 1591), *Novo theatro de machine* (Zonca, 1607), *Astronomia nova* (Kepler, 1609), *Discursi intorno a due nuove scienze* (Galileo, 1638), *De mundo nostro sublunari philosophia nova* (Gilbert, 1651). During the 17th century, more than a hundred books used the term "novus" in their title (Thorndike, 1971). As Mokyr (Mokyr 2016) notes, they no longer subscribed to "the Ecclesiastes view of history," which holds that long-term change is impossible, because "there is nothing new under the sun."

17th c. intellectuals were also more open to creativity and innovation. As McCloskey notes, words such as "innovation" and "novelty" often used to have negative connotations before the 17th c.. These same words started to be more positive, and emotional attachment to traditional ways of doing things progressively decreased (McCloskey 2016, p .94).

These examples suggest that the cultural change that occurred during the period conventionally identified as the Scientific Revolution consisted at least partially in changes in mindset or mentality, as if the obstacles to the spread of the new scientific ideas were psychological, rather than technical (e.g., the need for a new instrument) or economic (e.g., the need for more education, time, books, etc.). For instance, Galileo tells the story of a professor who refused to accept that the nerves were connected to the brain rather than the heart because this was at odds with Aristotle's explicit statement—and stood his ground even when he was shown the pathways of the nerves in a dissected cadaver (Wootton 2015). He also reports that his close philosopher friend Cremonini refused to look through his telescope for the simple reason that Aristotle did not use telescopes, and were therefore irrelevant (Wootton 2015).

This shift in views on the progress of science predates actual scientific progress, which also argues for our hypothesis. In his famous study on the decline of magic, Keith Thomas noted that:

In many different spheres of life, the period saw the emergence of a new faith in the potentialities of human initiative. (…) The change was less a matter of positive technical progress than of an expectation of greater progress in the future. (…) It marked a break with the characteristic medieval attitude of contemplative resignation. (Thomas 1971 p. 1184)

Thomas was struck that this optimism in the power of technical progress could not be based on actual evidence. “It is often said that witch-beliefs are a consequence of inadequate medical technique. But in England such beliefs declined before medical therapy had made much of an advance” (Thomas 1971 p. 1211). In the same way, the popularity of the work of Francis Bacon in the 17th century — that is, before the great wave of technical progress — attests that the English were very receptive toward optimistic ideas (Mokyr 2016).

Similar observations can be made in the domain of technological innovation. As Howes (Howes 2016b) observes, 18th- and 19th-century innovators had an “improving mentality”, seeing room for improvement everywhere. Henry Dircks, an English engineer who improved steam engines and designed optical illusions, offered this very clear characterization of this new mentality:

No work of art appears perfect to an enterprising mind. However simple its purpose, it may possibly be made lighter, stronger, more efficacious, or be done away with altogether. The man whose mind is thus constituted becomes an Inventor. (as cited in Howes 2016a p. 8).

But if Northwestern Europeans had different preferences that were more conducive to innovation, why this association with economic development and living standards? Recent work in behavioral sciences have found that resource abundance triggers cognitive exploration, curiosity, independent- and open-mindedness, whereas resource scarcity triggers conservatism and conformism, in order not to take the risk of an unfruitful exploration (Dubourg *et al.* 2021; Dubourg & Baumard 2022; Jacquet *et al.* 2018; Nettle 2018). This interpretation, fit well with the fact that at the time of the Scientific Revolution, North-Western European had a very specific psychology that was more future-oriented, with higher levels of social trust, lower levels of interpersonal violence, a greater interest in romantic love, a greater interest in parental investment (Baumard 2018).

The rising living standards experienced by Europeans may thus have changed individuals’ psychology toward more optimism and non-conformism. As a result, Europeans would have started being more confident in their capacity to change the world, to propose new theories and to test them. In turn, this optimism may have made the experimental method and natural philosophy more appealing (despite the fact that, in the 17th century, there was as yet no evidence that experiments and science could really improve people’s situation).

Methods

Scientific and Artistic Production

To collect the datasets, we used a top-down approach based on Wikipedia categories (Laouenan *et al.* 2022). First, we manually identified all the relevant Wikipedia categories (for instance, "18th century Italian mathematicians").

We only included individuals working in the "hard sciences": mathematicians, physicists, astronomers, chemists, biologists, botanists, and zoologists (the first three categories account for more 90% of the sample). The rationale for this choice is that these domains correspond to the core domains of the 17th century Scientific Revolution. It also corresponds to what economists call "useful knowledge," the kind of knowledge involved in the manipulation of the material world, and the main source of growth during the Industrial Revolution (Jacob, 1997; Mokyr, 2016). In any case, the number of social scientists in Wikipedia before 1850 is too limited for a quantitative study. We also excluded physicians, because their biographies are mostly concerned not with scientific advances, but with their social role at the time. Moreover, given medical doctors' poor record at increasing medical knowledge before the late 19th century, they arguably do not represent a good proxy for innovation (Wootton 2007).

We also wanted to measure cultural creativity in general. We thus included all occupations that involve an important component of innovation and creativity: writers, philosophers, painters, musicians and sculptors. By contrast, we excluded rulers, military personnel, lawyers, religious leaders, and physicians because these occupations arguably do not involve the same level of creativity. Some extra creative occupations could have been included, but were excluded due to the small number of individuals in each category: engineers, geographers, explorers, cartographers, or architects. In total, 22,943 individuals were included in the dataset (see Table S1).

We included in our sample all modern countries for which there were lists by nationality in science for the 19th century or before. Our final list includes the following countries: Belgium, United Kingdom, France, Germany, Italy, the Netherlands, Iberia (Spain and Portugal), Poland, Russia and Scandinavia (see Fig. S1). We created two aggregated countries (Scandinavia and Iberia) because some environmental variables were only available at this level (see below, urbanization).

Where country of citizenship (around 30% of the pages) was not specified on the individual's Wikidata item page, we inferred it using two methods. First, when possible, we referred to the Wikipedia category in which we had found the page (e.g., someone belonging to the category of "Italian mathematicians" was considered Italian). When this was not possible, our code looked at the first words on the page and used the common structure "[Name] ([dates]) was a…". A page beginning with "Galileo Galilei (15 February 1564 – 8 January 1642) was an Italian astronomer" meant that Galileo was classified as Italian. Finally, we checked and completed by hand the most important dataset of this study, concerning Renaissance scientists.

We collected three proxies for the importance of an individual's contribution to the advancement of science (Gergaud *et al.* 2017a):

1. Length: The number of bytes in the Wikipedia page (from "Page Information") 2. Languages: The number of languages in which there was a page for the individual (from Wikidata) 3. Quotation: The number of Wikipedia pages containing a link toward this page (from the corresponding Wikidata item page).

To avoid a potential language bias leading to an overestimation of British production, we ran this study on the three largest Wikipedias: English, French and German. Contrary to our expectations, the datasets from the French and German Wikipedias were not always smaller than those from English Wikipedia (for instance, the German-language dataset of scientists is much larger than the English-language dataset, while the opposite is true for painters). Note also that previous work on notable individuals in Wikipedia has demonstrated that while a small portion of lesser-known individuals are present in non-English pages but absent in English pages, this is not the case for the most notable individuals (Gergaud *et al.* 2017a).

As we record three proxies for each of the three languages, we have 9 indicators of an individual's production (see Fig. S3). None of these indices is perfect, and they all have their biases, so we combined them through a PCA, to compute the *Individual Scientific productivity*. The resulting values are neatly distributed as a power law with $\alpha = 1$. This shape seems robust for different periods (e.g. scientists of antiquity) or different type of individuals (e.g. Renaissance artists).

Next, for a given year (here noted y), we computed the Total Scientific Product. Assuming an average peak productivity at 35, we used the following formula: National Scientific Product is the sum of the Individual Scientific Productivity of all individuals who reached the age of 35 between the year y -25 and the year y + 25 in a given country.

To get per capita estimates, we divided the National Scientific Product by the estimate population in year y (estimates are taken from the Atlas of World Population (McEvedy, Jones & others, 1978). This provided demographic estimates for every century, or every 50 years. We thus performed a linear extrapolation to derive population figures at ten-year intervals for each country.

Because we were interested in the dynamics of the Scientific Revolution, which is usually dated around 1650, we choose 1300 as the starting date of our study and 1850 as the ending date.

Environmental variables

In order to study the ecological determinants of scientific production, we used two measures of standard of living: GDP per capita (Broadberry *et al.* 2017) and urbanization ratio (Bosker *et al.* 2013).

To test the importance of universities, we used the number of universities retrieved from Wikipedia's "List of medieval universities" and "List of oldest universities in continuous operation". As mentioned earlier, we also used the number of days of parliamentary sessions to test the effect of inclusive institutions, and the majority religion of the country, for the effect of Protestantism. We took these environmental variables as predictors, ran linear regressions of country-level cultural production against each variable, and computed correlation coefficients for production (taken as the mean of the z-scores for the 9 estimates).

Data availability

All the data and code are available in this repository: https://github.com/regicid/Code_scientific_revolution.

Acknowledgements

We thank Lou Safra and Mauricio Martins for their help in analysing the data, Paul Reeve for his careful correction of the draft and Hugo Mercier and Mike Kestmont for their feedback on the manuscript.

Financial support

The project was funded by ANR-17-EURE-0017 FrontCog and ANR-10-IDEX-0001-02 PSL.

Author contributions

BdC and NB designed the initial project, BdC gathered the data, BdC and VT conducted the statistical analysis, NB wrote the first draft, the three authors revised it.

Conflicts of interest

The authors have no conflict of interest.

References

Abramson, S., & Boix, C. (2014). The Roots of the Industrial Revolution: Political Institutions or (Socially Embedded) Know-How? *Unpublished Typescript, Princeton University*. Retrieved from https://wws.princeton.edu/system/files/research/documents/Boix_Abramson_the%20_roots_of_the_industrial_revolution_0.pdf

Acemoglu, D., & Robinson, J. (2012). *Why nations fail: The origins of power, prosperity, and poverty*, Crown Business.

Adams, J. (1998). Benchmarking international research. *Nature*, **396**(6712), 615–618.

Akaliyski, P., Bond, M. H., & Welzel, C. (2021). Nations as gravitational fields of culture: In defence of "nationology."

Aksnes, D. W., Langfeldt, L., & Wouters, P. (2019). Citations, citation indicators, and research quality: An overview of basic concepts and theories. *Sage Open*, **9**(1), 2158244019829575.

Albarrán, P., Crespo, J., Ortuno, I., & Ruiz-Castillo, J. (2010). A comparison of the scientific performance of the US and the european union at the turn of the 21st century. *Scientometrics*, **85**(1), 329–344.

Allen, R. C., Bassino, J.-P., Ma, D., Moll-Murata, C., & Van Zanden, J. L. (2011). Wages, prices, and living standards in China, 1738–1925: In comparison with Europe, Japan, and India. *The Economic History Review*, **64**(s1), 8–38.

Allen, R. C., & Heldring, L. (2021). The collapse of civilization in southern mesopotamia. *Cliometrica*, 1–36.

Allik, J. et al. (2013). Factors affecting bibliometric indicators of scientific quality. *Trames*, **17**(3), 199–214.

Alonso, S., Cabrerizo, F. J., Herrera-Viedma, E., & Herrera, F. (2009). H-index: A review focused in its variants, computation and standardization for different scientific fields. *Journal of Informetrics*, **3**(4), 273–289.

André, J.-B., & Baumard, N. (2019). Cultural evolution by capital accumulation. *bioRxiv*, 707620.

André, J.-B., & Baumard, N. (2020). Cultural evolution by capital accumulation. *Evolutionary Human Sciences*, **2**.

Archambault, É., Campbell, D., Gingras, Y., & Larivière, V. (2009). Comparing bibliometric statistics obtained from the web of science and scopus. *Journal of the American Society for Information Science and Technology*, **60**(7), 1320–1326.

Baumard, N. (2017). Phenotypic plasticity. *Edge*.

Baumard, N. (2018). Psychological origins of the industrial revolution. *Behavioral and Brain Sciences*, 1–47.

Baumard, N. (2019). Psychological Origins of the Industrial Revolution: More Work is Needed! *Behavioral and Brain Sciences*.

Baumard, N., & Chevallier, C. (2015). The nature and dynamics of world religions: A life-history approach. In *Proc. R. Soc. B*, Vol. 282, The Royal Society, p. 20151593.

Baumard, N., Huillery, E., & Zabrocki, L. (2018). The origins of romantic love and asceticism: How economic prosperity changed human psychology in medieval europe. *Work. Pap., Sciences Po, Paris*.

Baumard, N., Hyafil, A., Morris, I., & Boyer, P. (2015). Increased affluence explains the emergence of ascetic wisdoms and moralizing religions. *Current Biology*, **25**(1), 10–15.

Blaydes, L., & Chaney, E. (2013). The feudal revolution and europe's rise: Political divergence of the christian west and the muslim world before 1500 CE. *American Political Science Review*, **107**(1), 16–34.

Boix, C., & Stokes, S. C. (2003). Endogenous democratization. *World Politics*, **55**(4), 517–549.

Bosker, M., Buringh, E., & Zanden, J. L. van. (2013). From Baghdad to London: Unraveling Urban Development in Europe, the Middle East, and North Africa, 800–1800. *Review of Economics and Statistics*, **95**(4), 1418–1437.

Broadberry, S. N., Guan, H., & Li, D. D. (2017). China, Europe and the Great Divergence: A Study in Historical National Accounting, 980-1850. Retrieved from https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2957511

Broadberry, Campbell, B. M., Klein, A., Overton, M., & Van Leeuwen, B. (2015). *British economic growth, 1270–1870*, Cambridge University Press. Retrieved from

https://doi.org/10.1017/ehs.2023.6 Published online by Cambridge University Press

https://books.google.fr/books?hl=fr&lr=&id=wJvWBQAAQBAJ&oi=fnd&pg=PR15&dq=broadberry+british+economic+growth&ots=f5PL6iht6F&sig=syBloMoAiV-qrl5mgjACncmxin8

Bukowski, M., Koryś, P., Leszczyńska, C., Tymiński, M., & Wolf, N. (2019). Urbanization and GDP per capita: New data and results for the polish lands, 1790–1910. *Historical Methods: A Journal of Quantitative and Interdisciplinary History*, **52**(4), 213–227.

Callahan, E. S., & Herring, S. C. (2011). Cultural bias in wikipedia content on famous persons. *Journal of the American Society for Information Science and Technology*, **62**(10), 1899–1915.

Chaney, E. (2018). Medieval Origins: A Review Essay on Campbell's The Great Transition. *Journal of Economic Literature*, **56**(2), 643–656.

Clark, G. (2008). *A farewell to alms: A brief economic history of the world*, Princeton University Press. Retrieved from https://books.google.fr/books?hl=fr&lr=&id=i-PLg2PsNd4C&oi=fnd&pg=PR7&dq=clark+farewell+to+alms&ots=fGcMxkyJ-h&sig=c6BauP72IIgMdBSEGx-DMZVM8Jw

Cohen, H. F. (1994). *The scientific revolution: A historiographical inquiry*, University of Chicago Press.

Cohen, H. F. (2012). *How modern science came into the world: Four civilizations, one 17th-century breakthrough*, Amsterdam University Press.

Collard, M., Ruttle, A., Buchanan, B., & O'Brien, M. J. (2013). Population size and cultural evolution in nonindustrial food-producing societies. *PloS One*, **8**(9), e72628.

Coşgel, M. M., Miceli, T. J., & Rubin, J. (2012). The political economy of mass printing: Legitimacy and technological change in the Ottoman Empire. *Journal of Comparative Economics*, **40**(3), 357–371.

Cummins, N. (2014). Longevity and the Rise of the West: Lifespans of the European Elite, 800-1800. *Browser Download This Paper*. Retrieved from https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2496939

Dubourg, E., & Baumard, N. (2022). Why imaginary worlds? The psychological foundations and cultural evolution of fictions with imaginary worlds. *Behavioral and Brain Sciences*, **45**, e276.

Dubourg, E., Thouzeau, V., Dampierre, C. de, & Baumard, N. (2021). Exploratory preferences explain the cultural success of imaginary worlds in modern societies.

Eisenstein, E. L. (1980). *The printing press as an agent of change*, Vol. 1, Cambridge University Press.

Falagas, M. E., Pitsouni, E. I., Malietzis, G. A., & Pappas, G. (2008). Comparison of PubMed, scopus, web of science, and google scholar: Strengths and weaknesses. *The FASEB Journal*, **22**(2), 338–342.

Febvre, L., & Martin, H.-J. (1997). *The coming of the book: The impact of printing 1450-1800*, Vol. 10, Verso.

Fogarty, L., Wakano, J. Y., Feldman, M. W., & Aoki, K. (2017). The Driving Forces of Cultural Complexity. *Human Nature*, **28**(1), 39–52.

Fouquet, R., & Broadberry, S. (2015). Seven centuries of European economic growth and decline. *The Journal of Economic Perspectives*, **29**(4), 227–244.

Fraiberger, S. P., Sinatra, R., Resch, M., Riedl, C., & Barabási, A.-L. (2018). Quantifying reputation and success in art. *Science*, **362**(6416), 825–829.

Gergaud, O., Laouenan, M., & Wasmer, E. (2017a). A Brief History of Human Time. Exploring a database of" notable people". Retrieved from https://hal.archives-ouvertes.fr/hal-01440325/

Gergaud, O., Laouenan, M., & Wasmer, E. (2017b). A Brief History of Human Time. Exploring a database of" notable people". Retrieved from https://hal.archives-ouvertes.fr/hal-01440325/

Grant, E., & Grant, E. E. (1996). *The foundations of modern science in the Middle Ages: Their religious, institutional and intellectual contexts*, Cambridge University Press.

Grossetti, M., Eckert, D., Gingras, Y., Jégou, L., Larivière, V., & Milard, B. (2014). Cities and the geographical deconcentration of scientific activity: A multilevel analysis of publications (1987–2007). *Urban Studies*, **51**(10), 2219–2234.

Harzing, A.-W., & Alakangas, S. (2016). Google scholar, scopus and the web of science: A longitudinal and cross-disciplinary comparison. *Scientometrics*, **106**(2), 787–804.

Haushofer, J., & Fehr, E. (2014). On the psychology of poverty. *Science*, **344**(6186), 862–867.

Henrich, J. (2004). Demography and cultural evolution: How adaptive cultural processes can produce maladaptive losses—the Tasmanian case. *American Antiquity*, **69**(2), 197–214.

Holmgren, M., & Schnitzer, S. A. (2004). Science on the rise in developing countries. *PLoS Biology*, **2**(1), e1.

Hörl, M., Kesternich, I., Smith, J. P., & Winter, J. K. (2016). Early-life Circumstances Predict Measures of Trust among Adults: Evidence from Hunger Episodes in Post-War Germany.

Howes, A. (2016a). The Improving Mentality: Innovation during the British Industrial Revolution, 1651-1851. Retrieved from https://pdfs.semanticscholar.org/883b/7149dca21fe88577f4c8164ce7ad49711e30.pdf

Howes, A. (2016b). The Relevance of Skills to Innovation during the British Industrial Revolution, 1651-1851. Retrieved from https://www.peter-boettke.com/app/download/7121915994/Howes_PPE.pdf

Huff, T. E. (2017). *The rise of early modern science: Islam, China, and the West*, Cambridge University Press.

Inglehart, R. (2018). *Cultural Evolution: People's Motivations are Changing, and Reshaping the World*, Cambridge University Press.

Inglehart, R., & Welzel, C. (2005). *Modernization, cultural change, and democracy: The human development sequence*, Cambridge University Press.

Jacquet, P. O., Safra, L., Wyart, V., Baumard, N., & Chevallier, C. (2019). The ecological roots of human susceptibility to social influence: A pre-registered study investigating the impact of early-life adversity. *Royal Society Open Science*, **6**(1), 180454.

Jacquet, P. O., Wyart, V., Desantis, A., … Waszak, F. (2018). Human susceptibility to social influence and its neural correlates are related to perceived vulnerability to extrinsic morbidity risks. *Scientific Reports*, **8**(1), 13347.

King, A. A., Nguyen, D., & Ionides, E. L. (2016). Statistical inference for partially observed markov processes via the r package pomp. *Journal of Statistical Software*, **69**(i12).

King, D. A. (2004). The scientific impact of nations. *Nature*, **430**(6997), 311–316.

Kremer, M. (1993). Population growth and technological change: One million BC to 1990. *The Quarterly Journal of Economics*, **108**(3), 681–716.

Laouenan, M., Bhargava, P., Eyméoud, J.-B., Gergaud, O., Plique, G., & Wasmer, E. (2022). A cross-verified database of notable people, 3500bc-2018ad. *Scientific Data*, **9**(1), 1–19.

Leroi, A. M. (2014). *The lagoon: How Aristotle invented science*, Bloomsbury Publishing.

Lindberg, D. C. (2010). *The Beginnings of Western Science: The European Scientific Tradition in Philosophical, Religious, and Institutional Context, Prehistory to A.D. 1450, Second Edition*, University of Chicago Press.

Maddison, A. (2007). *The world economy volume 1: A millennial perspective volume 2: Historical statistics*, Academic Foundation.

Malanima, P. (2011). The long decline of a leading economy: GDP in central and northern Italy, 1300–1913. *European Review of Economic History*, **15**(2), 169–219.

Martins, M. de J. D., & Baumard, N. (2020). The rise of prosociality in fiction preceded democratic revolutions in early modern europe. *Proceedings of the National Academy of Sciences*, **117**(46), 28684–28691.

Maslow, A. H. (1943). A theory of human motivation. *Psychological Review*, **50**(4), 370.

May, R. M. (1997). The scientific wealth of nations. *Science*, **275**(5301), 793–796.

McCloskey, D. N. (2016). *Bourgeois equality: How ideas, not capital or institutions, enriched the world*, University of Chicago Press.

McEvedy, C., Jones, R., et al. (1978). *Atlas of world population history.*, Penguin Books Ltd, Harmondsworth, Middlesex, England.

Meo, S. A., Al Masri, A. A., Usmani, A. M., Memon, A. N., & Zaidi, S. Z. (2013). Impact of GDP, spending on r&d, number of universities and scientific journals on research publications among asian countries. *PloS One*, **8**(6), e66449.

Mesgari, M., Okoli, C., Mehdi, M., Nielsen, F. Å., & Lanamäki, A. (2015). "The sum of all human knowledge": A systematic review of scholarly research on the content of wikipedia. *Journal of the Association for Information Science and Technology*, **66**(2), 219–245.

Mesoudi, A. (2011). *Cultural evolution*, University of Chicago Press.

Mesoudi, A., & Thornton, A. (2018). What is cumulative cultural evolution? *Proceedings of the Royal Society B*, **285**(1880), 20180712.

Milanovic, B. (2013). Income level and income inequality in the Euro-Mediterranean region: From the Principate to the Islamic conquest. Retrieved from https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2265877

Mokyr, J. (2016). *A Culture of Growth: The Origins of the Modern Economy*, Princeton University Press.

Mongeon, P., & Paul-Hus, A. (2016). The journal coverage of web of science and scopus: A comparative analysis. *Scientometrics*, **106**(1), 213–228.

Montgomery, D. R. (2012). *Dirt: The erosion of civilizations*, Univ of California press.

Morris, I. (2013). *The measure of civilization: How social development decides the fate of nations*, Princeton University Press.

Needham, J. (1981). *Science in traditional China: A comparative perspective*, Chinese University Press.

Nettle, D. (2018). State-dependent cognition and its relevance to cultural evolution. *Behavioural Processes*.

Nielsen, F. Å. (2007). Scientific citations in wikipedia. *arXiv Preprint arXiv:0705.2106*.

North, D. C. (1990). *Institutions, institutional change and economic performance*, Cambridge university press.

Ober, J. (2015). *The rise and fall of classical Greece*, Princeton University Press.

Özmucur, S., & Pamuk, Ş. (2002). Real wages and standards of living in the ottoman empire, 1489–1914. *The Journal of Economic History*, **62**(2), 293–321.

Pamuk, Ş., & Shatzmiller, M. (2014). Plagues, Wages, and Economic Change in the Islamic Middle East, 700–1500. *The Journal of Economic History*, **74**(01), 196–229.

Pepper, G. V., & Nettle, D. (2017). The behavioural constellation of deprivation: Causes and consequences. *The Behavioral and Brain Sciences*, 1.

Petersen, M. B., & Aarøe, L. (2015). Birth Weight and Social Trust in Adulthood Evidence for Early Calibration of Social Cognition. *Psychological Science*, **26**(11), 1681–1692.

Pleijt, A. de, & Zanden, J. L. van. (2020). The maddison project.

Ponting, C. (2007). *A new green history of the world: The environment and the collapse of great civilizations*, Random House.

Rashed, R. (2002). *Encyclopedia of the history of Arabic science*, Routledge.

Robinson, J. A., & Acemoglu, D. (2012). *Why nations fail: The origins of power, prosperity and poverty*, Profile London.

Rossi, P. (2001). *The birth of modern science*, Wiley-Blackwell.

Rousset, F. (2017). An introduction to the spaMM package for mixed models.

Russo, L. (2013). *The forgotten revolution: How science was born in 300 BC and why it had to be reborn*, Springer Science & Business Media.

Safra, L., Algan, Y., Tecu, T., Grèzes, J., Baumard, N., & Chevallier, C. (2017). Childhood harshness predicts long-lasting leader preferences. *Evolution and Human Behavior*. Retrieved from http://www.sciencedirect.com/science/article/pii/S1090513817300053

Safra, L., Chevallier, C., Grèzes, J., & Baumard, N. (2019). Tracking the rise of trust in history using machine learning and paintings. *In Review*.

Santos Silva, M., Alexander, A. C., Klasen, S., & Welzel, C. (2017). *The roots of female emancipation: From perennial cool water via pre-industrial late marriages to postindustrial gender equality*, Discussion Papers.

Schich, M., Song, C., Ahn, Y.-Y., … Helbing, D. (2014). A network framework of cultural history. *Science*, **345**(6196), 558–562.

Serafinelli, M., & Tabellini, G. (2017). Creativity over time and space.

Shennan, S. (2001). Demography and cultural innovation: A model and its implications for the emergence of modern human culture. *Cambridge Archaeological Journal*, **11**(1), 5–16.

Sinatra, R., Wang, D., Deville, P., Song, C., & Barabási, A.-L. (2016). Quantifying the evolution of individual scientific impact. *Science*, **354**(6312), aaf5239.

Smith, A. M. (2014). *From sight to light: The passage from ancient to modern optics*, University of Chicago Press.

Stark, R. (2007). *The victory of reason: How Christianity led to freedom, capitalism, and Western success*, Random House.

Starr, S. F. (2013). *Lost enlightenment: Central Asia's golden age from the Arab conquest to Tamerlane*, Princeton University Press.

Stocks, T., Britton, T., & Höhle, M. (2020). Model selection and parameter estimation for dynamic epidemic models via iterated filtering: Application to rotavirus in germany. *Biostatistics*, **21**(3), 400–416.

Thomas, K. (1971). *Religion and the decline of magic: Studies in popular beliefs in sixteenth and seventeenth-century England*, Penguin UK.

Vaesen, K., Collard, M., Cosgrove, R., & Roebroeks, W. (2016). Population size does not explain past changes in cultural complexity. *Proceedings of the National Academy of Sciences*, **113**(16), E2241–E2247.

Van Bavel, B., Buringh, E., & Dijkman, J. (2018). Mills, cranes, and the great divergence: The use of immovable capital goods in western Europe and the Middle East, ninth to sixteenth centuries. *The Economic History Review*, **71**(1), 31–54.

Van Zanden, J. L., Buringh, E., & Bosker, M. (2012). The rise and decline of European parliaments, 1188–1789. *The Economic History Review*, **65**(3), 835–861.

Vinkler, P. (2008). Correlation between the structure of scientific research, scientometric indicators and GDP in EU and non-EU countries. *Scientometrics*, **74**(2), 237–254.

Welzel, C. (2014). Evolution, empowerment, and emancipation: How societies climb the freedom ladder. *World Development*, **64**, 33–51.

Willinsky, J. (2010). Socrates back on the street: Wikipedia's citing of the stanford encyclopedia of philosophy. In *Emerging digital spaces in contemporary society*, Springer, pp. 157–171.

Wootton, D. (2007). *Bad medicine: Doctors doing harm since Hippocrates*, Oxford University Press.

Wootton, D. (2015). *The invention of science: A new history of the scientific revolution*, Penguin UK.

Xu, T. (2017). The Production and Circulation of Manuscripts and Printed Books in China Compared to Europe, ca. 581-1840. *Europe*, **581**. Retrieved from http://technologygovernance.eu/files/main/2013070208164949.pdf

Zanden, J. L. van, Felice, E., et al. (2017). *Benchmarking the middle ages. XV century tuscany in european perspective*.